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A Note on Order Statistics and Property Losses from Catastrophic Hurricanes and Floods in the USA

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Abstract

The relative short time scale and limited spatial scales of hurricanes allow a normalization of damages to the present time. The most damaging hurricane in the period 1925–1995 was one that hit South Florida in 1926, following a path north of that followed by Hurricane Andrew in 1992, and also caused damage along the Alabama coast. The normalized losses from the 1926 hurricane totaled $72 billion compared with the normalized $33 billion loss caused by Andrew. The most probable loss for a hurricane causing a loss greater than the 1926 hurricane is $152 billion. In constant current dollars, the average yearly loss from floods in the USA is $3.1 billion while losses exceeded $4 billion in 25 years. The largest yearly flood-related loss was from the 1993 Midwest flood, which caused a loss of $19.5 billion. The most probable value for yearly loss greater than that of 1993 is $32.5 billion.

About the Author

Gordon J. MacDonald is Director of the International Institute for Applied Systems Analysis (IIASA), an international, non-governmental organization that conducts policy-oriented, multidisciplinary research in areas of energy and technologies, population and society, environment and natural resources. He received his bachelor's degree *summa cum laude* and earned a master's and a doctorate (1954) in geophysics at Harvard. He has held various educational and administrative positions at MIT, UCLA and University of California, Santa Barbara. He served as a member of the President's Science Advisory Committee under President Lyndon Johnson and was a member of the first Council on Environmental Quality under President Nixon. He was Henry Luce Third Century Professor and Director of Environmental Studies at Dartmouth College from 1972 to 1979, when he joined the MITRE Corporation as chief scientist, later also becoming vice president, a position he held until 1990. He then joined the faculty of the University of California at San Diego as Professor of International Relations and Director of Environmental Studies, Institute of Global Conflict and Cooperation. During this time, he founded the Journal of Environment and Development, currently published by Sage Publications. In 1992, he served as the first chairman of the Environmental Task Force, sponsored by the Office of the Vice President, and then chaired its successor organization, MEDEA, until 1996. He is a member of several learned societies, including the American Academy of Arts and Sciences, American Philosophical Society, Council on Foreign Relations and the National Academy of Sciences. In 1994 he received the Central Intelligence Agency Seal Medallion, the agency's highest civilian award.

Among some recent publications:

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A Note on Order Statistics and Property Losses from Catastrophic Hurricanes and Floods in the USA

Gordon J. MacDonald

Extreme climate events, such as floods, droughts, and hurricanes, can result in property losses measured in billions of dollars. Such extreme climate events are located in the tails of the distribution of climate variables. Rank ordering statistics (David, 1981; Embrechts, *et al.*, 1997) provide a powerful tool to study the largest elements of a population, while the better-known statistics of cumulative distributions are well suited to describe the frequent small events. Order statistics are particularly useful if the tails follow a power law or Pareto distribution. Power law distributions have been found to be useful descriptors for a wide variety of complex natural systems and social systems (Mandelbrot, 1983, 1997).

In a warming climate, the tails of the distribution of property loss due to natural catastrophes can be expected to undergo greater percentage change than the mean. But these changes can be confounded by a growing wealthy population that settles in risk-prone, exposed areas. Increased losses due to increased population and wealth are labeled endogenous, while losses due to changes in climate are exogenous because governments' policy actions have no immediate impact on the frequency and intensity of catastrophic weather-related events. The movement of people to Southern Florida over the past decades illustrates endogenous change. In 1990, Brouward and Dade counties in South Florida were home to more people than all 100 coastal counties from Texas, east and north through Virginia in 1930 (Pielke, 1995). In 60 years, the mass migration of people and their wealth significantly increased the potential for massive property loss from hurricanes striking Southern Florida.

Thus, increased prosperity heightens potential losses. Population migration coupled with higher values of property, particularly in areas of industrial development, leads to a high concentration of risk. Shopping malls, trailer parks, hotels and holiday homes locate even in areas that are known to be high risk. In such a high-risk region, even small- and moderate-intensity storms and/or floods can lead to high losses. Changes in population density together with increased prosperity mean that it is be difficult to separate endogenous and exogenous factors determining property loss.

Available Data Sets

Pielke and Landsea (1998) provide a valuable data set for the 30 costliest hurricanes that made landfall in the United States during the period 1925–1995. Pielke and Landsea normalize past impacts to 1995 dollar values, assuming the updated loss is proportional to three factors: inflation, changes in wealth, and changes in population. The normalization produces the estimated impact of a storm as if it had made landfall in 1995. Use of the implicit price deflator for gross national product as reported periodically in the Economic Report of the President accounts for inflation. An economic statistic kept by the US Bureau of Economic Analysis called " Fixed Reproducible Tangible Wealth (FRTW)" measures wealth and includes equipment and structures owned by individuals, private business, and non-profit institutions as well as government-owned equipment and structures. Use of the ratio of today's wealth to that of past years normalizes losses in terms of the increased wealth of the nation. For changes in population density, Pielke and Landsea use US census data provided by the US Census Bureau for each of the 168 counties that lie along the coast from Texas to Maine.

Numerous factors lead to large uncertainties in property loss estimates, particularly those from catastrophic floods and hurricanes. In the case of losses due to high winds, insurance contracts provide useful estimates. However, there is no central clearing house to report flood losses in the United States. For example, in the case of government-maintained infrastructure, some portion of the cost to repair a washed-out bridge might be covered in a budget item as routine maintenance. Another portion might appear as a separate line item in the budget for the year following the damage. Frequently the new structure is one of higher quality and the costs are greater than the cost of repairing the damaged structure, a factor not included in damage estimates. In situations where the responsible agency carries no third-party insurance, it may decide to forgo some repairs or postpone them indefinitely.

The capital cost to repair or replace a bridge is easily identified as a loss, provided the cost data are available. Other cases may not be as straightforward. If flooding prevents a farmer from planting, the evaluation of the loss presents numerous problems. The farmer could plant a crop generating a lower profit or could plant later in the season, producing a lower yield. For the private sector, losses due to missed business opportunity can be insured, as can the cost arising from dismissing unneeded employees.

Losses from floods and hurricanes can easily be normalized to a given year by using the price deflator to correct for inflation. In the case of floods, it is much more difficult to normalize for changes in population density and wealth, since flooding typically impacts a much larger geographical area than do tropical storms and the detailed spatial resolution of the losses is generally not available.

A further complicating factor in using yearly flood loss is that in years where the flood loss is small, the losses due to drought conditions may be significant. For example, in 1988 there was extensive drought damage while the reported flood losses were only $225 million which, when corrected for inflation, corresponds to $300 million in year 2000 dollars. Quantifying drought damage is even more difficult than estimating flood losses, since droughts primarily affect agriculture and related industries, and tourism. Damage to infrastructure is low, though fires associated with drought may result in extensive damage to infrastructure.

Yet another difficulty of estimating non-insured losses is that the estimates may be recorded in different ways. In some cases they may be available only at an aggregated state or county level. As noted above, these data may or may not comprehensively include all damages. The data set for flood losses used in this note is that provided by the National Weather Service (www.nws.noaa.gov/oh/hic/flood_stats/Flood_loss_time_series/html). In considering the reliability of the estimates, one must take into account that the National Weather Service's primary responsibility is to provide weather forecasts, not estimates of loss from floods.

Rank Order Statistics and Power Law Distributions

The first step in determining whether property losses follow a power law or Pareto distribution is to take the *n* largest losses and rank them in descending order such that L_1 is the largest loss and L_n is the smallest loss,

$$L_1 > L_2 > L_3 \ldots L_{n-1} > L_n \quad .$$

Order statistics are particularly useful in analyzing the tails of a distribution–the highest values or lowest values. For our purposes, we are interested in the largest losses.

Let *r* denote the rank of loss L_r, By definition, L_r varies inversely with *r*. A special case, but one often observed in natural and social systems, L_r varies inversely with *r*

$$L_r \sim r^{-1/\alpha} \quad ,$$

a version of a Pareto distribution. The cumulative distribution function (CDF) for a Pareto distribution is

$$\text{CDF}\ (x) = 1 - \left(\frac{k}{x}\right)^{\alpha}$$

with a tail distribution $\left(\frac{k}{x}\right)^{\alpha}$.

The corresponding probability distribution function (PDF) is

$$\mathrm{PDF}(x) = \alpha\, k^{\alpha}\, x^{-1-\alpha} \quad .$$

(Embrechts, *et al.*, 1997). Pareto (1896) found empirically that this distribution described the distribution of the incomes of rich individuals. Pareto was a well-established economist who studied economic equilibrium, but whose arguments about income distribution received scant attention. The well-known probabilist Feller (1966; p. 49) dismissed Pareto with the statement, "It was thought (rather naively from a modern statistical standpoint) that income distributions should have a tail with a density $Ax^{-\alpha}$ as $x \to \infty$ … ".

George Zipf (1949) used the rank-size relation

$$L_r \sim F r^{-1/\alpha}$$

$$\log L_r \sim \log F - \frac{1}{\alpha} \log r$$

to describe the relations among a large number of variables in the social sciences.

For example, Zipf plotted the logarithm of the frequency of a word's occurrence in a text versus the log of the rank of the word and obtained a straight line relation. In many English texts, the four most frequent words are *the*, *of*, *and*, and *to,* with corresponding relative frequency of 0.1, 0.05, 0.033, and 0.025 indicating

$$\text{frequency} \sim 0.1\ 1/r; \quad \alpha = 1,\ F = 0.1 \quad .$$

Unlike Pareto, Zipf was not a member of the establishment, but was dismissed as an eccentric, single-minded zealot, who lectured at Harvard for twenty years, determined in pursuing a Zipf plot description of the world. Lacking the essential technical background to study the origin of his observations, Zipf grandly assumed that an undefined "principle of least effort" was the theoretical basis for his observations. Despite their suspect parentage

(Pareto, Zipf) power law distributions turn up today in the analysis of many complex systems.

Mandelbrot (1997) has emphasized the notion of scaling in connection with power law distributions. Let $P(x)$ denote the tail distribution where

$$P(x) = \text{Probability } (X > x)$$

$$= \text{Pr } [X>x]$$

Suppose it becomes known that X is at least equal to y. This changes the unconditioned variable X to the conditioned variable Y

$$\text{PY}[x] = \text{Pr}[Y>x] = \text{Pr}[X>x \mid X>y] = \frac{\text{P}(x)}{\text{P}(y)} \quad .$$

With a tail distribution $\text{P(x)} = \left(\frac{k}{x}\right)^{\alpha}$, and with y>k conditioning we have

$$\text{P}_{\text{Y}}[x] = \left(\frac{y}{x}\right)^{\alpha} \quad .$$

Conditioning alters the scale from k to y for power law distributions and only these distributions are scaling under this type of conditioning (Mandelbrot, 1997). The change of scale does not alter the functional form of the distribution. This invariant property of the distribution is described as being selfsimilar. Self-similar distributions are fractal, having similar geometric properties at all scales where the distribution is scaling.

The mean and variance of a power law distribution are easily calculated

$$\text{E}[\text{L}] = \frac{\alpha \text{L}_{min}}{\alpha - 1}$$

$$var[\text{L}] = \frac{\alpha \text{L}^2_{min}}{(\alpha - 1)^2 (\alpha - 2)} \quad .$$

The mean is not defined for $\alpha<1$. Similarly, the variance does not exist in a mathematical sense for $\alpha<2$.

Tropical Cyclones and Hurricanes

Each year, about 80 cyclones form in tropical ocean areas. These powerful storms, if located in the North Atlantic and Caribbean, are known as hurricanes. The intensely warm and humid air masses making up tropical cyclones are fueled by the heat contained in tropical oceans. The precondition for a cyclone to form is that the surface temperature of the ocean must be at least 26.5^{o} C to a depth of about 50 meters (Saunders and Harris, 1997). As the intense solar radiation in tropical regions evaporates water from the sea, the air making up the tropical cyclone becomes extremely humid. If air temperature reaches 35^{o} C then it holds about four times as much water vapor as does air at 10^{o} C (Emanuel, 1994).

The warming expands the air, leading to vertically moving moisture condensing into raindrops, and the air mass forms a low pressure area into which the humid air mass spirals upward. The atmospheric general circulation guides the horizontal motion of the tropical cyclone generally moving from East to West. The speed of the horizontal motion depends greatly on local conditions but averages between 20 and 50 km/h. The lifetime of the tropical cyclone varies greatly from one or two days to two or more weeks. As soon as the storm system leaves the warm ocean and moves over land, the fuel (heat stored in the ocean) for the storm is removed, the air mass cools and the cyclone dissipates.

As the moisture-laden air mass making up the tropical cyclone hits land, the rising and cooling of the humid air produces extremely heavy rains. The intensity of precipitation is largest in the wall of the eye and decreases outward. The total amount of rainfall from a hurricane can be extremely large; 20 trillion liters per day have been estimated for intense storms. Thus, flooding often results from the passage of a hurricane such as Floyd in 1999, which maintained its structure for several days over North Carolina and surrounding states.

The low pressure associated with the center of the hurricane together with the high winds lead to a storm surge as the hurricane makes landfall and winds push ocean water over land, compounding the flooding associated with the precipitation. Bangladesh has one of the most exposed coasts in the world; a storm surge with flooding in 1970 killed some 300,000 people.

Figure 1 shows the Pielke and Landsea (1998) data base of the thirty storms causing the greatest losses in the interval 1925–1997. Hurricane Andrew of 1992 is the second costliest hurricane in terms of damage. The costliest hurricane normalized to present time in terms of inflation, wealth and population change was one in 1926 that made landfall just north of the path taken by Andrew. It caused more than $63 billion (1995) of damage in the Miami area before making a second landfall on the Florida/Alabama gulf coast. According to the normalization, the total loss was $72 billion. Third on the list is a 1944 South Florida storm, followed by the great hurricane of 1938 that hit New England, both causing more than $16 billion in normalized losses.

Figure 1 shows no evidence for endogenous or exogenous variations. Pielke and Landsea (1998) have normalized for endogenous change, and the record is short compared to the time scale expected for climate to influence the severity and frequency of hurricanes.

Examination of the record of the number of hurricanes for the North Atlantic, including those not making landfall in the US, shows substantial year variability but no significant trend (Landsea *et al.*, 1999). In contrast, the number of major hurricanes has gone through multi-decade variations. As illustrated in Figure 1, active years occurred from the mid-40s to 1970, while quiet years occurred from the 1970s to the early 1990s, and there has been an increase in tropical storms during the period 1995 to the present. Thus, there is a close correspondence between the frequency of hurricanes in the North Atlantic and those making landfall in the US.

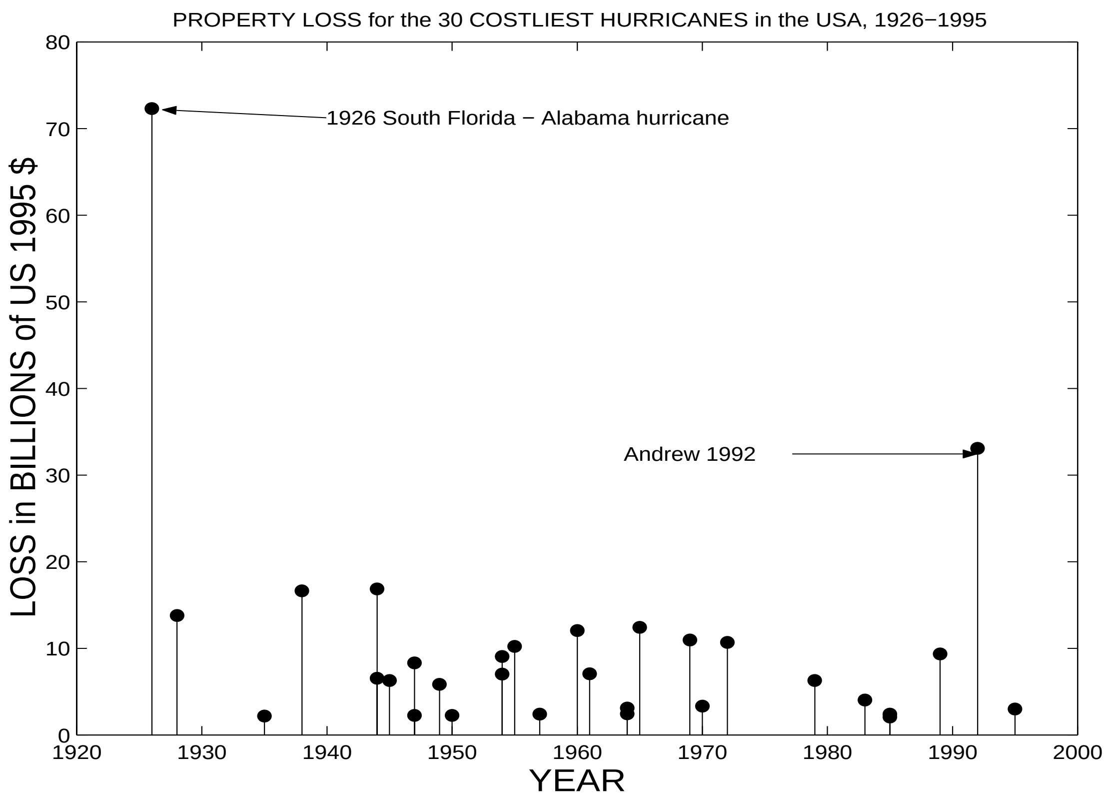

Figure 1. Pielke and Landsea (1998) data base of the thirty hurricanes making landfall that caused the greatest losses in the period 1925–1995.

From historical records, Fernandez-Partagas and Diaz (1996) estimated that the overall Atlantic tropical storm and hurricane activity for the years 1851–1890 was 12% lower than the corresponding 40-year period of 1951–1990 though little can be said regarding the intensity of the hurricanes. Elsner *et al.* (2000) argue that during the period 1943–1964 an average of 3.8 major hurricanes were observed in the North Atlantic as contrasted to 1.7 during the 1965-1994 period.

Turning to rank order statistics, Figure 2 displays a log-log plot, known in the literature as a Zipf plot, where the log of the property loss is plotted against the log of the rank of the loss (the largest loss has rank 1). If the tail of the distribution follows the power law distribution then the points should cluster along a straight line in the log-log space. As noted above, the slope of the line equals the inverse of the exponent α in the power law distribution. A valuable feature of this graphical display is that the exponent of a power law distribution can be determined with good accuracy by rank ordering statistics from the observation of only a few tens of the largest events. The mean of the losses shown in Figure 1 is \$10.1 billion, while the standard deviation is \$13.4 billion with a sample range of \$70.2 billion. These statistics are characteristic of a power law distribution where the magnitude of the loss as a function of rank drops off much more slowly than an exponential. The exponent in the power law α estimated from the slope of the line in the Zipf plot is 1.01. An alternative measure of $1/\alpha$ is given by the standard deviation of the log of the losses (Mandelbrot, 1997). The standard deviation is 0.874, corresponding to an alternative estimate of $\alpha = 1.14$.

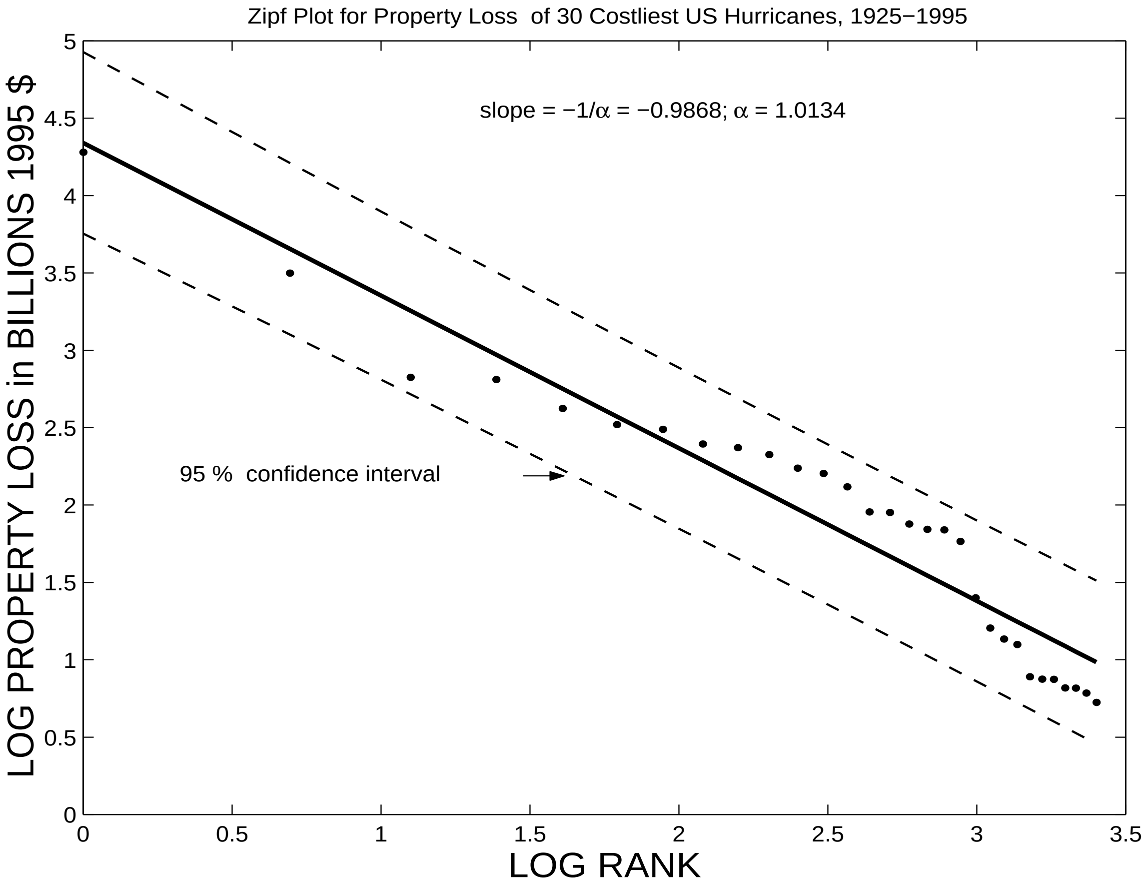

Figure 2. Log-log plot of the property loss against the rank of the event for the 30 largest losses due to hurricanes in the period 1925–1995 (see Fig. 1).

As noted above, many natural events show a power law distribution in the tails. The classic example is the frequency magnitude distribution of earthquakes (Gutenberg-Richter scale). A power law distribution indicates an underlying self-similarity or fractal nature of the phenomenon.

Self-similarity means a lack of characteristic size. As a consequence, there is no limit to the magnitude of a loss from a hurricane in the region where scaling is observed. In general, scaling cannot be extended to infinity. In the case of hurricane losses, the losses must be significantly less than a small fraction of the global GDP. The variance of the power law distribution can be expressed in terms of the terms of exponent α and the value of the smallest member of the population L_{min} where for the ordered set of losses from the hurricane $L_{\text{min}} = L_{30}$. Since the estimates of α are near 1, this implies that the variance does not exist in a mathematical sense and that the conventional interpretation of confidence intervals is invalid. However, we include that statistic as a measure of goodness of fit. The interpretation of $\alpha < 1$ means that there is no such thing as an average hurricane loss; $\alpha < 2$ implies that there is no characteristic standard deviation for hurricane losses. In this case, standard deviation is an inappropriate statistic to measure the spread of losses.

Rank ordering statistics can be used to infer the magnitude of future losses. If there were to be an event larger than the normalized loss for the 1926 South Florida hurricane, we can estimate the magnitude of that loss by recognizing that the largest event recorded to date has now moved to rank 2, the second largest event to rank 3, and so on. Using the best fit least square line to the order statistics, this implies that $L_{\text{next}} = \left(\frac{L_1}{L_2}\right)^{1/\alpha} L_1$, which means that the most probable normalized catastrophic loss for a hurricane with a loss greater than that of the 1926 hurricane is \$152 billion.

Floods

In terms of estimates of property loss, tropical cyclones are relatively easy to characterize compared with floods. Tropical cyclones are relatively well-defined single events; in contrast, there are numerous causes for floods whose temporal and spatial scales can be large compared with those of cyclones. A common characteristic of floods is that a river overflows its banks, inundating and damaging infrastructure, personal property, and agricultural land. But that characteristic is insufficient to describe all forms of damage due to excess water. The conventional picture of flooding involves prolonged rainfall, lasting for many days or weeks, saturating the soil. As a result, an increasing proportion of rain flows straight into the river beds. The tributaries to the river lead masses of water into the main river channel, which becomes incapable of handling the added inflow. Dikes or embankments on either side of the channel can ensure that the flood water reaches the sea without causing any damage. However, if the inflow of water exceeds the capacity of the channel or if the flood protection fails for other reasons, the result is extensive long-term flooding. The flooding in the Oder river in Poland in 1997 illustrates this kind of flood. Continuous rainfall over several days led to some 6,000 km^2 being flooded along the river, causing damage amounting to some $2 billion.

Flooding can also result from storms such as hurricanes, as has been noted above. Storm surges along the coast are triggered by a combination of tropical cyclones and tides. Storm-generated high winds pile up water against the coast over hours or days, and if this pile-up coincides with a high tide, vast volumes of water move inland and large areas may be flooded. Bangladesh has suffered severely over the years from storm surges; in 1970 and 1991 the death tolls reached 300,000 and 140,000 respectively.

Flash floods are the most frequent type of flood and can cause high damage, though for the most part it is spatially localized. High-intensity local precipitation continuing for several hours can set off a flash flood. The precipitation is of such intensity that the rain cannot be absorbed by the soil and runs off along the surface. As a result, floods occur not only along small or medium-sized waterways, but wherever the masses of water from two or three tributaries meet.

Excess water from rainfall can loosen the heavily soaked soil lying on a slope in mountainous areas, which then slides downhill spontaneously. At high saturation levels, the flow becomes a fast-moving mass of mud that follows the water courses. Mud flows are a combination of landslides and floods: the high density of the water and rock mixture together with considerable flow velocities gives the mud flow an enormous destructive potential. The mud flows in 1999 in Venezuela resulted in property damage in excess of $15 billion.

Figure 3 presents a summation of the estimated yearly damages resulting from floods in the United States for the period 1903 to 1999. The increase in loss over the years is apparent. Most of the increase in probably due to the endogenous growth of population and wealth. But there also may be an exogenous component: the intensification of the hydrological cycle caused by global warming may lead to increasing frequency of droughts and wet spells (Karl *et al*., 1995). Because of the difficulty in evaluating flood losses as well as determining changes in flood patterns, it will undoubtedly be difficult to disentangle the endogenous and exogenous causes of the increased property loss associated with floods.

Three examples of flooding in the USA underline the diversity of flooding phenomena. The great Midwest flood of 1993 actually began in the fall of 1992. That fall, rains and winter snows produced near-saturated soil and well above normal water storage conditions. The spring and summer months of 1993 exhibited persistent storm systems along with broad areal extent of rainfall that depleted possible rainfall storage areas from mid-June into August of 1993, and this led to the vast area of flooding. In the summer months, some areas received more than 1.2 meters of rain. The duration, extent and intensity of the flooding defined this event as the flood of the 20th century. The flood waters remained in many areas for nearly 200 days, a very unusual event for North America. While people identify the flood with the Mississippi river, major flooding occurred along dozens of rivers in the midwestern United States, including the Missouri river. Nine states, with more than 15% of the area of the contiguous USA, were catastrophically impacted. Measured in terms of 1999 dollars, the 1993 flood resulted in losses of almost $19.5 billion.

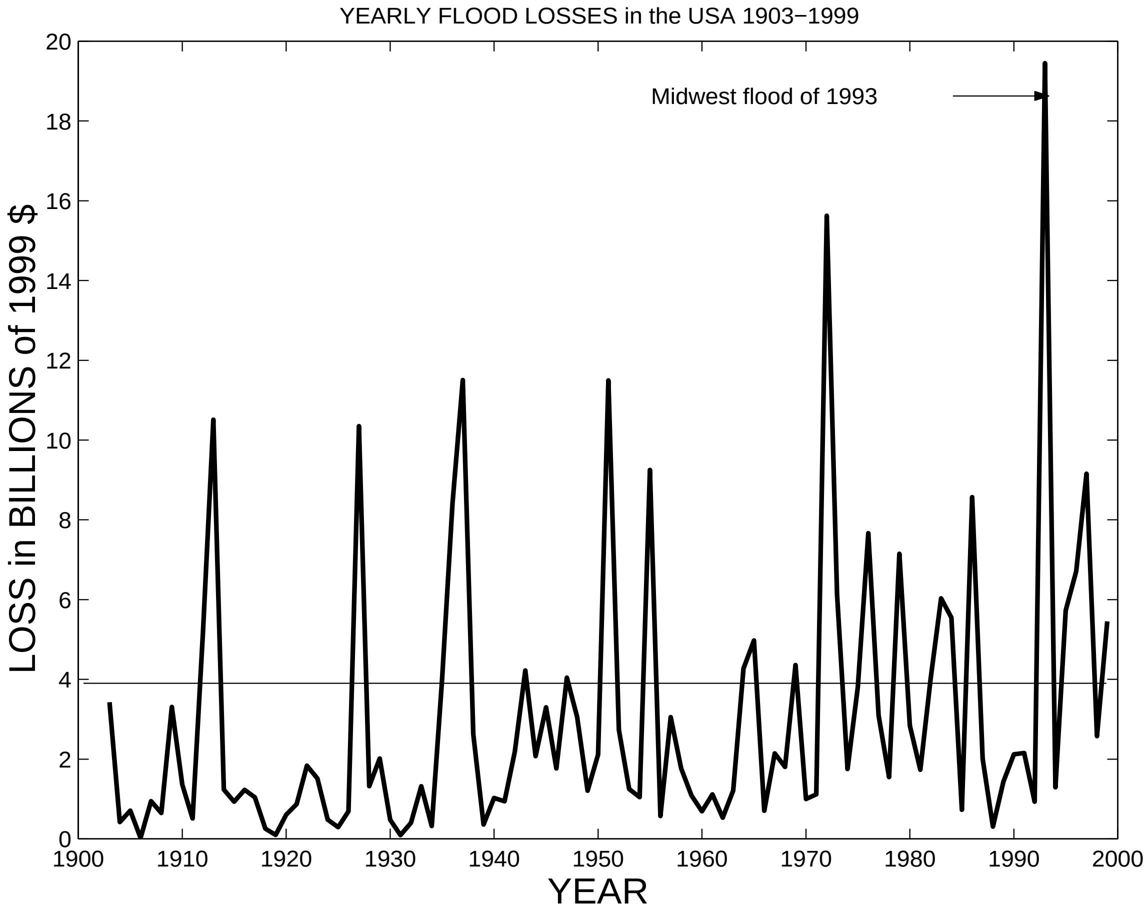

Figure 3. Estimated yearly damages resulting from floods in the United States from 1903 to 1999 (after National Weather Service, www.nws.noaa.gov/oh/hic/flood_stats/Flood_loss_time_series/html).

While the great flood of 1993 caused vast damage, it is dwarfed by the 1998 summer floods in the Yangtze river. An indication of the magnitude of the two floods is provided by the flux of water. On the Yangtze, a flow of 68,300 m^3/sec was recorded. The peak flow value of the Mississippi in 1993 was only 27,000 m^3/sec, while the Oder flood (1997) was 3,600 m^3/sec. Chinese economists estimate the loss from the Yangtze disaster at more than $35 billion. As in the case of many other floods, the losses in the basin of the Yangtze were accentuated by a high population density and the rapid economic growth leading to increased concentration of wealth.

An examination of Figure 3 shows several periods where the flood loses were very low. These coincide with times of drought. Severe drought took place in 1988 as well as during the 1931–33, 1919, and 1906 periods. So while flood losses were low during those epochs, losses due to drought are not included in the overall loss figures.

In order to carry out an analysis of rank order statistics, the values of losses greater than $4 billion were used. This upper tail contains 25 values and the corresponding log magnitude–log rank plot (Zipf) is shown in Figure 4. The value of the exponent for the powerlaw distribution derived from the slope is $\alpha = 1.986$. The dashed line shows the 95% confidence interval and the goodness of the fit as measured by R^2 is 0.95.

Since α is approximately 2, the mean exist in the mathematical sense, there would be some question as to whether the standard deviation exists. As in the case of the next greatest annual hurricane loss, we can compute the next greatest yearly flood loss. The resulting value is $32.5 billion. Thus, the most probable loss during the next largest catastrophic flood loss year will be in excess of $30 billion.

Conclusions

Despite the difficulties in obtaining and interpreting data on damages, the data for hurricane and flood losses in the USA can be expected to be as good as or better than data from many other countries. However, the many uncertainties that exist in evaluating overall loss reduce the accuracy of the estimates. Nonetheless, order statistics can be applied to the upper tails of loss values to obtain our most probable values for the next catastrophic single hurricane or flood loss year.

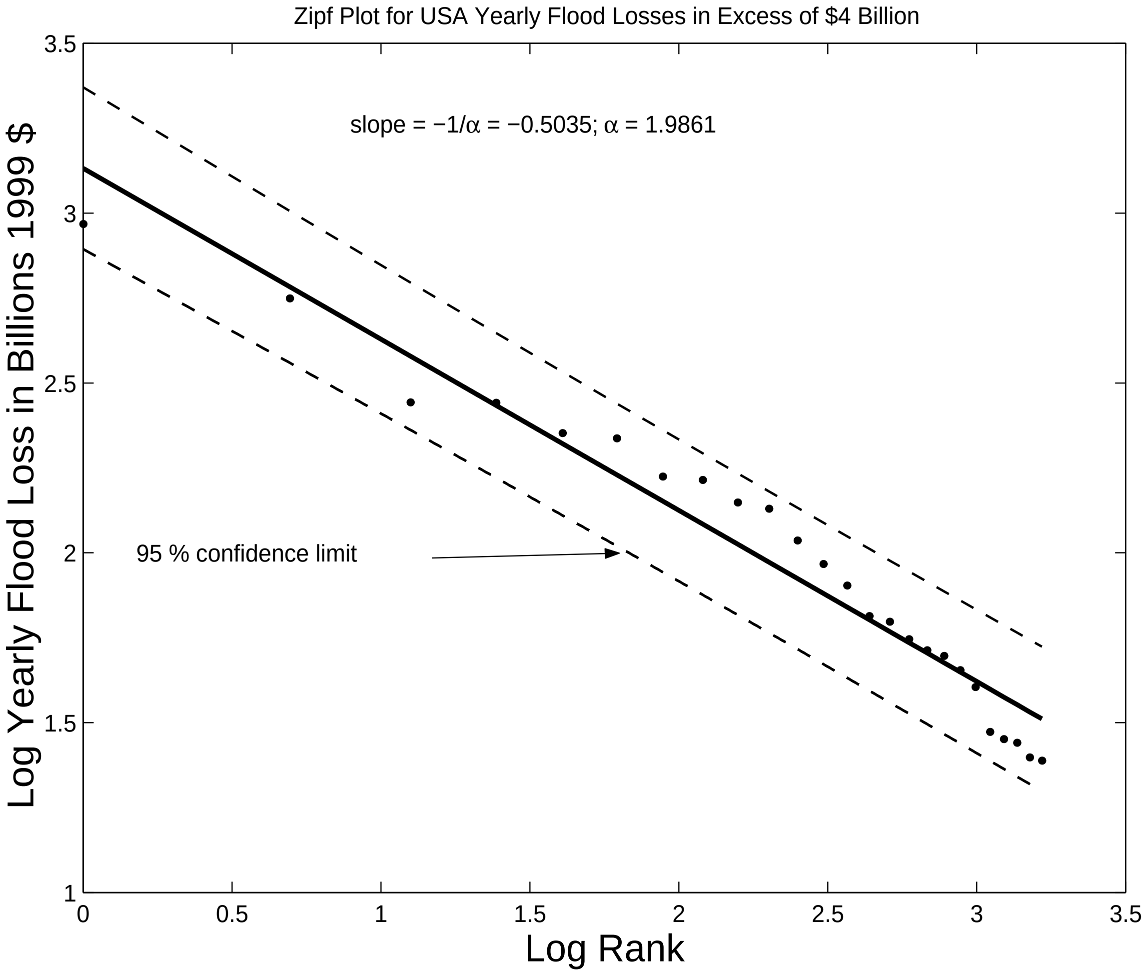

Figure 4. Zipf plot for flood losses in excess of $4 billion (1999) (see Fig. 3).

It is interesting to note that the most probable value for the next flood loss year is comparable to the estimated losses in the Yangtze river for 1998. Even though the flow of water over the Yangtze is greater than that of the Mississippi, the difference can be made up by the higher value of the infrastructure on the banks of the Mississippi.

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