Catastrophes, computing, and containment: living with our restless habitat

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Abstract It may be easy for those who have spent their lives in the tranquil English countryside to misunderstand what others who live elsewhere know only too well. Namely, that mankind lives on the thin skin of a restless planet, and that geophysical hazards are omnifarious and omnipresent. Surely, the odds for any one of us to be killed by a grapefruit-sized hailstone, a meteorite or by one of the the more common geophysical hazards (*e g* lightning strikes) are small, and are not likely to be considered catastrophic to anyone but the individual involved. But for some localities, the risk to life and property from specific geophysical hazards is extreme, and can be sufficiently well established that measures such as defensive structures or warning systems become viable as societal undertakings The computer is proving to be of great use in the establishment and operation of many real-time warning systems Further, computers are increasingly being used for the storing and massaging of maps and related large data bases which permits newer, more sophisticated and more accurate estimates of the probabilities of rare catastrophic events, and hence the wiser allocation of restricted government funds amongst a plethora of hazard reduction projects. The remainder of the paper is confined to a specific class of hazard, namely floods; and more specifically compares the classic procedures for estimating the probabilities of extreme events with some of the newer, robust procedures that have become possible since the event of powerful, cheap computers.

Introduction

Geophysical hazards are neither uniformly distributed in space (see Figure 1) nor in time, and for those who have lived all their lives in the tranquil English countryside it may be easy to forget that they are indeed inhabitants of a restless planet. geophysical catastrophes can and do occur continuously, and the aftermaths of the major events are reported on radio, television and in the daily newspapers, Sunday supplements, and magazines. Further, the Earth's burgeoning population assures that the future will not be any less catastrophic than the past. Hence, in spite of an increased understanding of the phenomena, and better monitoring of the data necessary for modelling and prediction, we can still expect that loss of life and property from geophysical catastrophes will increase inexorably.

Geophysical catastrophes are omnifarious. They vary from the bizarre and rare (meteor attack or lake degassing) to the commonplace (floods and droughts[1]): from the slow acting (rising sea levels and climatic changes) to the very rapid (the shock wave from the Mount St Helens eruption travelled at nearly the speed of sound[2]): and from the spectacular and obvious (Hawaiian lava flows,[3], volcanic explosions and earthquakes) to the invisible (Antarctica's ozone hole[4] and the rising concentrations of atmospheric CO_2,[5]). As Richard Critchfield has shown, large prolonged droughts can be catastrophic. However, like wars, they are phenomena for which the origin and containment are primarily socio-economic

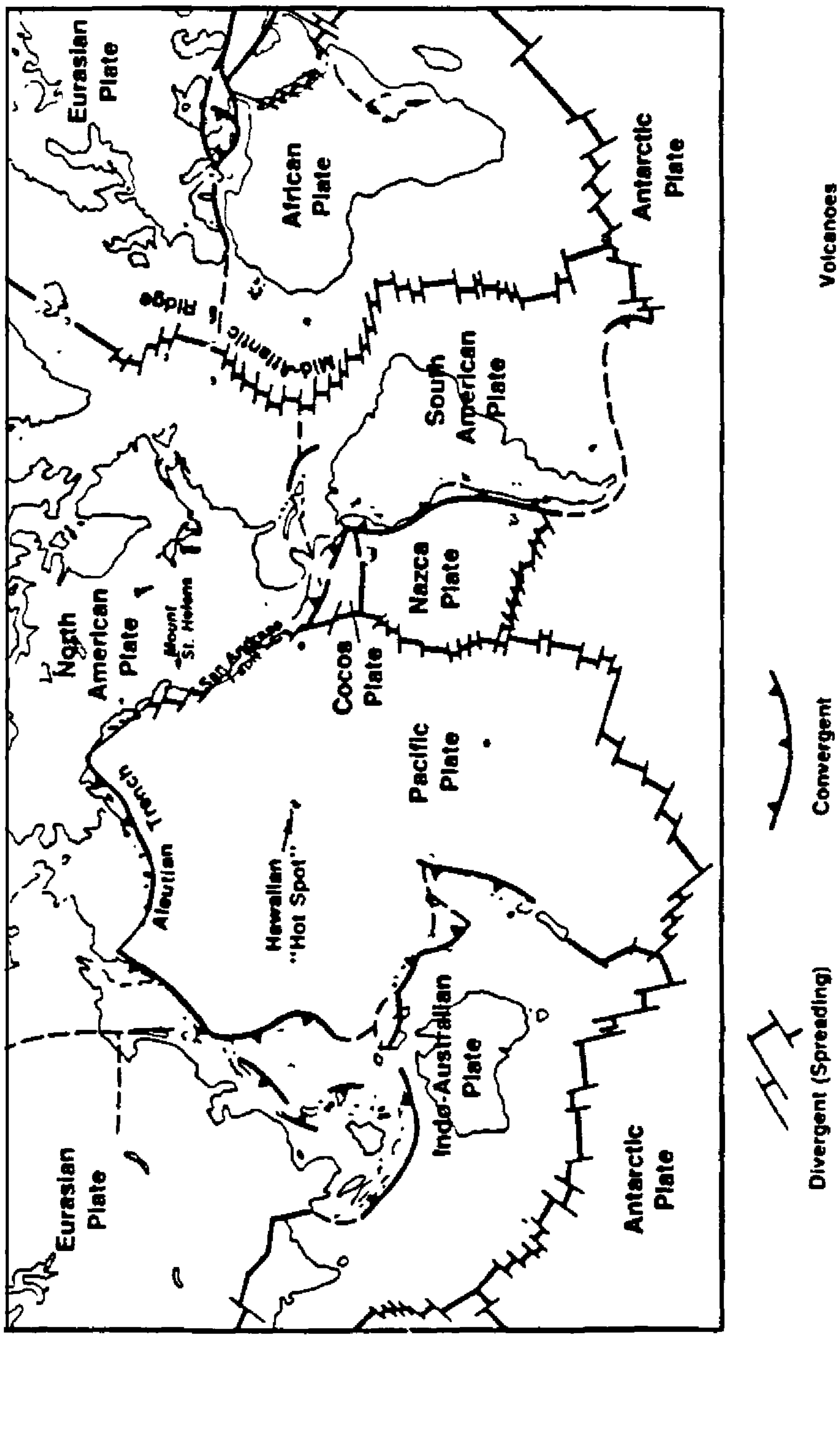

Figure 1 *Volcanoes and earthquakes tend to be located along or near the boundaries of the Earth's shifting tectonic plates (taken from "Eruptions of Hawaiian Volcanoes", USGS, 1987).*

or political questions rather than scientific ones, and will not be considered here.

Compilations of the annual toll in loss of life and property damage from geophysical catastrophes of all kinds result in astronomically large numbers. The precision of such estimates is not large; they can in fact be defined as Type II imaginary numbers,[6] *i.e.* a "collections of someone's estimates of the unknowable", but they sound true and they are probably close enough for government work, as well as for the purposes of this paper. Before proceeding to discuss containment we will consider some examples of geophysical catastrophes.

Climatic changes

When discussing climatic change it is often convenient to divide climatologists into two sets, the "freezers" and the "boilers". The freezers predict an imminent return to an ice-age, on the basis of a sunspot - weather correlation. Usually, no physical model is offered to support the climatic variable correlation, and the resulting predictions can be considered as scientifically controversial.[7] The Russian meteorologist, A.S. Monin, characterised this field as remarkable for "its succession of successful experiments in autosuggestion", and statisticians have been even less kind.[8] Other freezers arrive at similar dire predictions of a coming ice-age from orbital calculations leading to Milankovitch climatic cycles. An imminent return to an ice-age would produce vast economic dislocations, and catastrophic loss of life and property. However, the probabilities of such climatic changes occurring within the reader's lifetime, while unknown, do appear low. Further, there appears little that could be realistically accomplished that would forestall or alleviate the long-range impacts of a return to an ice-age. (The probability of a man-caused "nuclear winter" will not be considered here.)

Nowadays amongst climatologists the boilers are in the ascendant. Rising atmospheric CO_2 level from the burning of fossil fuels is preventing heat from radiating into space, and leading to a general climatic warming (the "greenhouse effect"). In addition to the measured increases in atmospheric CO_2 levels, support for this type of anthropocentric climatic change comes from measurements of thinning polar ice,[9] disappearing continental glaciers,[10] and rising sea levels[11] with its adjunct, our disappearing coastlines.[12] One can hypothesise that a consequence of climatic warming should be that the Earth's heat engine has more stress put upon it, and that the fluctuations and intensity of weather changes at the higher latitudes should be more severe than was witnessed "in the good old days".[13] Whether the phenomena of changing weather patterns is true or false, few amongst the populace at large would disagree with the sentiment that our current weather is worse than it was in grandfather's time (if asked, grandfather would probably have said the same). The long-term economic and political consequences of a general climatic warming are huge, and have scarcely begun to be estimated.

Earthquakes

Eighty percent of earthquakes occur in specific continuous narrow zones that result from the relative motion of the Earth's crustal plates. Earthquakes associated with transform faults (where one plate slides laterally past another, *i.e.* strike-slip), are the most frequent type, but other causal mechanisms are recognised, and these have given rise to some of the biggest earthquakes on record.

The Mexico City quake of September 1985 had a Richter magnitude (ML), of 8.1, and caused between 10,000 and 20,000 deaths, and did about $6 billion in damage. The Tangshan, China, earthquake of 1976 (ML 7.8) flattened the entire city and left more than

25,000 dead. The recent Tokyo earthquake on 16 December, 1987 was a rare, big quake (ML 6.6) in that its epicentre was near a densely populated area, but only two people were reported killed, 10 injured, and damage was negligible.[14]

The notorious San Andreas fault is a transform fault: its average movement is only a few centimetres a year (about as fast as human fingernails grow), but with a lifetime of 15 to 20 million years, the total offset now amounts to some 600 km. Sections of the San Andreas fault may remain "frozen" for long periods while the strain in the rocks accumulates, to be released in a sudden, jolting series of earthquakes. The maximum offset recorded in the 1906 San Francisco quake (ML 8.3) was 6.5 m. It is not surprising that man-made structures get damaged by earthquakes! The 1906 earthquake and subsequent fires took 700 lives and resulted in millions of dollars in damages. The 1987 Whittier, California, earthquake (ML 6.1) on a previously unsuspected extension of the Whittier-Elsinore fault caused $125 million in damages.

Luckily, big earthquakes are rare events. For instance, within the Unites States, during the period 1965-80, there were only seven earthquakes with damages sever enough to result in Federal- declared disasters (for which damages totalled £405 million in 1982 dollars).

Floods

Year in and year out the greatest natural catastrophes that mankind experiences are caused by too much water. Floods, big and little, head all attempts at a complete inventory of natural catastrophes. For example, consider the Hwang Ho (Yellow River) in China, which has a huge sediment load entrained as it flows through upstream loess deposits, which is then deposited downstream, forming natural levees and raising the stream bed as much as 15 m above the surrounding densely populated floodplain. Recurring floods breach the levees, flood water depths can be as much as 30 m, and the river may re-establish itself hundreds of kilometres away from its original channel. Disruption and destruction can be immense, and millions have lost their lives (6 million estimated during the last 100 years).[15] The river has earned its nickname, "the river of sorrows".

Within the United States, during 1965-85, there were 531 Federal- declared disaster events of which 392 were flood related, with losses totalling $4,700 million in 1982 dollars.[16] Further, structural flood control measures may lead to a false sense of security, a seven of the above 392 disasters were caused by the collapse of flood control structures (dams and levees). Floods caused by structural failures can be spectacularly large, for instance, the highest natural flow recorded for the Teton River at St Anthony, Idaho, during 1890-1984 was 311 m^3/s, but the US Bureau of Reclamation's Teton Dam failure produced a flood of 48,000 m^3/s. During the period 1971-78, the US Army Corps of Engineers categorised 9,000+ non-Federal dams as "unsafe", hence, within the USA, the probability of further man-abetted catastrophic floods remains high. Man abetted flood catastrophes are not just a US problem. In October 1963, a large landslide terminated in a reservoir, a flood wave of 200 m then overtopped the dam, and half of the population of the town of Langerone, Italy, drowned. However, the official Italian investigative report stated that: Bureaucratic inefficiency, muddling, withholding of alarming information and buck-passing among top officials was behind the Vaiont Dam disaster, a point to which we shall return later [17]

Tropical cyclones, born in the oceans, generate heavy rains and cause floods when they reach shore. In addition, low lying shore areas may receive oceanic flood surges. Losses in the tens of thousands of lives are commonplace in India, Bangladesh and the countries of the western Pacific rim from storms of this type. Single events can be truly catastrophically destructive. If winds from a tropical cyclone exceed an arbitrary threshold, then the storm is classified as a hurricane (*e.g.* the 1970 Bangladesh event which took 300,000 to 500,000 lives). Historically, hurricane losses are reported separately from those of other floods.

Hurricanes (typhoons)

Hurricanes are large circular storms with high winds, rotating anti-clockwise in the Northern Hemisphere, and clockwise in the Southern Hemisphere, with wind speeds > 200 km/hour, usually over an area of 200 km or more in diameter. Hurricanes cause catastrophic damage. On the average in the USA, two major hurricanes every three years make landfall somewhere along the Gulf of Mexico or the Atlantic coasts (see ref.18 for a good source of all data on US hurricanes). However, most of the population at risk has not experienced a direct hit by a major hurricane (*i.e.* one in categories 3-5) because the coastal population has swelled in numbers during the last 25 years, which coincidentally has been a period with a comparative dearth of major hurricanes. Hurricane Agnes, which devastated the North- eastern USA in 1972, was only recorded as a category 1 hurricane in terms of its wind speed, but it claimed 122 lives.

Hurricane warnings, even if acted upon, cannot eliminate catastrophic property damage: the forces unleashed are just too powerful, and much valuable property is either not sufficiently mobile or insufficiently strong. Damage from Agnes was $4,800 million in 1980 dollars, while Gloria in 1985 caused $765 million of damages, and is rated as the seventeenth most costly hurricane to hit the USA in this century. It is worth noting that the *London Times*, while reporting on Britain's surprise hurricane in October 1987, stated that Gloria was the most costly hurricane ever recorded (£3,500 million based upon an unknown base year). The contrast in the above estimates illustrates the "softness" of most of the statistics concerned with geophysical catastrophes.

Lahars

Lahars (mudflows) are common in many mountainous areas, and they occasionally entomb towns and villages. For instance, the eruption of the Peruvian volcano Nevado del Ruiz melted snows which resulted in lahars that swept over the town of Armero, killing 22,000 people and causing an estimated $212 million in property damage.

In general, areas susceptible to mud and debris flows are easy to identify (unconsolidated material on steep slopes), as is the usual trigger mechanism (excess water). It was not surprising that the Nevado del Ruiz flow occurred where it did, only the source of water was unusual. (Rarer and harder to predict are dry flows such as occurred at Turtle Mountain, Alberta, in 1903, which obliterated much of the town of Frank.) The Japanese routinely monitor unstable geologic deposits that pose a hazard to downstream towns and villages. The technology is quite similar to that used for monitoring and forecasting "flash floods".

Lake degassing

The August 1986 catastrophic caused by degassing of dissolved CO_2 from Lake Nyos killed 1,746 people by asphyxiation, some of whom were as far away as 23 km; it also left many others comatose for up to three days.[19] As far as is known this phenomenon has only occurred twice, both times in August, and both times in Cameroon; hence whilst of interest, catastrophic lake degassing is not an item of general concern.

Lightning strikes

Lightning strikes do not kill many people, except possibly those with a propensity to shelter under trees during thunderstorms (in the period 1959-82 there were 2,456 deaths attributed to lightning strikes within the continental USA, see ref.20). Lightning strikes occasionally do trigger catastrophic events. On lands administered by the US Forest Service during 1985 there were 5,428 wildfires started by lightning strikes.[21] For this same year, the last for which data have been compiled, the toll for the USA as a whole was 44 civilians and firefighters killed, with 12,200 km^2 burnt-over, and 1,400 homes and structures destroyed. Suppression costs to local state and federal agencies were $400 million, with an additional $500 million in property damages. (1985 was not an exceptionally severe year for wildfires).[22]

Meteor strikes

To be killed by a meteor fall is popularly regarded as being a very rare event, but Meteor Crater, Arizona, is a silent witness that the possibility exists. Further, it is now widely accepted that the catastrophic species extinction at the Cretaceous/Tertiary boundary which is associated with the worldwide distribution of an iridium enriched layer of sediment resulted from an extra-terrestrial bombardment .[23] Note, there are nay-sayers for the above causal mechanism,[24] but not for the fact that a mass extinction occurred. The probability of a re- occurrence is unknown, and there are no known preventive measures.

Tornadoes

Tornadoes have violently rotating winds (observed speeds of 160 to 320 km/hour are normal, with maximum peaks of 480+ km/hour), their passage is generally slow, say 50 km/hour, but occasionally they move at twice this speed. A typical path may be 15 m or so wide by a few kilometres in length, but some are much greater in both length and width.

Tornadoes are known in many parts of the world, but nowhere are they as prevalent as they are in "tornado alley" which stretches from Texas into the Dakotas and east to Indiana. This area averages more than five tornadoes per 25,000 km^2 every year.[25] The distribution of the time of occurrence of tornadoes is far from uniform; for instance. 148 were counted within a single 24 hour period during April 1974.

The destruction from a single tornado can be immense. The Tri- state tornado of 18 March, 1925 was the worst in United States history. Starting in south-central Missouri, it pursued a remarkably straight course across Illinois, and into south- western Indiana. The total affected land area was over 260 km^2, of which half was totally devastated. There were 689 fatalities, 11,000 left homeless, and $16.5 million of damage in 1925 dollars.[26]

However, most tornadoes are minor affairs when compared to the Tri-state event. For the USA as a whole in the 28 year period 1953-80 there were 20,455 tornadoes reported, with a death toll of 2,938 (107 per year).[27] No comparable figures for total damages are available, although in the period 1965-85 there were 109 tornado events, for which damages were sufficiently high that a Federal disaster was declared, and for these events the damages totalled $648 million.

Volcanic explosions

There are 500+ active volcanoes on the Earth, and most are located on or near the boundaries of the Earth's shifting tectonic plates (see Figure 1). Catastrophic volcanic eruptions are nevertheless rare events. Still, it has been estimated that 270,000 people have lost their lives as a result of volcanic activity during the last 500 years. The Tambora eruption of 1815 resulted in 50,000 to 90,000 deaths, the Mount Pelee eruption in 1902 resulted in 30,000, while Krakatau in 1883 resulted in 36,000. By comparison with past major events (Mount Mazama, Tambora, Krakatau and Mount Katmai), the recent Mount St Helens eruption (18 May 1980) was comparatively small in volume of ejecta, but the best estimates of the total damages from this one eruption are in the neighbourhood of $1.1 billion. Because of timely warnings and evacuation of the hazard zone the loss of life was only 57.

Computers, containment, politics and income redistribution

It should be evident from the above list that geophysical catastrophes are an ever present part of the human habitat. Frequently, once the process has been triggered, the forces unleashed act so fast and are so great that no human intercession to alleviate danger and lessen loss of life is possible. However, in many cases the hazards are well defined and the probabilities of occurrence sufficiently large that preventive actions become possible. Responses to perceived geophysical hazards can be of four general types.

- First, general programs designed to alleviate the consequences of catastrophes whenever or wherever they may occur, *e.g.* civil defence measures of the Red Cross and similar organisations. In this regard, a new and exciting use for small computer systems is the low cast (< $3,000 per site) satellite communications project (PACSAT) of the Volunteers in Technical Assistance (VITA), which offers assurance of communication even when formal communication systems have been made inoperable by earthquake or other geophysical catastrophe.[28]
- Second, would be zoning ordinances (certain land uses proscribed in certain localities), or other legal measures (Building codes, *etc.*). Geographic information systems (GISs) with inter-active computer graphics are coming into use with many authorities, and these tools have a great potential for selecting the optimum economic boundaries for all zones and codes.
- Third, would be the formation of monitoring and warning systems, and again, computer modelling and GISs are the mainstay of all modern warning systems.
- Fourth, when conditions warrant and the political will is evident, physical barriers or diversions may be constructed. Computer aided design (CAD) now plays a large role in the planning for all sizeable structures designed for geophysical hazard reduction.

Zoning, codes and laws

Zoning, the delineation of geographic areas where certain land uses are restricted or prohibited, is an effective form of hazard reduction, but the risk may be so slight or so heavily discounted by those at risk that zoning may be a politically unfeasible antidote for hazard reduction. Political and cultural factors influence the establishment as well as the effective policing of zoning ordinances. There are difficult questions here; it is not just a question of establishing the geophysical risk. For instance, consider the hypothetical zoning response to a perceived relatively rare threat, tsunami inundation (6,000 people world-wide have died from tsunamis within the last 10 years and property damage has occasionally been large). At what point should society say to an individual "thou shalt not build thy house here because tsunami may knock it down"? In Japan some areas subject to high tsunami hazard have been protected by walls (like hurricane walls in the USA). There are 22 countries around the Pacific with some lands that have an appreciable tsunami threat, but there are no zoning ordinances. Should there be? Would it make a difference if the structures at risk were large tourist hotels rather than individual residences? And last, what is the probability of tsunami events of different magnitude and how accurately can these probabilities be estimated?

Beside zoning there are other non-structural preventive measures that can sometimes be incorporated into codes. For instance, in the USA wooden buildings are the norm and these tend to be fairly earthquake resistant when compared with un-reinforced masonry structures. Japan has some of the toughest earthquake proofing building codes in the world, which may well account for the extremely small amount of damage and loss of life reported in the Tokyo quake of 1987. In Los Angeles county, remedial strengthening of buildings against earthquake shaking has been mandated, but compliance is a slow and costly business. In many earthquake-prone areas new, large buildings are now erected with reinforced steel frames with an ability to withstand shaking without toppling or disintegrating. But the mandate of most codes are restricted and one does not have to go far from the San Andreas fault before encountering concrete-slab construction that is not designed to withstand even moderate quakes. A recent example of inappropriate concrete-slab design was the failed Benito Juarez Hospital in Mexico City which collapsed like a house of cards in the 1985 quake, crushing more than 1,000 patients and staff.

Monitoring and warning centres

Most countries have some kind of meteorological office concerned with monitoring and predicting the passage of meteorologic events that are likely to be large or severe enough to cause loss of life or extensive property damage. For example, in the USA there are the National Hurricane Center (NHC) in Coral Gables, Florida, and the National Severe Storms Forecast Center (NSSFC) in Kansas City, Missouri.

In areas where phones, radios and TVs are prevalent, warning centres tend to be effective at reducing loss of life and often can be credited with changing a potential catastrophe into merely an unfortunate incident. However, as might be expected, warning centres tend to be less effective when property damage is the measure of effectiveness, and also in areas where the communication infrastructure is poorly developed.

Tropical storm warnings issued by the NHC have been particularly effective for lessening loss of life from hurricanes, but they are not a guarantee that a future hurricane might not become a great killer if it were to make a direct hit on a major southern US city (the Galveston, Texas, hurricane of 1900 killed 6,000). Even if the population at risk cooperates with the authorities, evacuation times for major population areas are multi-hour events. Hurricane forecasts for extended periods are still not very accurate. For instance, the difference between the 24-hour predicted and the actual 24-hour-later location of all tropical storms monitored by the NHC in the period 1970-86 averaged 190 km, and the chances that a storm centre passed at or near its predicted landfall site were only 40 percent, 15 percent and 10 percent at the 24, 48 and 72-hour forecast intervals.[29] The NHC has a policy of overwarning of coastal regions subject to hurricane landfall, and normally three times more coast is warned than the length of coast that actually experiences destructive storm surge and/or winds. The NHC would like to reduce the number and size of the falsely warned areas as evacuation and preparatory measures are expensive, and false alarms also produce a loss of credibility in the minds of those at risk. In 1980 it cost $41 million to evacuate Galveston when hurricane Allen approached and then bypassed the city.[30] New computer models using global dynamical forecasting are being developed and it is expected that these models will greatly reduce the track errors. However, improvements in the accuracy of hurricane intensity forecasts are proving more elusive.

Computer models currently in use have fetching acronyms like SLOSH (Sea,Lake and Overland Surge from Hurricanes) and SPLASH (Special Program to List the Amplitudes of Surges from Hurricanes).

Similarly, most countries have national hydrologic forecast centres that issue warnings of flood crests on major rivers. Large, area-wide forecast centres often use complex rainfall- runoff models to make their flood forecasts: there are theoretical and conceptual problems in the use of such models, and these have been ably documented elsewhere.[31] In this context, Georgakakos[32] has shown that "short-term model predictions are not significantly sensitive to the runoff-generating model component when updating is performed". However, if the computer model lacks an automatic tracking and correcting algorithm for the errors of forecast, then rainfall-runoff forecasts can drift far from reality (*e.g.* the hurricane Agnes forecasts made for the Susquehanna River).

In the USA there are 13 River Forecast Centers (RFC) operated by the National Weather Service, which issue flood crest warnings for some 3,000+ sites. These RFCs tend to be concerned with major streams, while headwater streams with a potential to reach flood crest in 0 - 6 hours are usually under the jurisdiction of locally controlled flood warning centres from which "flash flood warnings" are issued. In many countries, flash flood warning systems use simple computer models, with upstream sensors and telemetry or cellular phone communication: the systems can be relatively cheap to install and maintain (< $50,000). Many of the simple models in use are derivatives of the constrained linear systems (CLS) approach, incorporating Kalman filter updates.[33-35] Surprisingly, in the USA there are still at least 16,000+ municipalities and towns with a potential for inundation by flash floods with no locally implemented flood warning system.[36]

In Japan there is also an earthquake warning centre, as well as centres that monitor sites from which potentially dangerous lahars may be expected.

Structures

Structures to contain geophysical hazards are expensive and government funds for their construction are limited. The allocation of government funds amongst varies structural projects is highly competitive and highly political. However, occasionally the hypothetical losses are perceived to be too high and the people likely to be affected so vocal that containment becomes reality and a structure is built, even though massive income redistribution may be involved in the process.

The Thames Barrier in London is a good example of a structure built to contain a known geophysical hazard. The barrier was built at a cost of $535 million, and it takes 65 people and costs £3.3 million per year to operate and maintain. The bill was paid for 75 percent by central government and 25 percent by local ratepayers (the beneficiaries of the protection). This was an expensive project, but the losses from a major no-barrier flood had been previously estimated to be in excess of £3,000 million, with some districts of London being under 2.5 m of water for up to 6 days.[37]

It is a problem for sociologists and political scientists to decipher as to why a Thames Barrier was built, while many other projects of comparable net worth languish (*e.g.* the Venice lagoon faces a similar hazard when strong winds blow from the south- east, but similar containment structures have not been built).

Estimation of event probability: at-site procedures

An essential step in the design of any containment structure is the estimation of the probabilities of occurrence of the events which the structure is designed to alleviate. The statistical methodology for making such probability estimates has been revolutionised by computers, and the current best methodology is much better than the classic at-site procedure described below.

Assume a set of independent annual maxima x_i, where $i = 1,\ldots, n$ and n is the number of years in the record, then the T-year event is that event which has a probability $P[X > x] = 1/T$ of being exceeded, and corresponds to the quantile $x(F)$ of the distribution function $F(x) = P[X \leq x]$, where $F = (T - 1)/T$. The distribution is unknown, and is selected by fit or by reference to one or more standard goodness-of-fit tests. The parameters of the distribution are estimated by some procedure (*e.g.* methods of moments, maximum likelihood, probability weighted moments (PWM, see appendix for definition). The $x(F)$ are derived analytically or by numerical integration.

Application of the above methodology to geophysical problems has encountered several problems: violation of the assumption of independence between the x_i values; the $x(F)$ depending upon the method of fit, and its arbitrary rules; problems with small samples and their effects aggravated by the fact that $n << T$; and finally, the lack of power inherent in goodness-of-fit tests, *i.e.* the ability of known tests to correctly identify the distributional origin of a sample.

The cumulative effect of the above defects is sufficiently large that the at-site approach can no longer be condoned for real applications. However, in view of the fact that examples of this type of approach to probability estimation are still being published in journals, a little elaboration on some of these points appears in order.

Lack of independence

Correlation amongst the x_i does not alter the expected values of the $x(F)$, but it does increase the uncertainty of the estimates as measured by confidence limits or root mean square errors (RMSE). In addition, there is another type of lack of independence that impinges upon the accuracy of the classic methodology, namely, the fact that the lack of occurrence of an event may actually increase its probability of occurrence. Fumerolologists and tourists at Yellowstone Park are familiar with this idea. It also inflicts seismologists who are called upon, or feel the need, to predict the intensity and time of occurrence of the next major earthquake. It is possible that it is this kind of non-stationarity that leads seismologists to use statistical terminology in such unusually creative ways, *e.g.*"... there is a better than 40 percent probability that the big one will strike within the next 30 years"[38] (a statement that apparently refers to a future earthquake that will occur somewhere within the Los Angeles basin). For the formulation of wise government policy a more precise and scientific statement of the location, probability and severity of a possible hazard is needed, but unfortunately, seismology is not yet a predictive science.

Differences in x(F) *as a function of choice of distribution*

To understand the magnitude of this problem it is easiest to consider a specific example. It is possible to fit the extreme value Type I and II (EV I and EV II) distributions to data of annual maxima, and for some data sets the differences in the $x(F)$ as a function of using even these closely related distributions can be staggering. This has been done for wind speed maxima at 129 different US localities,[39] and the results reported for Corpus Christi, Texas, have been reproduced in Table 1.

The estimates of Table 1 were based upon a sample of 34 values with one hurricane influenced value of 206 km/hour. The observed maximum in the sample is equivalent to

Table 1 T, *return period in years versus annual maximum wind speed in km/hour for Corpus Christi, Texas, estimated by Simiu* et al.,[39] *using two extreme value distributions (EV I and EV II).*

T	EV I	EV II
10	119	116
100	161	247
1,000	203	659
10,000	245	1,960
100,000	287	6,090
1,000,000	329	19,100

T = 1,500 for the EV I distribution, and to T = 60 for the EV II distribution. It should be stressed that the objective of this study was to give architects and engineers a reasonable estimate of the probabilities of various wind loads so that critical buildings could be designed to withstand high recurrence interval wind stress. The EV I estimate for the $T = 10^6$ event equals the commonly observed maximum wind speed for large hurricanes, while the comparable value for the EV II distribution is almost half the velocity needed to escape from the Earth's field of gravity! Neither estimate appears particularly reasonable, and a more satisfactory statistical analysis of the same data can be found elsewhere.[40]

In conclusion, unless the distribution is known, at-site estimates of $x(F)$ (*i.e.* estimates made from a single sample of data) should neither be calculated nor used. A possible exception to this rule might be in those situations where $T << n$.

Lack of statistical power

It is only since computers became cheap enough to make extensive Monte Carlo studies feasible that the lack of power inherent in at-site goodness-of-fit tests has become widely apparent. It is the lack of power present in the tests used that has led to the incongruous result that annual maximum flood peaks are said to be distributed as log Pearson III within the USA,[41] while they are said to be three parameter log Normal in Ontario,[42] and to follow a generalised extreme value (GEV) distribution in the UK.[43] Similarly, annual maxima for California point rainfall data have been reported to be distributed as Pearson III,[44] and elsewhere as GEV-like.[45]

A physical explanation of the above distributional differences is not necessary because the goodness-of-fit tests being used are insufficient to succeed in reliably delineating distributional differences, given the available sample sizes. This is a generic problem of all at-site goodness-of-fit tests, and people who use or advocate such tests should be encouraged to perform Monte Carlo experiments with synthetic data sets of similar length and character to their observed records to confirm this property before making interpretations and predictions of extreme $x(F)$.

To illustrate what is meant by lack of power, consider a simple example. Generate GEV data with skewness = 3 and coefficient of variation, CV = 0.4. Take 1,000 repetitions of n = 20, 30, 40, 60 and 100, and to each sample fit distributions by the four methods listed below.

1) At-site GEV by PWM.[46]
2) At-site three parameter log Normal using L-moments.[47]
3) At-site log Pearson III using moments.
4) At-site log Pearson III using L-moments.

Estimate the $x(F)$ for each sample and method, and determine the goodness-of-fit by two tests, the average of the relative deviations D_α, and the average of the square of the relative deviations, D_r, where the deviations are between the ranked x_i and the comparable predicted values X_i. The results of such an experiment are presented in Tables 2 and 3, from which it can be seen that:

* The correct distribution is identified less than 50 percent of the time even with the better of the two tests and with records as long as 100.

* The log Pearson III distribution is the prevailing choice for the D_α statistic, and a commonly selected distribution for the D_r test even for samples as large as 60

Table 2 *Count the number of times that the* D_α *statistic with Gringorten plotting positions selected various choices as "best fit". Data were GEV distributed.*

	Method of fit			
n	1	2	3	4
20	31	10	15	44
30	34	10	14	42
40	40	10	12	38
60	44	11	8	37
100	48	12	7	33

Table 3 *Count the number of times that the* D_r *statistic with Gringorten plotting positions selected various choices as "best fit". Data were GEV distributed.*

	Method of fit			
n	1	2	3	4
20	20	34	20	26
30	30	30	18	22
40	36	25	18	21
60	43	24	18	15
100	49	24	17	10

It is scarcely surprising that those who have used these tests with small samples of annual flood maxima have concluded that log Pearson III emerges as the "best distribution to use".[48,49]

As a second example of a goodness-of-fit test, consider sample estimates of skewness and kurtosis that have been averaged and the compared with the corresponding theoretic distribution values (equivalent to $n = \infty$) to produce a goodness-of-fit test. The test is seriously flawed. As Dalen [50] has remarked, "It is an established but not very well-known fact that many types of samples statistics are bounded algebraically by some function of the sample size". In particular, skewness and kurtosis estimates are bounded, and the small sample estimates of CV, skewness and kurtosis are biased, with the amount of bias depending upon the distribution.[51] (But, to make accurate bias corrections it is necessary to first know the distribution: a chicken and egg type problem.)

Nevertheless, Goodridge, in the study cited above, used exactly this procedure to conclude that California annual rain-fall maxima were distributes as Pearson III; an erroneous conclusion that Hosking and Wallis showed leads, on the average, to a 10 percent under-estimation of the $T = 100$ event, and a 30 percent under-estimate of the $T = 1{,}000$ event.

L-moments to the rescue!

While at-site goodness-of-fit tests are not useful as a basis for selecting the distribution to

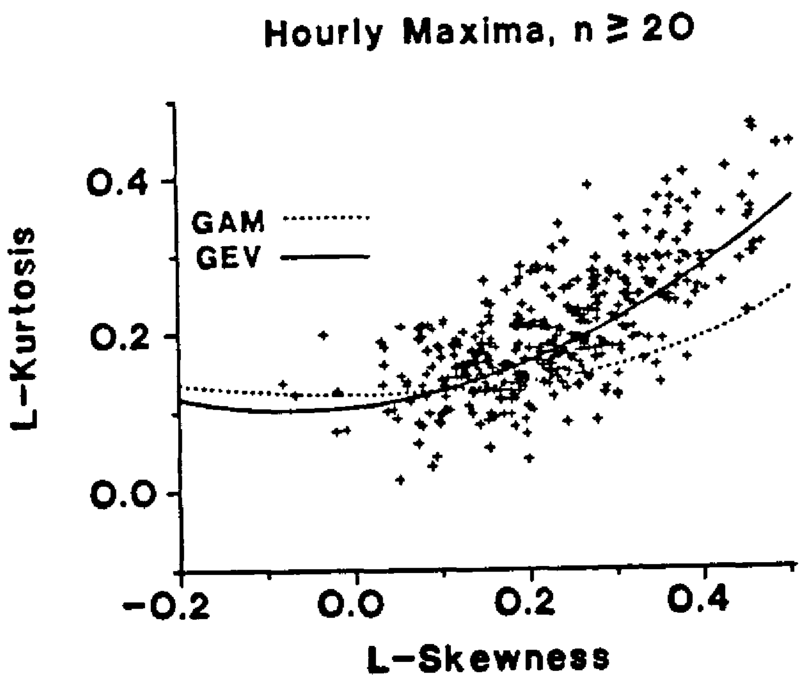

Figure 2 *L-skewness versus L-kurtosis for Californian hourly rainfall maxima (after Hosking and Wallis[52]). These are the same sites for which Goodridge reported a Pearson III (GAM) distribution to be the "best fit". The theoretic curve for the generalised extreme value (GEV) distribution is shown for contrast.*

use for estimating extreme $x(F)$, all is not lost. When multiple sets of records are available, the new technique of L-moments can be useful as a basis for eliminating many candidate distributions from further consideration, and as a help in identifying a group of the most likely distributions to use in the subsequent modelling.

Samples from a selection of distributions have been tested, and their L-CV, L-skewness and L-kurtosis estimates have been found to be essentially unbiased, and very close to normally distributed estimates for quite small samples and for some otherwise intractable distributions.[52]

In Figure 2 it can be seen that the maximum annual California hourly rainfall data used by Goodridge does not fit the hypothesised log Pearson III (Gamma) distribution and, as pointed out by Hosking and Wallis, the data are GEV-like, heterogeneous, and can be readily subdivided into more homogeneous sub-groups

In Figure 3 are plotted the L-skewness and L-kurtosis values for annual flood flows for 44 sites. The L-skewness and L-kurtosis values were taken from those listed in Hosking and Wallis.[53] These same sites were fitted with an EV I distribution by Jain and Singh[54] on the basis of the D_α and D_r goodness-of-fit tests. The L-moment statistics are not normally distributed around the theoretic EV I values, and the choice of an EV I parent distribution appears inappropriate.

Figure 4 shows the L-skewness versus L-kurtosis values for maximum annual wind speeds at 115 sites in the USA. The L- skewness versus L-kurtosis were taken from a study by Hosking and Wallis.[55] The data were given in the Simiu *et al.* report previously mentioned,[39] where it was stated that 80 percent of the sites had wind speeds distributed

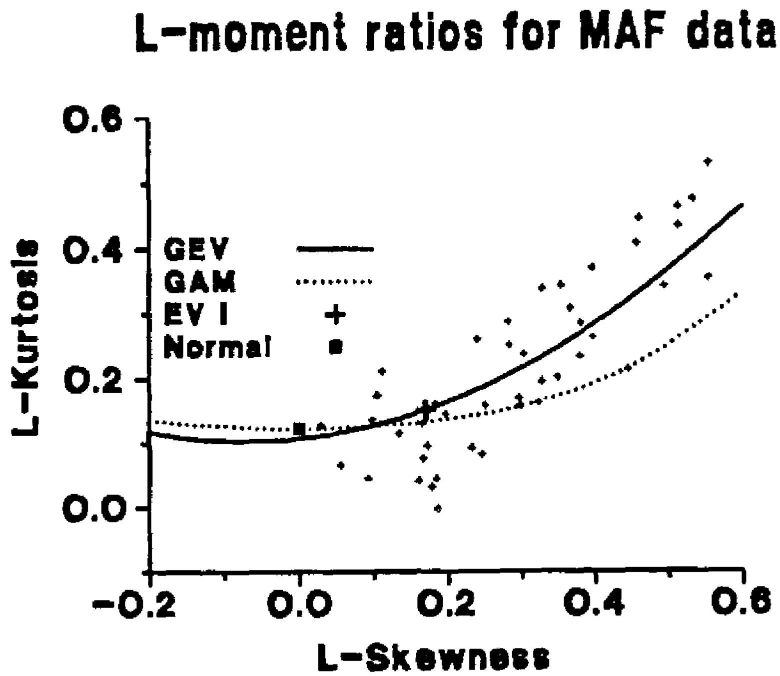

Figure 3 L-*skewness versus* L-*kurtosis values for 44 sites used by Jain and Singh*[54] *and to which they fitted the EV I distribution on the basis of the goodness-of-fit tests* D_α *and* D_r. *The* L-*moment values for the data are not normally distributed around the theoretic value for the EV I distribution, and their choice of this distribution appears invalid*

as EV I and 20 percent as EV II (based upon another closest fit criterion, the so-called maximum probability plot correlation coefficient criterion). The geographical locations of the differing distributional types could not have resulted from any obvious geophysical mechanism, and the statistical justification for the distributional classification also appears weak.

Estimation of event probability: the new robust procedures

As shown above, goodness-of-fit tests applied to at-site sets of geophysical data are an exercise in futility. However, if sets of related data are available, then *L*-moment graphs can probably be used to produce a set of likely candidate distributions. The new statistical methodology takes the above as given and looks for an estimation procedure for $x(F)$ that is likely to give reasonably consistent estimates over the range of likely distributions (*i.e.* robust estimators are selected). The final estimates of $x(F)$ are given confidence limits by appropriate Monte Carlo or analytic procedures.

Recently, much work has been done with various modernised versions of Dalrymple's Index Flood procedure.[56] These are "regional " procedures in which data from many sites are used to improve the estimates at individual sites. Index Flood procedures and robust estimators are explained elsewhere,[57] and only a brief summary will be given here:

1) $Q_i(F)$ is the growth curve of the annual maximum values for set *i*.
2) Assume $Q_i(F) = \mu_i q(F)$ = (site mean)x(regional growth curve). The regional growth curve being that curve expected for a set of physically similar sites.

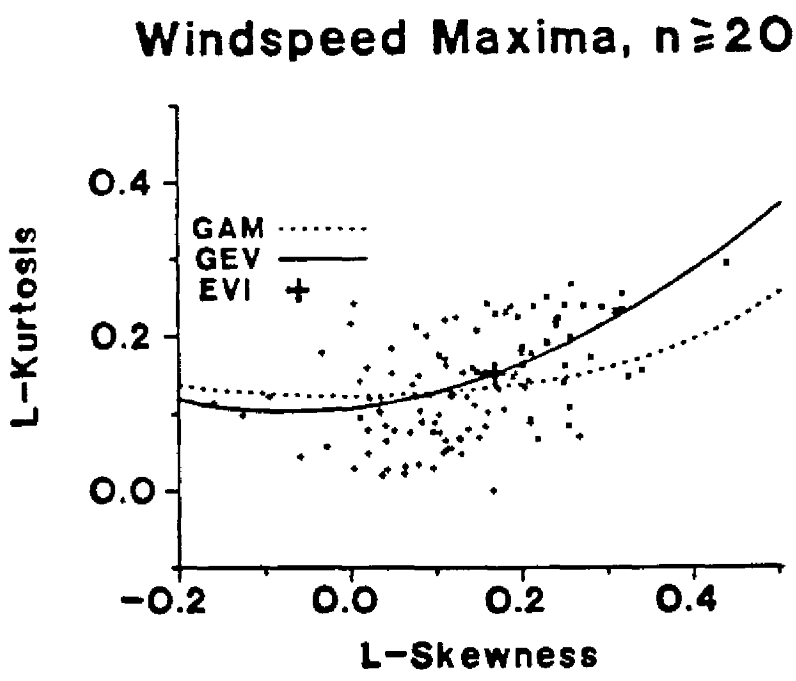

Figure 4 *L-skewness versus L-kurtosis for wind speed data at 115 sites with n ≥ 20. Simiu* et al.[39] *classified this data as either being EV I distributed (vertical crosses) or EV II distributed (diagonal crosses) based upon a goodness-of-fit test (the maximum probability plot correlation*

3) Estimate μ_i by $\hat{\mu}_i = \bar{Q}_i$. Using the sample mean is convenient for expository purposes, but is not a mandatory condition. Other estimators are possible and some have been tried.
4) Fit a distribution to $\{q_{ij} \equiv Q_{ij}/Q_i, j = 1,..., n_i, i = 1,..., N\}$, where N is the number of data sets available in the set.
5) Let $\hat{q}(F)$ be the inverse cdf of the fitted distribution.
6) The quantile estimator for set i is $\hat{Q}_i = \hat{\mu}_i\hat{q}(F)$.

If the distribution chosen is a GEV and PWMs are used, the method will be referred to as GEV/PWM,[46,58] while if the distribution chosen is the three parameter log Normal and the fit is by PWMs, then the procedure will be designated as LN3/PWM.[47,59]

In general, these new estimating techniques have been found to yield robust estimates of $x(F)$ even if the set of sites is mildly heterogeneous,[60] and small amounts of cross-correlation are present.[61]

Statistically, one would expect the variance of $\hat{Q}_i$ to decrease as $1/\surd(Nn)$, and in general this is approximately true for the GEV/PWM and LN3/PWM estimators. The above point can be illustrated with a simple Monte Carlo experiment. Generate data distributed as GEV with CV = 0.4 and skewness = 3.00 (L-CV = 0.194 and L-skewness = 0.2888), for at-site estimates take N = 1, with n = 10, 20, 30, 40, 60 and 100, while for the regional estimates set n = 40 and N = 1, 2, 3, 4, 5, 10, 50 and 100. Estimate the T = 1,000 quantile by at-site and regional methods, and preserve the scaled estimator $(\hat{Q}_j - Q_j)/Q_j$ for 10,000 repetitions to yield an estimate of the average scaled RMSE.

Results for the GEV/PWM at-site and regional fit to the above data are shown in Figure 5, where it can be seen that at-site estimates are unacceptably large with scaled RMSE error > 0.3, even when samples are as large as 100. The expected $1/\surd(Nn)$ decline

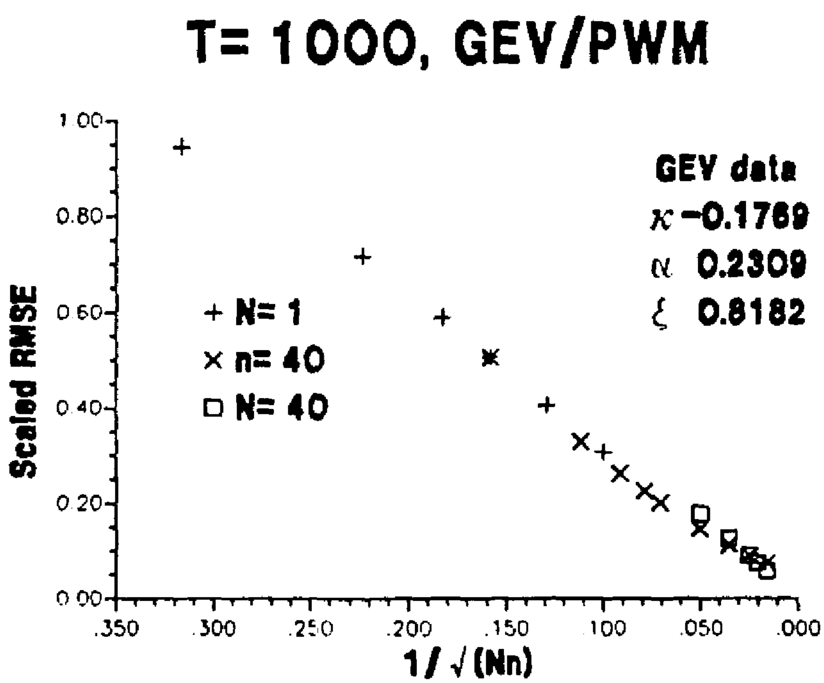

Figure 5 *Scaled RMSE versus* $1/\surd(Nn)$ *for GEV/PWM at-site regional fits.*

in RMSE is apparent. The smallest value of the scaled RMSE (0.076) occurring at $Nn \approx$ 4,000 probably represents a realistic lower bound for the accuracy of this type of statistical estimation. In real situations, records longer than n = 100 either do not exist or are likely to be non-stationary (all the statistical procedures discussed here assume that series stationarity exists over the design life of the project, plus the preceding measurement period), while the benefits from increasing N beyond 40 are probably more than outweighed by the losses incurred from the additional heterogeneity and correlation that are likely to be associated with increasing N. Note, this is contrary to the philosophy that by increasing data sets into the millions a corresponding increase in the accuracy of the estimates of the extreme quantiles can be obtained.[62]

Results for the LN3/PWM at-site and regional fits to the above data are shown in Figure 6, where it can be seen that if $Nn \approx$ 2.00 (or less), then fitting LN3/PWM yields appreciably smaller RMSEs than would be observed for a comparable GEV/PWM fit, even though the data are actually GEV distributed. This paradox is not widely known and its importance to flood frequency analysis little appreciated; its existence depends upon the extreme robustness of the LN3/PWM procedure.

In the USA the prescribed method of flood frequency analysis is the log Pearson III procedure[41] which is widely known to be non-robust,[63] and for which, when $T > 100$ it is recommended that the procedure not be used.[62] One can fit a log Pearson III distribution by PWMs and use it for at-site and regional quantile estimates (LPIII/PWM procedure). LPIII/PWM quantile estimates, while still not very good, are better than those obtaineable with the moment estimator procedure recommended by the US Water Resources Council Figure 7 shows results for the LPIII/PWM procedure and the previously described GEV distributed data. The RMSEs for the n = 10 and n = 20 cases were so large that they could not be plotted. It is noted that over the whole range of the experiment the results obtained

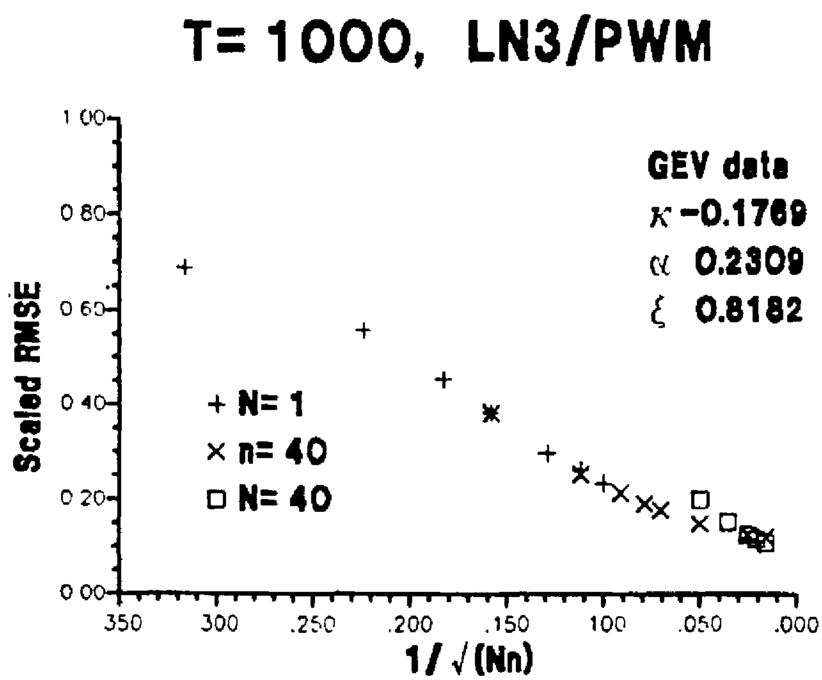

Figure 6 *Scaled RMSE versus* $1/\sqrt{(Nn)}$ *for LN3/PWM at-site regional fits*

from using a log Pearson III distribution were consistently less accurate than those obtainable by either GEV/PWM or LN3/PWM (Figures 5 and 6 versus 7). It is of interest that the distribution previously found to be a "best fit" is also the worst distribution for producing accurate estimates of flood sized $x(F)$.

In addition, we have another hydrological paradox, namely, the US water bureaucracy clings tenaciously to an estimation procedure known to be non-robust and to give fallacious answers when $T > 100$, but this is the very region of interest, *i.e.* the region where most loss of life and damage from floods actually occurs.[64] This second paradox can probably only be explained in socio- political terms.

C.P. Snow's "two cultures" has entered folklore; we have scientists doing their complicated inhumane thing, and humanists doing their blissful, unscientific thing, and with each group knowing nothing of each other's search for truth. However, there is yet a third culture, and it is of extreme importance to the containment of geophysical catastrophes and hence to living with our restless habitat. The third culture consists of:

"... The politicians, the ad men, the convincers, the talkers, dabbling in science and technology with little knowledge of either, employing the age-old humanistic art of persuasion to delude the public.

".. The most notorious examples of third-culture people are those in government administration. For them, it is never a question of thought or research or discovering the truth and then telling it, but rather the expedient, the transient, trying to adopt the most praiseworthy stance, making the most acceptable temporary statement, and then hoping against hope that it might all turn out to be correct. (The previously mentioned Vaiont Dam disaster is illustrative of this point)

"... The quality of a science is defined by the nature of the data accepted as evidence.

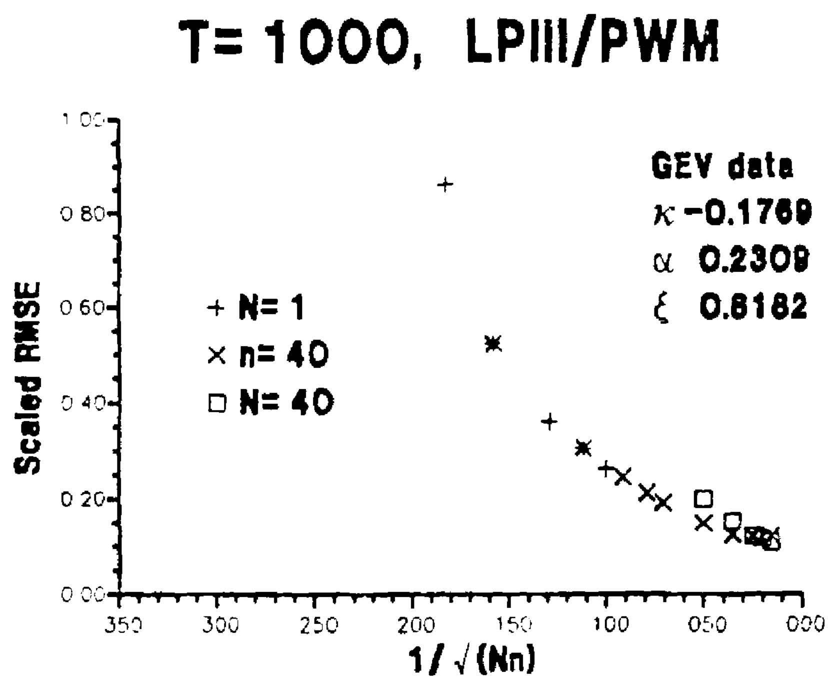

Figure 7 *Scaled RMSE versus* 1/√(Nn) *for LPIII/PWM at-site regional fits.*

The third-culture people do not have any standards for data or evidence. They just say it how they think it - and hope it might turn out to be true."[65]

We now have the explanation for the above log Pearson III paradox, it is a third-culture phenomenon. However, more importantly, this paradox is symptomatic of a general third-culture malaise that may divert and dilute the effectiveness of those who desire to contain geophysical catastrophes on a global scale.

The recently created International Decade for Natural Hazard Reduction (IDNHR)[66] is, in fact, a program of income re- distribution on a global scale, and the program implementation will be largely controlled by the third-culture. To expect an equitable, economically effective program from the dowsers,[67,68] the PMFers and the MCEers would be naive, and the allocation of scarce government funds amongst projects with risks defined using third-culture terminology and analyses does not appear propitious. PMFs (probably maximum floods) or SPFs (standard project floods, arbitrarily defined as 50 percent of a PMF) are not based upon probability analysis, but rather upon estimates of the PMP (probable maximum precipitation) which are themselves random variables with probabilities varying over orders of magnitude.[69] MCE (maximum credible earthquake) is an event of unknown but varying probability. It is a concept used by many US Federal Agencies. IDNHR can be expected to provide impetus for additional, similar psuedo-scientific terms to start appearing: MPT (maximum probable tsunami); MCV (maximum credible volcanic eruption), *etc.*? Further, for maximum efficiency uniformitarianism would lead us to believe that the great majority of IDNHR's funds should be directed towards flood-loss mitigation, but this is not an area in need of innovative science. Except for flash floods, loss of life from floods occurs principally in areas of poor infra-structure (transportation, communication and education). An adequate technology of flood warning systems already exists, and its further implementation depends upon socio-economic rather than scientific questions. In contrast, most property losses from floods occur in the industrialised areas of the world: but again, while there may be interesting geophysical problems in need of study, the solution to the general problem is known and the existing technology is adequate (if used effectively).

In summation, containment of geophysical hazards is an economic and political problem, made doubly intractable by the existence of a third-culture. To increase the level of global catastrophe protection does not, in general, depend upon the need for new or better science, but rather upon the removal of economic, political and sociological constraints that prevent the use of existing technology.

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