THEME 1

EXTREME STORMS AND EXTREME FLOODS

International Seminar on Hydrology of Extremes 1-3 December, 1988
Roorkee (India)

PALAEOFLOOD HYDROLOGY OF TROPICAL RIVERS

V. R. Baker
Regents' Professor of Geosciences

The University of Arizona
Tucson, Arizona 85721 U.S.A.

SYNOPSIS

In recent years very accurate and complete catalogs of ancient, extraordinary floods have been developed through scientific study of slackwater deposits and palaeostage indicators (SWD-PSI) in stable-boundary fluvial reaches. SWD-PSI palaeoflood hydrology is particularly suited to studies of tropical bedrock rivers, such as the Narmada River in India. Advances in geochronology, hydraulic flow modeling, and censored-sample maximum likelihood flood-frequency analysis have produced a scientific breakthrough in palaeoflood studies. Palaeoflood information is of immense value for determining the likelihood and frequency of extraordinary floods larger than can be documented with conventional flow data. Applications of palaeoflood hydrology include the design of dam spillways and testing the reasonableness of flood estimates obtained in modeling studies.

1.0 INTRODUCTION

1.1 Palaeoflood hydrology is the study of past or ancient flood events which occurred prior to the time of human observation or direct measurement by modern hydrologic procedures. Most studies involve prehistoric floods, although the methodology may also be applicable to historic or modern floods in remote areas not subject either to modern hydrologic analysis or to human observation. Thus, palaeoflood hydrology may be distinguished from both historical flood analysis and conventional flood hydrology. The latter involves continuous monitoring of flood properties by hydrologists, while the former requires human documentation of flow events, generally in a non-systematic manner by non-hydrologists.

1.2 The most accurate and complete palaeoflood hydrological studies are achieved in work on stable-boundary fluvial reaches characterized by slackwater deposits and palaeostage indictors (SWD-PSI) emplaced by extraordinatry floods [3,7,19]. Slackwater dpeosits consist of sand and silt (occasionally gravel) that settle relatively rapidly from suspension during major floods, particularly where flow boundaries result in markedly reduced local flow velocities [6,18,29]. For palaeoflood studies, the selected slackwater sedimentation sites should be optimum for both the accumulation and the preservation of the relatively fine-grained flood sediments carried high in flood flows at their maximum stage [6,8,20]. The slackwater deposits and other palaeostage data are transformed to discharge estimates by hydraulic flow modeling [14,26,28]. Flood palaeodischarges can then be used for comparison to conventional flood data, or they can be used in a flood-frequency analysis.

2.0 APPLICATIONS

2.1 Historical and palaeoflood data have been used since the early 1970s for flood-frequency analysis related to spillway design for high-risk dams in China [5,12,23,32,33,40]. In the United States a National Research Council review of dam safety [24] advocated the analysis of physical evidence of large palaeofloods to provide objective evidence of the likelihood and frequency of larger floods than can be documented by gauged flows. Another recent major review of methods for estimating extreme flood probabilities [25] concluded that palaeoflood hydrology provided one of several opportunities to improve the practice and science of rare flood hydrology. Dawdy and Lettenmaier [13] propose a procedure in which palaeoflood data are combined with recorded flood series in censored-sample maximum likelihood estimation procedures [35] to extend flood frequency distributions to the magnitudes of extremely rare events. The resulting estimates of low probability floods can then be compared to conventional estimates of the Probable Maximum Flood, determined by hydrometeorology and rainfall-runoff modeling.

2.2 The use of palaeoflood data as a test or check on conventional flood estimates contributes to a scientific basis for design [1,17]. Especially important are applications in regions where conventional hydrological data records are sparse [9,11,39] and where the temporal and spatial variability of rainfall and runoff yield complex flood behavior [31]. The coupled arid-semiarid-savanna regimes of the tropics are important regions for applied palaeoflood hydrology.

3.0 STUDY AREAS

3.1 The best palaeoflood sites are located in channel reaches with flow boundaries constrained by bedrock, immobile sediment, or other resistant boundary materials. Such channels produce relatively large stage changes for changes in flood discharge [2,4,8,27]. Moreover, they do not change their cross sections appreciably during major floods, as commonly occurs in alluvial channels. The relatively high stages achieved by floods in resistant-boundary channels produce several kinds of high-water indicators. Most common are deposits of sand, silt, and (rarely) gravel that accumulate relatively rapidly from suspension in highly energetic floods. These accumulate in local areas of reduced flow velocity and are called "slack-water deposits."

3.2 SWD-PSI palaeoflood studies are best accomplished in river reaches displaying the following characteristics: (i) adequate concentrations of sand and silt in transport by floods, (ii) resistant-boundary channels not subject to appreciable aggradation, (iii) depositional sites with high potential for preservation of SWD-PSI features, and (iv) narrow, deep canyons or gorges in resistant geological materials. Major studies accomplished to date or in progress are located in near-tropical areas affected by severe storms (Fig. 1).

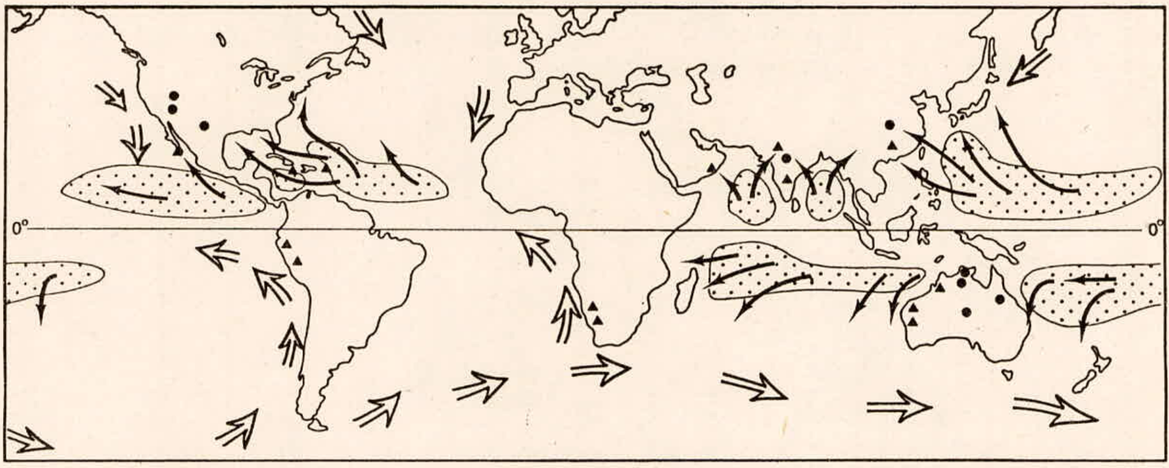

Figure 1. Sites of SWD-PSI palaeoflood hydrological investigations, including active (dots) and potential (triangles) study areas. Source areas of tropical storms (small arrows) are indicated by dot pattern. Cold-water ocean currents are indicated by large arrows.

3.3 Local bedrock reaches suitable for SWD-PSI studies generally display sedimentary and erosional landforms related to floods of exceptional stream power per unit area ω, calculated as

$$\omega = \frac{\gamma Q S}{w} = \tau V,$$

where ω is expressed in Wm^{-2}, γ is the fluid specific weight in Nm^{-3}, Q is the discharge in $m^3 s^{-1}$, w is the channel width in m, τ is the boundary shear stress in Nm^{-2}, and V is the mean flow velocity in ms^{-1}. Typical ω values achieved by extreme floods at SWD-PSI sites range from 10^3 to 10^4 Wm^{-2} [4,8]. The local sites of slackwater sediment accumulation in such rivers include the following: (i) tributary mouths, (ii) abrupt channel expansions, (iii) in the lee of bedrock flow obstructions, (iv) in channel-margin caves and alcoves, (v) at meander bends, and (vi) upstream of abrupt channel expansions. Laboratory flume studies [6,21] and field observations [6,20,29] have confirmed the flood-emplacement processes for these deposits.

3.4 An example of an excellent SWD-PSI study reach is the central Narmada River Valley in the state of Madhya Pradesh, India (Fig. 2). Historical floods in this reach have achieved discharges of approximately 60,000 $m^3 s^{-1}$, generating an estimated power per unit area of 3000 Wm^{-2}. The newly discovered palaeoflood features of this area are presently under study.

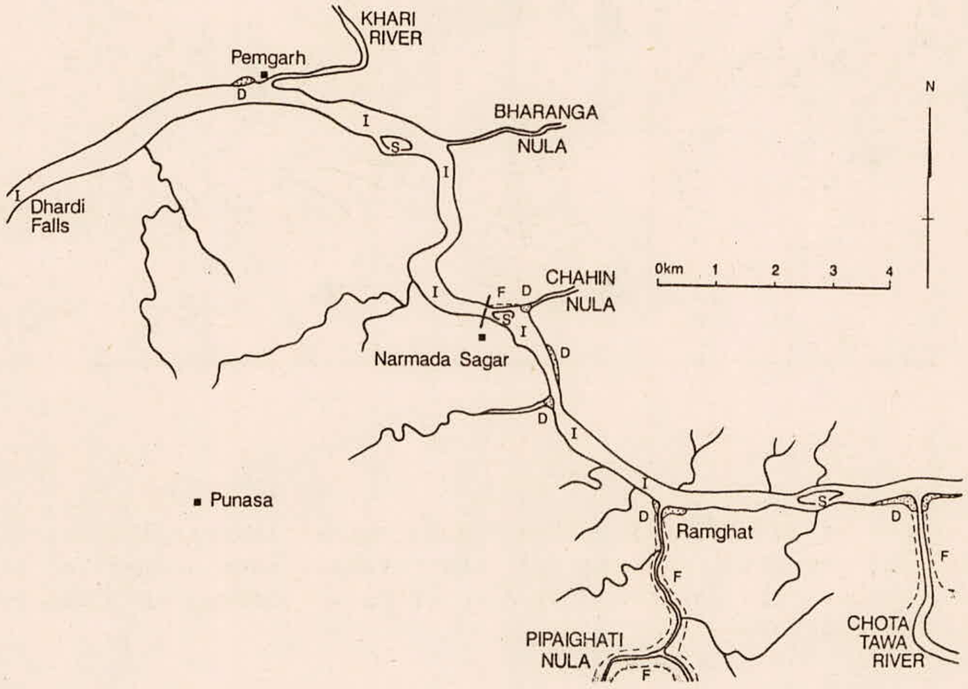

Figure 2. Map of Narmada River Valley near village of Punasa, Madhya Pradesh, India. Areas of coarse-grained slackwater deposition (D) are indicated by coarse dot pattern. Areas of fine grained slackwater deposition (F) are indicated by fine dot pattern at Chota Tawa River and Pipaighati Nula. Bedrock erosional features in this reach include streamlined hills (S) and inner channels (I).

3.5 In tropical countries, such as India, there are numerous local opportunities to generate excellent SWD-PSI palaeoflood records. The expense of such studies is minor in relation to planning costs for major high-risk projects such as large dams. At present these opportunities are largely being ignored, with the notable exception of work in the People's Republic of China (5,12,23,32,33,40]. In some cases valuable palaeoflood records are actually being destroyed by reservoir construction. There is a critical need to generate palaeoflood data at optimum SWD-PSI study sites.

4.0 METHODOLOGY

4.1 The field investigation and subsequent laboratory analysis of palaeoflood information are interdisciplinary activities combining expertise in geology, geomorphology, hydrology, and hydraulic engineering. The slackwater sedimentation sites are analyzed by stratigraphic geology. Individual flood sedimentation units are recognized, discriminated, and correlated between multiple sites along a palaeoflood study reach [3,20,28,39]. Most important is the use of geochronologic procedures to provide absolute dates of the individual flood events. Numerous recent advances have been made in the geochronology of palaeofloods [3,10,19]. Palaeoflood records up to 10,000 years long have been analyzed [30]. The goal of the stratigraphic analysis is to obtain a complete catalog of the largest palaeostages indicated by slackwater deposits, silt lines, erosion scars, and other indicators over a known time span.

4.2 The palaeostages indicated by the geological analysis of the SWD-PSI study reach are transformed to palaeoflood discharges by step-backwater analysis [14,26,28,39]. A significant advantage of the method is that the calculations can be run independently of the high-water indicator survey. Thus, problems in the geomorphology of palaeoflood indicators can be separated from problems in specifying the hydraulics of the study reach. Recent advances in computer flow modeling [27] have greatly facilitated the latter. Of prime importance to accurate flow modeling is a precise characterization of channel geometry. In stream channels with non-deformable boundaries (the preferred application) the survey cross sections should be chosen to account for the major energy losses that occur at channel expansions and constrictions.

4.3 Discharge estimation error in palaeoflood hydrologic analysis can be reduced in several ways. The categories of error reduction include: (a) palaeoflood cross-sectional stability, (b) palaeoflood water-surface estimation, and (c) palaeoflood flow coefficients. An important strategy is to separate the problems of categories (a) and (b), which depend on field conditions, from category (c), which depends on calculation procedure. Discharge estimation error in palaeoflood studies is somewhat analogous to estimation error in historic flood studies. However, several aspects of palaeoflood studies allow more precise controls on error than possible in historic flood studies or even some systematic flood studies. The main reason for this is the preservation of the best palaeoflood information at exceptionally stable geological sites. Methods of reducing palaeodischarge estimation error in the various categories are discussed by Baker [3], O'Connor and Webb [26], and Webb and others [39].

5.0 FLOOD FREQUENCY ANALYSIS

5.1 A recent scientific breakthrough has occurred in the use of both historical and palaeoflood information in flood-frequency analysis [34]. The key to the new approach is in structuring the information content of SWD-PSI sequences through the concept of censoring levels or thresholds. Palaeoflood evidence for various time intervals is analyzed in terms of exceedances or nonexceedanes of the censoring levels or threshold discharges [35]. Maximum-likelihood methods are then used to fit both palaeoflood and conventional flood data to various probability distributions [34,35]. Stedinger and Cohn [36] show in Monte Carlo tests that the maximum-likelihood analysis of censored data is more flexible, efficient, and robust than are alternative procedures. The maximum-likelihood procedure has recently been demonstrated in application to a dam spillway design problem in central Arizona [37], in which palaeoflood data [14,15,28] were key inputs for generating accurate estimates of extreme flood probabilities and magnitdues.

5.2 It must be noted that some statistical procedures do not make appropriate use of palaeoflood information. The standard U.S. method of moments technique [38] has recently been shown to contain flawed assumptions with regard to palaeoflood data [22]. It makes inefficient use of historical and palaeoflood information in the estimation of flood quantiles [36]. Similarly, the maximum-likelihood approach advocated by Hosking and Wallis [16] applied the wrong censoring procedure for use with SWD-PSI palaeoflood data.

6.0 CONCLUSIONS

6.1 The emerging science of palaeoflood hydrology allows the accurate, quantitative reconstruction of flood histories in appropriate settings. Narrow deep bedrock canyons with stable channel geometries and appropriate sediment characteristics may preserve remarkably detailed sequences of ancient flood slackwater deposits and palaeostage indicators (SWD-PSI). Recent advances in geochronology, flow modeling, and statistical analysis of palaeoflood data have greatly increased the ability to extract useful hydrologic information from SWD-PSI studies. SWD-PSI investigations can provide reconstructions of discharges and magnitudes for multiple palaeofloods with remarkably high accuracy over time scales of centuries and millennia. The new censored-sample maximum-likelihood procedures of Stedinger and Cohn [35] are particularly suited to flood frequency analysis incorporating palaeoflood information.

6.2. Palaeoflood information should be sought in appropriate tropical fluvial reaches as a part of risk analyses for major dam projects. The information can be incorporated into flood-frequency analysis, or it can be used to test the reasonableness of flood estimates from modeling procedures. The palaeoflood data may be generated at sites that lack a record of conventional flow measurements.

7.0 ACKNOWLEDGMENTS

7.1 My studies of palaeoflood hydrology were initially supported by the Division of Earth Sciences, Surficial Processes Program, National Science Foundation Grants EAR 77-23025, EAR 81-00391, EAR 81-19981, and EAR 83-00183. Subsequent work was supported by the U.S. Department of Interior Water Resources Research Institute Program and by the Salt River Valley Water Users' Association. Contents of this publication do not necessarily reflect the views and policies of the United States Department of the Interior, nor does mention of trade names or commerical products constitute their endorsement by the United States Government.

7.2 My studies in India were made possible by an Indo-American Fellowship awarded by the American Secretariat of the Indo-American Subcommission on Education and Culture. I thank the National Institute of Hydrology (NIH), Roorkee, and Deccan College, Pune, for hosting my visit and for collaboration in the research. Dr. Satish Chandra and Mr. M. Perumal of NIH, and Professor S.N. Rajaguru and Dr. S. Misra of Deccan College were instrumental in the success of the project.

8.0 REFERENCES

1. Baker, V.R., (1982), 'Geology, determinism, and risk assessment,' in 'Scientific Basis of Water Resource Management,' National Academy Press, Washington, D.C., pp. 109-117.

2. Baker, V.R., (1984), 'Flood sedimentation in bedrock fluvial systems,' in 'The Sedimentology of Gravels and Conglomerates' (Ed. E.H. Koster and R.J. Steel), Canadian Assoc. Petrol. Geol. Memoir 10, Calgary, Canada, pp. 87-98.

3. Baker, V.R., (1987), 'Paleoflood hydrology and extraordinary flood events,' Jour. Hydrology, Vol. 96, pp. 79-99.

4. Baker, V.R., and J.E. Costa, (1987), 'Flood power,' in 'Catastrophic Flooding' (Ed. L. Mayer and D. Nash), Allen and Unwin, London, pp. 1-21.

5. Baker, V.R., L.L. Ely, J.E. O'Connor, and J.B. Partridge, (1987), 'Paleoflood hydrology and design applications,' in 'Regional Flood Frequency Analysis' (Ed. V.P. Singh), D. Reidel, Boston, pp. 339-353.

6. Baker, V.R., and R.C. Kochel, (1988), 'Flood sedimentation in bedrock fluvial systems,' in 'Flood Geomorphology' (Ed. V.R. Baker, R.C. Kochel, and P.C. Patton), John Wiley and Sons, N.Y., pp. 123-137.

7. Baker, V.R., R.C. Kochel, and P.C. Patton, editors, (1988), 'Flood Geomorphology,' John Wiley and Sons, N.Y., 503 pp.

8. Baker, V.R., and G. Pickup, (1987), 'Flood geomorphology of the Katherine Gorge, Northern Territory,' Geol. Soc. America Bull., Vol. 98, pp. 635-646.

9. Baker, V.R., G. Pickup, and H.A. Polach, (1983), 'Desert palaeofloods in central Australia,' Nature, Vol. 301, pp. 502-504.

10. Baker, V.R., G. Pickup, and H.A. Polach, (1985), 'Radiocarbon dating of flood events, Katherine Gorge, Northern Territory, Australia,' Geology, Vol. 13, pp. 344-347.

11. Baker, V.R., G. Pickup, and R.H. Webb, (1987), 'Paleoflood hydrologic analysis at ungaged sites, central and northern Australia,' in 'Regional Flood Frequency Analysis' (Ed. V.P. Singh), D. Reidel, Boston, pp. 325-338.

12. Chen Chia-Chi, Yeh Yung-Yi, and Tan Wei-Yan, (1974), 'The important role of historical flood data in the estimation of spillway design floods,' Scientia Sinica, Vol. 18, pp. 669-680.

13. Dawdy, D.R., and D.P. Lettenmaier, (1987), 'Initiative for risk-based flood design,' Jour. Hydraul. Eng., Vol. 113, pp. 1041-1051.

14. Ely, L.L., and V.R. Baker, (1985), 'Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona,' Phys. Geogr., Vol. 6, pp. 103-126.

15. Ely, L.L., J.E. O'Connor, and V.R. Baker, (1988), 'Paleoflood hydrology of the Salt and Verde Rivers, central Arizona,' Eighth Annual U.S. Committee on Large Dams Meeting, Salt River Project, Phoenix, Arizona, pp. 3.1-3.35.

16. Hosking, J.R.M., and J.R. Wallis, (1986), 'Paleoflood hydrology and flood frequency analysis,' Water Resources Research, Vol. 22, pp. 543-550.

17. Klemes, V., (1982), 'Empirical and causal models in hydrology,' in 'Scientific Basis of Water Resource Management,' National Academy Press, Washington, D.C., pp. 95-104.

18. Kochel, R.C., and V.R. Baker, (1982), 'Paleoflood hydrology,' Science, Vol. 215, pp. 353-361.

19. Kochel, R.C., and V.R. Baker, (1988), 'Paleoflood analysis using slackwater deposits,' in 'Flood Geomorphology' (Ed. V.R. Baker, R.C. Kochel, and P.C. Patton), John Wiley and Sons, N.Y., pp. 357-376.

20. Kochel, R.C., V.R. Baker, and P.C. Patton, (1982), 'Paleohydrology of southwestern Texas,' Water Resources Research, Vol. 18, pp. 1165-1183.

21. Kochel, R.C., and D.F. Ritter, (1987), 'Implications of flume experiments on the interpretation of slackwater sediments,' in 'Regional Flood Frequency Analysis' (Ed. V.P. Singh), Reidel, Boston, pp. 371-390.

22. Lane, W.L., (1987), 'Paleohydrologic data and flood frequency estimation,' in 'Regional Flood Frequency Analysis' (Ed. V.P. Singh), D. Reidel, Boston, pp. 287-298.

23. Luo Cheng-Zheng, (1987), 'Regionalization of historical floods in China,' Jour. Hydrology, Vol. 96, pp. 41-51.

24. National Research Council, (1985), 'Safety of Dams: Flood and Earthquake Criteria,' National Academy Press, Washington, D.C., 276 pp.

25. National Research Council, (1988), 'Estimating Probabilities of Extreme Floods: Methods and Recommended Research,' National Academy Press, Washington, D.C., 141 pp.

26. O'Connor, J.E., and R.H. Webb, (1988), 'Hydraulic modeling for paleoflood analysis,' in 'Flood Geomorphology' (Ed. V.R. Baker, R.C. Kochel, and P.C. Patton), John Wiley and Sons, N.Y., pp. 393-402.

27. O'Connor, J.E., R.H. Webb, and V.R. Baker, (1986), 'Paleohydrology of pool and riffle pattern development, Boulder Creek, Utah,' Geological Society of America Bull., Vol. 97, pp. 410-420.

28. Partridge, J.B., and V.R. Baker, (1987), 'Paleoflood hydrology of the Salt River, Arizona,' Earth Surface Processes and Landforms, Vol. 12, pp. 109-125.

29. Patton, P.C., V.R. Baker, and R.C. Kochel, (1979), 'Slackwater deposits, a geomorphic technique for the interpretation of fluvial paleohydrology,' in "Adjustments of the Fluvial System,' (Ed. D.P. Rhodes and G.P. Williams), Kendall/Hunt, Dubuque, Iowa, pp. 225-253.

30. Patton, P.C., and D.S. Dibble, (1982), 'Archeologic and geomorphic evidence for the paleohydrologic record of the Pecos River in West Texas,' American Jour. Sci., Vol. 282, pp. 97-121.

31. Pilgrim, D.H., T.G. Chapman, and D.G. Doran, (1988), 'Problems of rainfall-runoff modelling in arid and semiarid regions,' Hydrological Sciences Journal, Vol. 33, pp. 379-400.

32. Sauer, V.B., (1987), 'Flood-frequency analysis with historical data in China,' in 'Hydrologic Frequency Modeling' (Ed. V.P. Singh), D. Reidel, Boston, pp. 173-182.

33. Shi Fucheng, Yi Yuanjun, and Han Manhua, (1987), 'Investigation and verification of extraordinary large floods on the Yellow River,' Jour. Hydrology, Vol. 96, pp. 69-78.

34. Stedinger, J.R., and V.R. Baker, (1987), 'Surface water hydrology: Historical and paleoflood information,' Reviews of Geophysics, Vol. 25, pp. 119-124.

35. Stedinger, J.R., and T.A. Cohn, (1986), 'Flood frequency analysis with historical and paleoflood information,' Water Resources Research, Vol. 22, pp. 785-793.

36. Stedinger, J.R., and T.A. Cohn, (1987), 'Historical flood frequency data: Its value and use,' in 'Regional Flood Frequency Analysis' (Ed. V.P. Singh), D. Reidel, Boston, pp. 273-286.

37. Stedinger, J.R., R. Therivel, and V.R. Baker, (1980), 'The use and value of historical and paleoflood information in flood frequency analyses,' Eighth Annual U.S. Committee on Large Dams Meeting, Salt River Project, Phoenix, Arizona, pp. 4.1-4.31.

38. U.S. Water Resources Council, (1982), 'Guidelines for determining flood flow frequency, Bulletin 17B,' U.S. Water Resources Council, Washington, D.C., 28 pp.

39. Webb, R.H., J.E. O'Connor, and V.R. Baker, (1988), 'Paleohydrologic reconstruction of flood frequency on the Escalante River,' in 'Flood Geomorphology' (Ed. V.R. Baker, R.C. Kochel, and P.C. Patton), John Wiley and Sons, N.Y., pp. 403-418.

40. Zhan Daojiang, and Zou Jinshang, (1987), 'Heavy rain storm floods in China an dtheir estimation,' in 'Application of Frequency and Risk in Water Resources' (Ed. V.P. Singh), D. Reidel, Boston, pp. 35-44.