

Extreme Rainfall, Flood Scaling and Flood Policy Options in the United States

by

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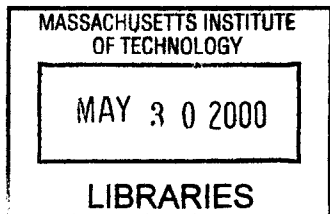
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ABSTRACT

River flood and rainfall have been shown to exhibit scale invariance behavior over a range of space and time scales. Although various approaches have been taken to investigate and model the various scaling aspects of rainfall and floods, little theoretical work has been done on the relation between the scaling of rainfall and flood. If available, such a theory would provide frequency estimate for extreme rainfall and floods outside the range of observations and could also be used to estimate floods at ungaged basins. The relationship between rainfall and flood scaling is the main focus of this thesis.

We use a two step approach to investigate the relationship between exponent of peak flows and the scaling of rain. First, we use data analysis to verify existing theories that relate the multiscaling behavior of rainfall to the simple scaling behavior of the IDFs. Second, we use a model to relate the scaling of the IDFs to the scaling of peak flows with basin area. We find that, although temporal rainfall shows multiscaling, the IDFs exhibit simple scaling and peak floods show simple or mild multiscaling. We validate our findings by using U.S. peak annual flow data and rainfall from a few New England stations.

Extreme floods damage mitigation requires sound and integrated policy making. We review the flood disaster mitigation situation in the U.S., carry out policy analysis and recommend options for a successful and sustainable flood disaster policy in the U.S.

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Source: Berndtsson and Niemczynowicz, 1988.

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CHAPTER 1

Introduction

It has been found that maximum annual floods, in a given region and within certain limits, have a scale invariant dependence on drained area. As an example, figure 1.1 shows the first four moments of annual peak flows from New England, U. S. Rainfall in space, time, space-time and rainfall intensity distribution frequency curves (IDFs) have also been observed to exhibit scaling behaviors of different types.

There are various aspects of rainfall scaling. Rainfall may be scaling in time, space or both space-time. The limits of scaling of rainfall in time and space are important to consider. It has been observed that the break in scaling varies from region to region. Another question is whether rainfall is scaling at all times or only inside storms. Studies have shown that even though temporal rainfall may show multiscaling, dry durations between storms do not scale and extreme rainfall (IDFs) has been observed to exhibit simple scaling. Moreover, season-specific IDFs have been shown to exhibit different scaling properties.

Scaling of floods and the connections between flood generating mechanisms, effect of spatial variability and scaling of rainfall and the role of basin response are topics of active research and have practical importance for regional flood frequency analysis. Both statistical frameworks and physically based models have been used to study the scaling of floods with basin area.

Most of the studies about scaling have dealt separately with either the scaling of rainfall in time, space or space-time or with the scaling of floods. The relation between the scaling behaviors of rainfall and flood has received relatively little attention. The present study aims at relating the scaling of the rainfall to the IDF curves and the scaling of IDFs to the scaling of river floods. We use a two step approach to investigate the relationship between exponent of peak flows and the scaling of rain. First, we use data analysis to verify existing theories that relate the multiscaling behavior of rainfall to the simple scaling behavior of the IDFs. Second, we use a model to relate the scaling of the IDFs to the scaling of peak flows with basin area. The results can be used to extrapolate the frequency of extreme events and for flood prediction and estimation at regions with sparse or no data.

We use theoretical results and empirical data analysis to: (1) verify if rainfall, IDFs and peak flows exhibit scaling; (2) the limits of such scaling, if any (3) the type of scaling (simple scaling or multiscaling in space or time); (4) the relation of scaling of rainfall to the scaling of IDFs; (5) the effect of seasonality on scaling characteristics of rainfall and IDFs; and (6) the relation of scaling of IDFs to the scaling of annual peak flows.

Extreme floods cause extensive damage to life and property. The techniques and approaches used to estimate the flood frequency have an important but limited role in mitigating the flood damage. The public perception of risk from flood and the way financial adjustment to that risk is carried out by the government are important factors in analyzing the damage mitigation situation. Over the last decade, the U. S. has faced

an unprecedented array of flood related disasters, costing billions of dollars. This has forced the government to review its policy toward flood damage mitigation.

This thesis deals with two aspects of floods. One is concerned with the scaling approach to floods; the other is about policy analysis and recommendation for flood mitigation in the U. S. The thesis is organized in two parts. Part 1 focuses on the scaling properties of rainfall, intensity duration frequency curves and peak flows in the rivers and how such properties can contribute to better knowledge of extreme hydrologic events. Part 1 consists of chapters 2 through 6. Part 2 presents an analysis of the flood mitigation policies in the U. S. and recommends an improved set of policies. We review the history of flood mitigation policy in the U. S., point out the problems with the current policy, identify barriers to effective policy making for flood mitigation and outline policy recommendations. The rest of this thesis is organized as follows:

Literature review is covered in Chapter 2. The objective of the review is to present the current state of the scaling approach in hydrology. We discuss the past studies and models of rainfall scaling in time, space and space-time, IDF scaling, and flood scaling.

In chapter 3, we present the analysis and modeling of temporal rainfall. We investigate the scaling of temporal rainfall. We compare our approach and results with the literature and propose a new model for distribution of duration of dry periods.

Chapter 4 presents the scaling of rainfall and point IDF curves in context of a theory which relates parameters of multiscaling rainfall to the parameters of simple scaling of

IDFs. We perform this analysis for the annual and the seasonal series and find good match with the theory.

In chapter 5, analysis of river floods is presented and the scaling of flood peaks is discussed. We present a simple model of floods which is based on the IDF scaling obtained in chapter 4. We focus on the processes and hydrologic variables controlling the scaling exponent of flood peaks with the basin scale. We find that the theoretical results for scaling exponents of flood peaks with basin scale, derived from IDFs, are in good agreement with the empirically observed exponents of flood peaks with basin scale.

Chapter 6 presents a summary of the findings, discussion of the results, conclusions and open questions and future research topics. This concludes part 1 of the thesis.

Part 2 of the thesis consists of chapters 7 and 8. Chapter 7 examines the past and current flood policies, the role of flood insurance policies and the fiscal management of flood damage mitigation measures by the government. We identify and discuss the problems with the current flood mitigation policies.

In Chapter 8, we focus on land use planning and flood insurance as the main tools for flood damage mitigation policy making. Chapter 8 outlines the barriers to effective policy making and provides recommendations for an integrated, consistent national policy for flood mitigation in the U. S.

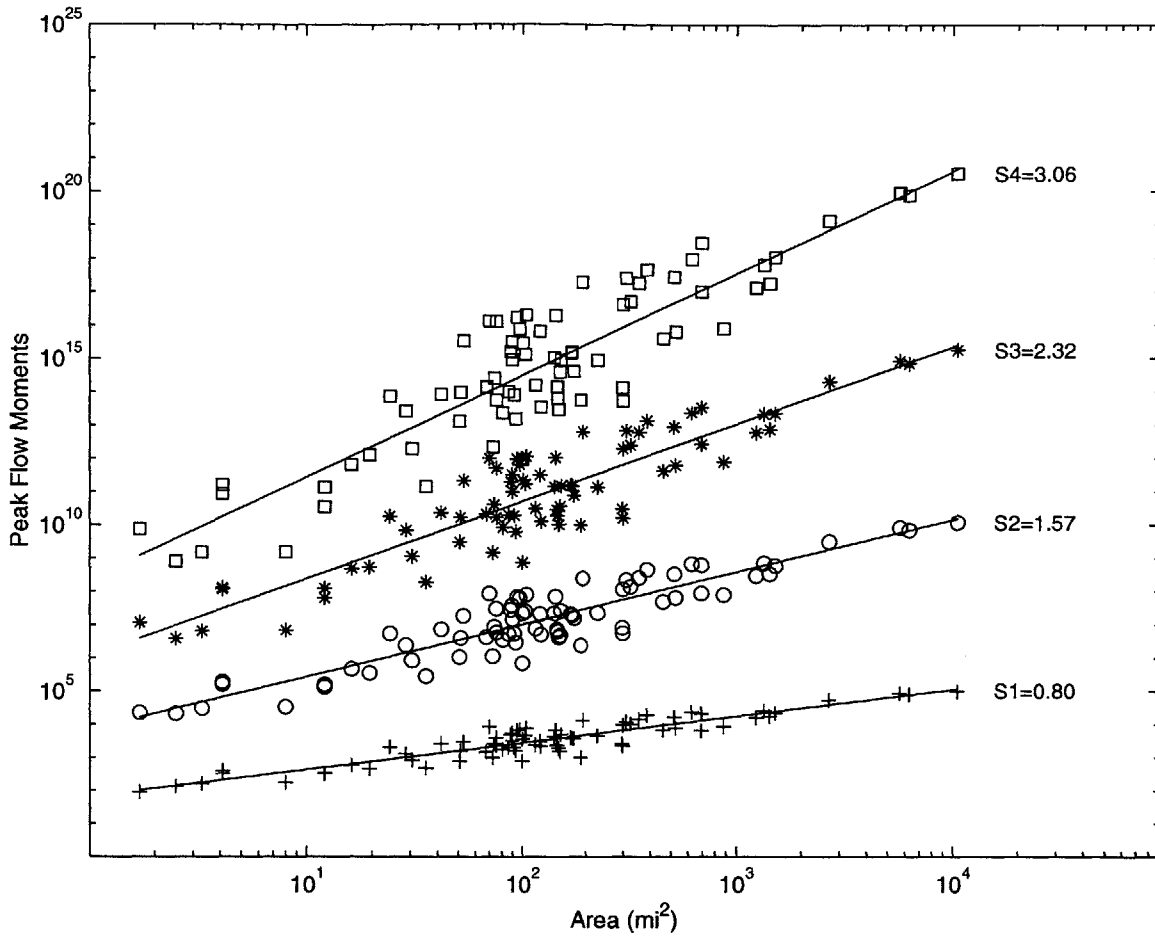


Figure 1.1. Scaling of annual flood peaks in New England Region. Moment orders shown are: (+) first moment, circles, second moment, asterisks, third moment and squares, fourth moment. The lines show the fitted regression to the moment orders 1 through 4. S1, S2, S3 and S4 show the slopes of the first, second, third and fourth moment of the peak flows respectively.

CHAPTER 2

Literature Review

In this chapter, we review scaling models of rainfall, intensity-distribution-frequency curves (IDFs) and peak river flows. We review and compare the main issues surrounding scaling approach to rainfall, IDFs and peak river flows. We are interested in finding out what characteristics of rainfall, IDFs and peak river flows scale and if so, in what way i.e., simple scaling or multiscaling. The issues we review are related to scaling (or nonscaling thereof) of: rainfall occurrence; complete rainfall series of including intensity; rainfall in space; rainfall in space and time; IDFs at a point and for basins; and spatial peak river flows.

If scaling exists, then there are a number of compelling questions about the controlling factors on the scaling behavior. One question is that if scaling exists, what are the limits of scaling and how does the approach, climate and data affect these limits? We are also interested in finding out the relationship of rainfall scaling in time to that of IDFs and to investigate the dependence of peak flow scaling on spatial rainfall scaling and basin characteristics. One objective of this review is to give an overall idea of the consensus and controversy on ideas surrounding scaling approach to rainfall, IDFs and peak river flows.

2.1 Scaling of Rainfall

Rainfall has a complicated temporal and spatial structure covering a wide range of scales in both time and space. Such complex properties make rainfall modeling a challenging task. Cox and Isham (1994) distinguish between three broad types of conventional (non-scaling) mathematical models of rainfall: empirical statistical models, dynamic meteorological models and intermediate stochastic models. Models of point rainfall lack the ability to describe the statistical structure of rainfall over a wide range of scales. A range of methods is needed depending on the time and spatial scales involved, which involves estimating parameters at different scales.

Successful application of scaling models to various geophysical processes has motivated hydrologists to explore scale invariance in hydrologic processes. Although there is literature to support theoretical arguments and empirical evidence of scale-invariance (Schertzer and Lovejoy, 1987; Gupta and Waymire, 1990; Gupta and Over, 1994; Gupta et al. 1996; Olsson, 1995; Schmitt et al. 1998) yet the findings differ on important issues and controversy exists about the approaches used to reach the conclusions.

Scaling models of rain have evolved from fractal geometry for rain areas, to monofractal fields, to multifractals, to generalized scale invariant models, to universal multifractals (Foufoula-Georgiou and Krajewski, 1995). Veneziano et al. (1996) have presented a detailed classification and discussion of scaling models of rainfall. The following brief description of the type of scaling models follows Veneziano et al. (1996). Simple scaling models are associated with additive mechanisms; either the cumulative rainfall rate process or the rainrate fluctuation process can be simple scaling. An example of simple

scaling model is the first of the two wavelet models proposed by Perica and Foufoula-Georgiou (1996). Again, there can be two ways in which rainfall may be considered multiscaling: cumulative rainfall process (Gupta and Waymire, 1993) and rainrate fluctuation process (Lovejoy and Schertzer, 1991). Multifractal models of rainfall can also be classified as either conserved (Gupta and Waymire, 1993; Over and Gupta 1994, 1996) or nonconserved (Lovejoy and Schertzer, 1991; Tessier, 1993).

Most of the scaling studies of rainfall focus either on temporal rainfall series at a point or the spatial distribution of rainfall at a given time. Scaling and multiscaling in rainfall time series has been reported by a number of empirical studies (e.g., Olsson et al. 1993; Olsson 1995, Svensson et al. 1996). Similarly scaling of spatial rainfall has also been investigated and it was found to show scaling behavior (Gupta and Waymire, 1990; Olsson et al. 1996). Progress has also been made on building a theoretical framework for scaling behavior of rainfall. A type of processes known as cascade processes have been proposed as a possible mechanism to realistically represent the scaling properties and the hierarchical structure of rainfall (Schertzer and Lovejoy, 1987; Gupta and Waymire, 1990, 1993; Tessier et al. 1996). Scaling theory has also been applied to the space-time rainfall (Marsan and Schertzer, 1996; Over and Gupta, 1993; Deidda, 2000); however, there is a debate whether the scaling in space-time rainfall is isotropic or anisotropic.

When analyzing empirical data for scale invariance, different methods have been used to investigate if the process exhibits scale invariance, the limits of scaling and to model the scale invariance behavior of rainfall process. Spectral analysis (Olsson, 1993), box counting and correlation dimension (Olsson et al., 1993) can be used to investigate the

existence and the limits of scaling for data sets; however, these techniques do not tell whether the process is multiscaling or not. Moment scaling analysis (Gupta and Waymire, 1990) is often used to investigate if the process possesses simple scaling or multiscaling. To model the multiscaling processes and to estimate the basic multifractal parameters, probability distribution/multiple scaling (PDMS) analysis (Lovejoy and Schertzer, 1990) or double trace moment (DTM) analysis (Lavallee, 1991, Tessier et al., 1993) may be used. Analysis employing above mentioned techniques has been carried out using both radar rain reflectivities (Lovejoy and Schertzer, 1990; Gupta and Waymire, 1993) and rain gage series data (Tessier et al. 1993; Svensson et al. 1996).

Moment scaling analysis is a common method used to investigate and analyze the scaling behavior of hydrologic processes at different aggregation levels. Moment scaling analysis has been applied to both time and space domains for rainfall and river flow among other geophysical processes. For illustration purpose, consider the case for rainfall moment scaling analysis. Let D be the duration of events for aggregation, and I_D be the aggregated rainfall over the duration D . Denote raw moment of order q and aggregation D by $E[I_D^q]$. The scaling analysis provides information about: (1) whether there is log-log linearity of statistical moments $E[I_D^q]$ and D , and (2) the nature of growth (linear or non-linear) of slopes of these moments $k(q)$. If condition (1) is satisfied, then the behavior of the slopes, called scaling exponents, determines whether the process obey simple scaling or multiscaling. If the slopes exhibit a linear growth with the moment order then, according to the scaling theory, the process is simple scaling. If however, condition (1) is satisfied but the slopes show deviation from linear growth, then the process is multiscaling (see figure 2.1).

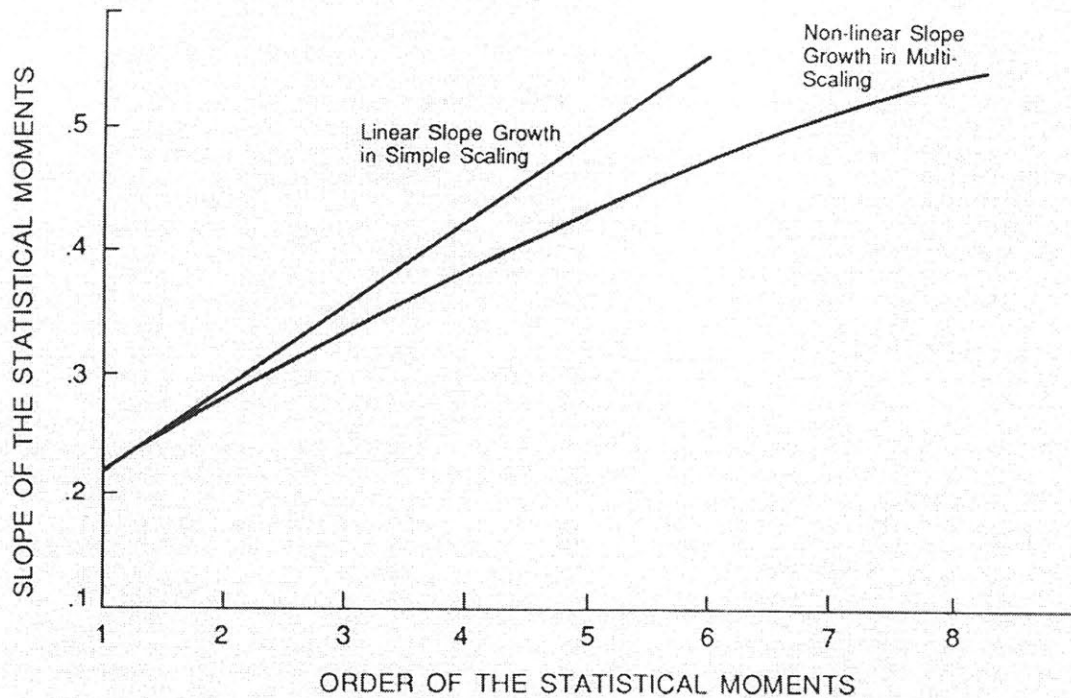


Figure 2.1. Illustration of simple and multiscaling behavior of empirical data.

Simple scaling implies that the statistical spatial variability in the physical process does not change with a change in scale. Simple scaling processes allow both scale magnification and downscaling. For multiscaling processes, the nonlinear growth in slopes with the order of the moment leads to the interpretation that statistical spatial variability in such processes may increase or decrease (for a concave growth) with an increase in scale. In the multiscaling case, the scaling properties can be used for either scale magnification or scale contraction, but not for both (Gupta and Waymire, 1990). In contrast to the simple scaling case where there is a linear growth in slopes, in the multiscaling case the scaling behavior is determined by a spectrum of exponents. Determination of these exponents in terms of measurable physical and geometrical parameters is not only a very important research topic but also has practical applications in rainfall downscaling and regional flood frequency analysis.

2.1.1 Temporal Scaling of Rainfall

It has been observed and verified by a number of studies (Olsson, 1992; Schmitt, 1998) that scale invariance of physical systems generally holds within a certain range of scales bounded by inner cut-off and outer cut-off limits. The region and local climatological factors are considered to play a role in imposing these limits. This represents an important consideration when one is applying scaling as a predictive model.

Investigation of the power law spectrum of a data set can give information about the scaling characteristic of the data set. If scaling holds for a data set, the energy spectrum $E(f)$ has the power law form: $S(f) \propto f^{-\beta}$ where β is spectral exponent. The power spectrum shows the scaling of the series second order moments. A number of researchers have included this analysis as a preliminary step to estimate the limits of the scaling regime. If the power law holds for a certain range, the spectrum will be approximately a straight line within that range in a double logarithmic plot.

Olsson (1993) carried out spectral analysis of rainfall data in Sweden and found a power law form of $E(f) = f^{-0.66}$ in the range of temporal scales between 8 min to approximately 3 days. However there is uncertainty and considerable variation in the range within which the spectrum is a straight line. It has been hypothesized that such break is related to the rainfall generation mechanism. The value of exponent β provides information about the stationarity of the data. If $\beta < 1$, the process is stationary. For β between 1 and 3, the process is nonstationary with stationary increments. Menabde et al. (1997) called the rainfall time series possessing power spectrum exponent $|\beta| > 1$ as self-

affine rainfall processes. Menabde et al. (1997) proposed that a cascade model with variable parameters over scales is better suited for self-affine rainfall processes. The exponent β also depends on the resolution of the data. Svensson et al. (1996) used daily rainfall data and found β to be 0.28 in Sweden and 0.37 in China.

Box counting is used to estimate the fractal dimension of a data set which can be interpreted as the degree of irregularity by which the set is distributed. The general procedure of box counting is as follows (Olsson et al., 1992): The total data set is divided into gradually decreasing, non-overlapping segments (boxes) of size r and for every r the number of boxes $N(r)$ needed to cover the set of points is counted. If the set exhibits scaling, i.e., $N(r) \propto r^{-D_s}$, then the plot of the log count $\log[N(r)]$ as a function of $\log(r)$ will be a straight line with the slope being an estimate of the box dimension D_s .

Olsson et al. (1992) investigated the scale-invariant behavior of rainfall in time by applying the functional box counting technique described above. They used two years of one minute observations, 90 years of daily observations and 170 years of monthly observations, all observed in Lund, Sweden. For the two years of one minute rainfall observations, the plot between durations against number of boxes showed three distinct segments with different slopes. Similar results were obtained for the other data sets. For the minute rainfall series, The slopes in the three sections were 0.82, 0.37 and 1 respectively and the first break occurred at 45 minutes, which was also found to be the average duration of the rainfall events. The rainfall events were defined as those rainy events which are separated by at least 10 minute intervals of no rain. The first section, 1-45 minutes, was interpreted as representing individual rainy minutes with the break in

scale indicating formation of single rainfall events. The gentler slope from 45 minute to 1 week was considered to be the reflection of rainfall events scattered over time. Beyond one week the unit slope indicated saturation of rainy boxes.

Veneziano et al. (1996) investigated the issue of scaling within a storm duration using data from seven high-resolution rain gages in Iowa. They found a segmented frequency spectrum of the logarithms of the series. From the slopes of the spectra, they conclude that a cascade model is not appropriate for these events. They proposed a non-scaling stochastic lognormal model with segmented log spectrum.

Now, we review the multifractal model theory and background and then present the techniques used to estimate the parameters of such models. Stationary multifractal models are in the form of discrete or continuous cascades. Discrete cascades are stationary and scaling in a limited way and provide crude representations of rainfall in space or time. Continuous cascades do not have these limitations. The assumption is that fluxes of water and energy in the atmosphere may be governed by multiplicative cascade processes transferring these quantities from larger to smaller scales. One starts at the largest scale with a given "mass" uniformly distributed over the support. Each subsequent step divides the support and generates a number of weights (equal to the "branching number" of the generator), such that mass is redistributed to each of the divided supports by multiplication with the respective weight. To achieve conservation in the ensemble average of the mass, the expected value of the weights should be equal to unity. Different distributions of the weights have been used to represent rainfall including multinomial, uniform, lognormal and log-Levy. In the multinomial case, the

weights take a finite number of values with certain probabilities. A discrete multiplicative cascade model is parameterized by its branching number, the probability distribution of its weights, and the initial mass. These branching numbers and the distribution of the weights determine the multifractal properties of the cascades.

A cascade model, known as the log-Levy model, was proposed by Lovejoy and Schertzer (1987 and subsequent work). In the log-Levy model, the logarithms of the weights are distributed according to a non-Gaussian stable distribution. Holley and Waymire (1992) have pointed out that the lack of ergodicity of models with log-Levy exponents greater than unity is a problem. In support of their model, Lovejoy and Schertzer (1990) have argued that due to nonlinear interaction at a wide range of scale, several details of the rainfall dynamics are unimportant, and the resulting fields fall within a universal class of log-Levy multifractals characterized by three parameters.

PDMS (Lovejoy and Schertzer, 1990) is based on the notion that the variability of the probability distribution at different scales is connected through a dimension function.

The relationship between average field intensity ε_λ and scale ratio λ is given as

$$\Pr(\varepsilon_\lambda > \lambda^\gamma) \approx \lambda^{-c(\gamma)} \quad (2.1)$$

where Pr is probability, γ is the order of singularity and $c(\gamma)$ is a characteristic function of the multifractal behavior, known as the codimension function. Values of the function $c(\gamma)$ are known as codimensions and are computed as the difference of the dimension in which the process is studied and the corresponding dimension of the process. According

to Olsson (1996): "The sign \approx should be interpreted as equality up to prefactors slowly varying with λ . In data analysis, these prefactors are normally ignored." The codimension function of temporal rainfall can be obtained parametrically from the moment scaling function $k(q)$ as

$$\gamma(q) = dK(q)/dq \text{ and } c(q) = q\gamma(q) - k(q).$$

$\tau(q)$ is a transformation which is sometimes used instead of $k(q)$. Double trace moment (DTM) is another technique used to estimate the multifractal parameters (mean codimension function, Levy index) under the assumption of universality (Lavalley, 1991). For an application of DTM analysis see Olsson, 1995.

Rainfall process can be viewed as consisting of exterior processes (storm arrival) and interior processes (during rainy periods). The multifractal models of rainfall have performed well for the interior processes but have less success in realistically modeling the exterior properties of storms. Schmitt et al. (1998) have shown that the β -model (Frisch et al. 1978), used by Over and Gupta (1994) to reproduce intermittency, lacks the ability to reproduce the probability distribution of the wet periods of rainfall time series. The β -model, is a simple random cascade model which has the characteristic that only one parameter specifies the distribution.

Schmitt et al. (1998) have proposed modeling rainfall time series as a two step approach: using two-state renewal processes to model the occurrence and non-occurrence of rainfall and multifractals to model the rainfall variability. The model of rainy/non-rainy

events is based on two-state renewal process with given probability densities for wet and dry periods. The variability in the rainfall is modeled by a modified multifractal model following Schertzer and Lovejoy's universal multifractal approach. The time series of the rainfall is obtained by multiplying the series generated with the alternate renewal process and the one provided by the multifractal model. Their approach takes care of the exterior rainfall by limiting the multifractal model to the interior process.

Schmitt et al. (1998) perform data analysis on a 29 year long, 10-min resolution time series in Uccle, Belgium. Schmitt et al. (1998) used the box counting technique to verify that the occurrence of rain is scaling. The box counting showed a break in scaling at 3.5 days. They also found that the residence time probability density of dry period scales with a slope of $(-D_s - 1)$, where D_s is the fractal dimension obtained from box counting analysis. Schmitt et al. obtained a $D_s = 0.55$ for the Uccle data. In contrast to their analysis, our data analysis in New England shows that the probability of dry period durations does not follow a power law.

There are two major assumptions in their analysis which need to be verified by data analysis. One is that the duration of the successive wet and dry events are independent. The second assumption, which is implicit in the analysis, is that the distribution of rainfall intensity is independent of the duration of rainy periods. Contrary to their assumption, Eagleson, (1970, p 186) has discussed the dependence of depth on duration. Acreman (1990) also reports evidence of dependence of intensity on duration for an hourly rainfall data series in England. Our analysis of rainfall data from New England, U. S. also shows dependence of rainfall depth on duration. Therefore, in order to

reproduce the statistical characteristics of the time series and the intensity-duration curve of the rainfall, one should make the intensity depend on the duration of the rainfall event.

It is of interest to relate the parameters of scaling of rainfall to physical characteristics of rainfall. Harris et al. (1996) reported evidence that the parameters of multifractal cascade models of rainfall are related to orography and specifically that they vary systematically as a function of altitude along a transect.

Now we present a few investigations with a focus on practical application of scaling theories. Svensson et al. (1996) analyzed whether presence of scaling, scaling limits and values of scaling exponents are related to the physical parameters of the storm environment. They compared the results of scaling analysis on rainfall data from two distinct climatic regions: East Asian monsoon (China) and a temperate climate (Sweden). Their analysis showed multifractal scaling to hold true for both cases in the range from one day to one month. The temporal data (range from 1-32 days) exhibited scaling for moments of orders up to 2.5 in the monsoon area and up to 4.0 in the temperate area. The monsoon climate time series was dominated by exceptionally high rainfall from a large typhoon. Since the high-order empirical moments are sensitive to large observations, the scaling breaks down for moment order above 2.5. This is precisely what our analysis shows for the data in Hartford, New England where a large storm in 1955 dominates the higher moments for the entire series.

Olsson (1996) described a method to use multifractal temporal rainfall properties in time

to extract statistical information about the rainfall processes at a scale smaller than the observation scale of the data. The method consisted of finding the valid ranges where scale invariance is assumed to hold, verifying scaling and estimating the unknown smaller-scale empirical pdf. There were two conditions required to estimate the smaller scale pdf: (1) the power spectrum should exhibit scale invariance near the resolution of the data and (2) the probability distributions Pr at different scales should follow the result in (2.1).

The method was tested on a 2 year time series of 1-min resolution data. To increase the accuracy, the raw 1-min data was aggregated into 8-min values. In order to enable a comparison of results for downscaled resolution, the 8-min values were further aggregated to 64-min resolution. The probability distribution functions for scales down to 8 minute were estimated and compared to actual probability distribution functions. The results showed that at low intensities the probabilities are underestimated by the estimated distribution and at high intensities the probabilities are overestimated. Overall scales from 8-min to 32-min showed satisfactory to good agreement. The deviations from the true pdf were attributed to the effect of prefactors which are dominant at the smaller scales and were ignored in the analysis. Olsson (1996) also reported some problems with the rain measurement system which makes these results somewhat uncertain. However, this approach illustrates a practical use of the multifractal theory as it has the potential to reduce the problem of inadequate rainfall data for hydrological calculations.

In another study, Olsson (1998) disaggregated daily rainfall time series into higher resolution by using a cascade-based scaling model. The model divided each rainy time period into halves of equal length and distributed the rainfall volume between the halves. Data analysis was used to verify the approach and the results showed that for a daily rainfall series, the model gave good results for disaggregation level of 45 minutes.

2.1.2 Spatial Rainfall Scaling

Analysis and modeling of spatial structure of the rainfall has been the topic of numerous investigations. The proposed scaling models for spatial rainfall include the work of Schertzer and Lovejoy (1987), Gupta and Waymire (1990), Over and Gupta (1993, 1994) and Olsson and Niemczynowicz (1996).

Gupta and Waymire (1990) identified that both spatial rainfall and river flows exhibited multiscaling properties. They proposed using continuous multiplicative process to provide a theoretical framework for multiscaling processes. Data from the Global Atmosphere Research Program, Atlantic Experiment was used for the analysis. The rainfall data were collected on an area of about 400 km in diameter with instantaneous rainfall data being available at 15 minute intervals, binned into 4×4 km² pixels. The scale parameter λ was varied by forming squares of sizes 4×4 , 8×8 and 16×16 km². The exponents of the conditional rainfall moments (conditioned on positive rainfall) showed a departure from the linear growth thus implying multifractal behavior of spatial rainfall.

Over and Gupta (1994) applied the theory of random cascades to radar derived rainfall

data and showed how the scaling characteristics depend on the average rain rate (large-scale forcing). The data sets used were GATE phase I and GATE phase II data from 1974. Phase I consisted of 19 days of data (6/28-7/16) and phase II lasted from 7/28 to 8/15. The data consisted of radar scans taken every 15 minutes in which the rainrates are averaged over 4×4 km pixels. Over and Gupta (1994) used a square region with 72 pixels (288 km) on each side and the spatial average rain rates for each scan were obtained by averaging the rainrate in the 72×72 pixels region. They presented evidence that the scaling properties of the mesoscale rainfall can be captured to a first order approximation by a single parameter of a cascade generator for scales smaller than 100 km. Over and Gupta (1994) described the dependence of this parameter on the large-scale forcing, as measured by the large-scale spatial average rainrate by a one-to-one function. The results were specific for the case when spatial pattern of rainfall is a simple function of the spatial average rain rate. A general approach was not described for the case when spatial pattern of rainfall is not a simple function of the spatial average rain rate.

Svensson et al. (1996) analyzed the spatial rainfall data for two climates (monsoon and temperate) allowing for stationary front, warm front, cold front and convective rainfall generating mechanisms. The spatial data for all rainfall mechanisms in the two climates exhibited scaling for 15-180 km ($225\text{-}332400 \text{ km}^2$) for the monsoon climate and 7.5-90 km ($55\text{-}8100 \text{ km}^2$) for the temperate climate. The results were good for moments of order up to 4.0. The convective group showed deviation from linearity for moment order higher than 2.5. Svensson et al. (1996) explained that this deviation from linearity may be due to the combination of highly localized nature of convective rainfall and the comparatively

sparse density of the rain gage network due to which the observation of an intense event at one gage is supported by small rainfall amounts at surrounding gages. The $\tau(q)$ functions of convective rainfall were convex, while the corresponding $\tau(q)$ functions of frontal rainfall were linear. Their results were in general agreement with the results of Over and Gupta (1994) where the slope of the function $\tau(q)$ depended on the average rain rate. Convective rainfall is associated with a large rain rate and results in a nonlinear or steep $\tau(q)$ curve.

In another related study, Olsson and Niemczynowicz (1996) performed the multifractal analysis of daily spatial rainfall observed by a dense gage network in Southern Sweden. Olsson et al. studied the variation of the average statistical moments with spatial scale which ranged from 8.2 km to 90 km (equivalent to an area approximately 70 to 8000 km² in size). The data were analyzed by classifying the rainfall according to: (1) the storm generating mechanism (warm fronts, cold fronts and convection) and (2) by pooling all the data together. The results showed that multifractal behavior exists in both cases (the $k(q)$ functions were convex) however the degree of convexity displayed was different for the two cases. The convective group showed the most pronounced convexity which is in agreement with the work of Svensson et al. (1996) discussed above. According to Olsson and Niemczynowicz (1996), "The fact that different rainfall generating mechanisms exhibit different multifractal properties indicates that the total rainfall process may be viewed as a mixture of multifractal processes". This also indicates the need for seasonal scaling analysis of rainfall processes. Convective precipitation is usually predominant in summer and is induced by simple surface heating or in combination with thermally-forced flows, such as sea breezes or mountain/valley winds.

Recently investigation of the statistical spatial structure of several storm types as well as the corresponding thermodynamical parameters of the storm environments has also been carried out. These studies are in contrast to the previous studies which look directly at the intensities of rainfall. These studies, which investigate the statistics of the rainfall structure and their relation to the physical properties, hypothesize that if spatial rainfall is decomposed in multiscale means, multiscale “fluctuations” are more likely to obey some simple universality condition like self-similarity than are rainfall intensities themselves. Studies by Foufoula-Georgiou et al. (1996) have shed light on the relationship of scaling parameters to physical observables such as convective available potential energy (CAPE). Foufoula-Georgiou et al. (1996) have also discussed the possibility of a downscaling scheme with parameters based on evolution of the convective instability of the storm environment measured by CAPE.

2.1.3 Space-Time Scaling of Rainfall

In this section we review and discuss studies on space-time scaling of rainfall. The fundamental issues with scaling of space-time rainfall include: the type of anisotropy if any type of scale invariance (self-similar, self-affine or generalized scale invariance) that can be assumed to exist and the causality and homogeneity and stationarity of data. We review the literature and then discuss how these results can be used for meeting our objectives of understanding the relation between extreme rainfall scaling and peak flow scaling.

We start with a review of the relevant terminology and background theory. To study the space-time scaling, one needs to make the time variable dimensionally equivalent to space variables. A commonly used method, Taylor's hypothesis of "frozen turbulence" (Taylor, 1938), states that temporal averages t and spatial averages l are related by a constant velocity v in the form $l=vt$. If the statistical properties of rainfall are the same in space and time after transformation by a velocity parameter, then rainfall scaling is isotropic in space and time. Therefore, Taylor's hypothesis leads to isotropic scaling of rainfall. In this case, the velocity v which is used to rescale the time axis is independent of scale. In the case of anisotropic scaling of space-time rainfall, a scale dependent velocity parameter $v_\lambda \sim \lambda^H$, where λ is the scale resolution, is used to rescale the time variables. Atmospheric turbulence exhibits this behavior with an exponent $H \approx 1/3$ (Kolmogorov, 1941).

With regards to the scaling models of rainfall, self-similarity of space-time rainfall corresponds to isotropic scaling of space-time rainfall. Self-affine processes, on the other hand, are a case of the anisotropic scaling of space-time rainfall. Schertzer and Lovejoy (1987) introduced the notion of generalized scale invariance to account for anisotropy in scaling models. The space-time transformation inferred from the turbulent value of $H \approx 1/3$ was expressed in the formalism of generalized scale invariance by Schertzer and Lovejoy (1987). Tessier et al. (1993) used generalized scale invariance to interpret anisotropy of space-time rainfall.

Marsan and Schertzer (1996) developed a causal space-time multifractal process model by introducing causality for the continuous cascade model. They also tested generalized

scale invariance by performing rainfall data analysis of the U.S. composite rainfall data sets derived from National Weather Service radars. The analysis was performed on a portion of the data set, corresponding to a 100×100 square domain in space and for 64 consecutive scans in time. The resolution was 8 km in space and 15 min in time. Scaling in both time and space was observed. They obtain $H \approx -0.1$ which is different from the expected value of $H \approx 1/3$ for fully developed turbulence. This result is actually close to isotropic space-time scaling for which $H \approx 0$. In a study of daily rainfall scaling, Tessier et al. (1996) found that for the range of 1-16 days, $H = -0.1 \pm 0.1$, and for the range of 30-4096 days, they obtained $H = -0.35 \pm 0.2$. Note that for the case of 1-16 days, $H \approx 0$.

Over and Gupta (1993) extended the cascade rainfall theory from space to space-time; however, the model is not multifractal in time. They proposed three a priori requirements of a time-evolving cascade theory: (1) consistency: at any fixed time the space-time cascade reduces to a spatial cascade; (2) causality (3) contingency: the evolution must respond in an appropriate manner to a time varying force. They used a discrete cascade model, preserving the spatial structure of the cascades. They noted that Taylor's hypothesis breaks at times of 30 min to 2 hours (Crane, 1990). The time dimension of the process has an evolutionary behavior that respects causality, while the spatial dimensions have an isotropic stochastic nature.

The developed theory was tested on data from McGill weather radar which consists of instantaneous radar snapshots taken at 5-minute intervals and converted to rain rate. The results showed that certain specific predictions of the theory, such as scaling of instantaneous and temporally averaged two-point Lagrangian temporal cross moments,

were well-satisfied for a given set of data, while other predictions showed evidence of deviation. The model presented by Over and Gupta (1996) suffers from the drawback that even though it is scaling in space but it is not scaling in time. Also, the model did not address the issue of conservation of rainfall mass.

Deidda (2000) presented a theory of scale covariant model and accompanying data analysis for rainfall downscaling in a space-time multifractal framework. Deidda has shown that space-time rainfall can be considered, with a good approximation, to be a self-similar multifractal process.

Deidda used the GATE radar rainfall data sets described earlier in this chapter. Deidda extracted sequences of consecutive rainfall frames from the data sets and performed multifractal analysis. The scaling was observed to hold from 4 to 256 km for space and from 15 min to 16 hours for time. Deidda then used different tracking techniques to estimate the velocity needed to rescale the time dimension. The velocity estimate ranged from 12 to 40 km/hour; values of 16 and 32 km/hour were used in the analysis. In the analysis of autocorrelation along the x - and y -directions (figure 4, Deidda), break in Taylor's hypothesis was not observed. As the results showed a preferential direction of motion along the x axis, Deidda assumed that the rainfall field is isotropic in space. Deidda extended this idea to the rescaled time axis (using a velocity of 16 km/hour) and argued that since the rescaled time axis does not add more anisotropy, the precipitation field can be assumed as isotropic in space-time.

Deidda also investigated if self-affinity assumption was valid for space-time rainfall. The resulting H values showed large variability with H_x often different from H_y . Average of the estimate of H was about -0.12 . These results indicate that, strictly speaking, the rainfall in space and time should be considered as a self-affine process. However, Deidda ignored the small average value of H and assumed a self-similar model ($H \approx 0$) because of better theoretical accuracy of the self-similar model.

2.1.4 Discussion

There are a number of open questions regarding the scaling of rainfall. The review showed that scaling models of rainfall in time need to take into account the external structure of rainfall. Schmitt et al. (1998) have presented a model which addresses this issue but needs improvement as some of the assumptions, e.g. independence of depth and duration of rainy events, are not realistic. The space-time scaling models of rainfall have received considerably less attention and there is a debate whether the space-time scaling models can be considered as isotropic or not. Deidda (2000) has performed a comprehensive analysis to show that indeed isotropic scaling is a valid assumption. This has important implications for extending the results of scaling from space-time models of rainfall to IDF scaling and subsequently to peak flow scaling. In the coming chapters, assuming that rainfall scaling is space-time isotropic, we will discuss and develop relationships between scaling exponents of rainfall and peak flows. This should allow us to understand the scaling characteristics of hydrologic phenomena in a consistent framework.

2.2 Scaling of Intensity-Duration-Frequency Curves

Intensity-duration-frequency (IDF) curves show the relation between duration of rainfall and the maximum rainfall intensity over that duration for the given return periods. IDF curves are cumulative distributions of rainfall intensity, conditioned on rainfall duration. They are derived from rainfall time series by extracting and ranking annual maxima of average rainfall intensities for desired durations (e.g., by moving average techniques). The ranked averages are used to calculate the intensity corresponding to required return period. IDF curves are important design tools and standard IDF curves are available for major cities and regions, usually derived from point values of rainfall measured by a dense network of rain gages. For most cases however, IDF over a finite area (e.g., a catchment) is required. To derive catchment IDF curves from point IDF curves, areal reduction factors (ARFs) are used. (ARFs) reflect the reduction in rainfall intensity with area.

It has been shown that IDFs obey power laws within a certain range of scales and their rescaled distribution behaves in a self-similar fashion (Burlando and Rosso, 1996). It is known that over a wide range of durations, I_D , the distribution of intensity corresponding to a given duration D , satisfies the simple-scaling relation (Menabde et al., 1999):

$$I_D = r^H I_{rD} \quad (2.2)$$

where H usually ranges between 0.6 to 0.8.

Let I_p be the rainfall intensity exceeded by I_p with a probability p . It follows that the IDF curves satisfy a power law of the form,

$$I_p(D) = g(p)D^{-H} \quad (2.3)$$

where $g(p)$ is some function of p .

For small p and for some α (Benjoudi et al., 1999)

$$g(p) \propto p^{-\alpha} \quad (2.4)$$

In a pioneering study, Burlando and Rosso (1996) studied the scaling and multiscaling models of depth-duration-frequency (DDF) curves for storm precipitation for a number of locations. Their comparison showed that in most cases the self-similar model works well and that in the few cases when a multifractal model fits better to the data, the nonlinearity of the slope growth curve is not large.

Burlando and Rosso (1996) analyzed the scaling properties of the maximum rainfall depth for durations of 1, 3, 6, 12 and 24 hours, for data collected at 2 stations in Italy over a period of 50 years. Moment orders from 1 to 5 were used. Their analysis of the scaling of the depth of rainfall showed simple scaling for Lanzada station and departure from simple scaling for Genoa University station. In addition to those 2 stations, Burlando et al. also studied 14 stations in the Arno river basin in Italy. It is interesting to note that

only 2 of those stations showed multiscaling behavior.

Burlando and Rosso do not report the scale invariance range. From their plots, we have estimated that for Lanzada station, the scaling holds from 1 hour to 24 hours and for Genoa University station, the scaling regime is from 5 minutes to 1 hour. Other studies, as discussed by Burlando and Rosso, indicate a range of scaling from 45 minutes to 6 hours.

In another study of scaling of extreme rainfall, Menabde et al. (1999) present a simple scaling model for annual maximum rainfall rate. They follow an approach of generalized IDF in the form of

$$i = \frac{a(T)}{b(d)} \quad (2.5)$$

where i is the rainfall intensity, T is the return period and d is the duration of the event.

The denominator $b(d)$ is expressed as,

$$b(d) = (d + \theta)^\eta \quad (2.6)$$

where θ and η are phenomenological parameters.

The scaling property is expressed in terms of the moments of I_d , the annual maximum mean rain intensity over the duration d and by the CDF, $F_d(i)$ which characterizes I_d .

Menabde et al. use two data sets to verify their model. Set I is from Melbourne, Australia (where it rains throughout the year) and is 24 years sequence of 6 minute rainfall intensities. Set II is from Warmbaths, South Africa (warm, semi-arid climate) and is a 48 year sequence of rainfall at 15 minute resolution. Both sets show simple scaling in the range of 30 minutes to 24 hours. The analysis is carried out by the method of moments and method of direct fitting of probability distribution. The slope of $k(q)$ against moment order, η is given as 0.65 for set I and 0.76 for set II. The results obtained from CDF scaling are obtained by assuming EV I distribution and are consistent, though slightly different, with the moment scaling method. By assuming EV I distribution, Menabde et al. derive a scaling relation between intensity and duration with three parameters one of which is η . The IDF slopes for the dataset I was 0.71, 0.66 and 0.68 for return periods of 2,5 and 10 years respectively. For dataset II, the IDF slopes were 0.75, 0.75 and 0.74 for return periods of 2, 5 and 10 years respectively.

The approach used by Menabde et al. (1999) requires a selection of probability distribution for the CDF. Therefore the scaling relationships depend on the fit of the assumed distribution. The study also does not consider the effect of seasonality on scaling of IDFs. As described next, Willems (1998) demonstrated the significance of seasonality for scaling analysis by showing that scaling behavior can be different for different seasons. Willem's analysis showed that at Uccle, Belgium, the summer IDFs possessed multiscaling and the winter IDF exhibited simple scaling.

Willems (1998) has investigated the compound IDF relationships of extreme precipitation for two seasons and two storm types in Belgium. Willems contends that the

properties of extreme precipitation may be very different for different storm types and different seasons. IDF relationships permit a decomposition into different components referring to storm types or seasons, depending on the type of decomposition. The storm types (or the distribution components) are divided into airmass thunderstorms of short duration (usually occurring in summer) and cyclonic and frontal storms of longer duration in winter. The seasons are defined as: winter (October-March) and summer (April-September).

The data set used by Willems was a 27 year long series of 10 minute rainfall at Uccle, Belgium. This is the same data which was used by Schmitt et al. (1998) for multifractal analysis of rainfall. Willems used generalized quantile plots, maximum likelihood method and two-component extreme value distribution to derive equations for rainfall probability distribution. Willems found out that winter population can be described by one distribution component and the winter IDFs follows simple scaling. The summer population is described by both components and the summer IDFs exhibits multiscaling. Willems showed that the parameters of the two-component distribution also exhibited simple scaling properties. For winter, the scaling exponent of the distribution and the scaling exponent of the moment showed a match with both being 0.58. For summer the scaling exponent of the moment did not match very well with the exponent of the distribution. Average slope of the mean annual IDF was 0.71 from empirical data and 0.58 from theory.

Hubert et al. (1993) have presented evidence that universal multifractal models for temporal rainfall give rise to the theoretical maximum point rainfall accumulations

whose magnitude versus duration relationship resembles the empirically found results.

Benjoudi et al. (1999) derived the parameters of IDF scaling from the codimension function of the rainfall process under the assumption that rainfall time series is multifractal. Let I_D be the maximum of the average intensity $I'_D(t)$ in duration of $[t, t+D]$. Benjoudi et al. (1999) define a form of return period (let us denote it by T_2) in which the return period is related to the marginal exceedance probability $P[I'_D(t) > i]$ as

$$T_2(D, i) = \frac{1}{P[I'_D > i]} \quad (2.7)$$

According to Schertzer and Lovejoy (1987), for multifractal processes, there's a critical moment order (denote it by q_D) beyond which the statistical moments diverge.

Benjoudi et al. (1999) start from the fundamental equation of multifractal fields, equation (2.1), with an explicit prefactor. Then they derive an expression for IDFs in terms of q_D (which depends on fractal dimension of the rainfall occurrence) and on a factor D_s (Benjoudi et al. call it D but we call it D_s to avoid confusion with the duration D) which is the effective dimension of the space-time over which the multifractal is averaged or integrated. The parameter q_D is estimated in terms of probabilities of exceedance and the prefactor. Benjoudi et al. (1999) hypothesize that D_s is the fractal dimension of rainfall occurrence and estimate it by box counting.

Veneziano and Furcolo (1999) developed a theory to link the parameters of simple

scaling of IDF to the multiscaling parameters of the rainfall process by making the same basic assumptions as Benjoudi et al including the definition of return period T_2 .

However their approach and results, are very different from those of Benjoudi et al.

Veneziano et al. (1999) derive a large-deviation property of multifractal measures and use the result to determine an analytical form of the scaling of the IDF curves. They show that i_2 , the rainfall intensity corresponding to T_2 must scale with T_2 and D as:

$$i_2 \propto T_2^{1/q_1} D^{-\gamma_1} \quad (2.8)$$

where γ_1 and q_1 are obtained from the moment scaling function $k(q)$ of the rainfall process. Let $c(\gamma)$ be the codimension function of temporal rainfall, which can be obtained parametrically from the moment scaling function $k(q)$ as $\gamma(q) = dk(q)/dq$ and $c(q) = q\gamma(q) - k(q)$. Let q_1 be the order of the moment for which $c(q_1) = 1$ and the associated slope of $k(q)$. Veneziano and Furcolo (1999) show that the IDF curves satisfy self-similarity in (2.2) and (2.4) with $H = \gamma_1$ and $\alpha = 1/q_1$. These theoretical results are asymptotic and hold strictly for $D \rightarrow 0$. Figure 2.2 illustrates the derivation of the parameters from the moment scaling analysis.

Numerical validation of this results was done by simulating a rainfall sequence using beta-lognormal model, which is a locally multifractal model, with an outer limit on scaling of 2 weeks. The simulation results satisfied the theoretical scaling over a wide range of durations, not just the infinitesimal durations under which (2.8) was derived.

This is an important result to link the scaling characteristics of rainfall to the scaling exponents of peak flows. We will return to this theory in chapter 4 where we perform data analysis to verify these results.

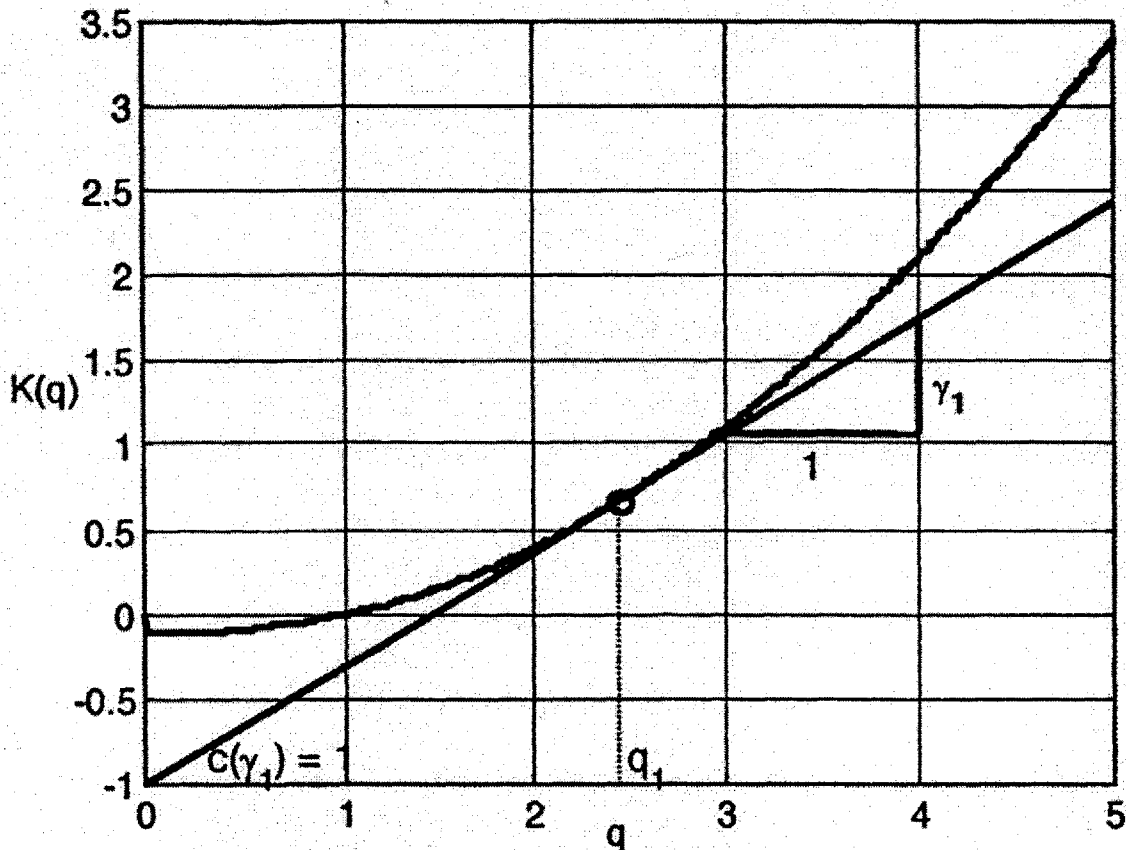


Figure 2.2. Illustration of the IDF scaling parameters γ_1 and q_1 .

The review of IDF curves so far has been about the point IDF curves. However, for most practical purposes, catchment IDF curves are needed. As the spatial extent of a storm increases, the average depth of rainfall over the catchment decreases. Areal reduction factors (ARFs) are used to construct the catchment IDF curves from the point IDF curves. ARFs are usually empirically derived functions of catchment area, storm duration and

soemtimes, the return period. ARF have a maximum value of unity for catchment area approaching zero. With increasing catchment area, ARF values decrease from unity, and catchment IDF curves become lower and flatter in appearance than the corresponding point IDF curves since both the mean and standard deviation of the point rainfall are proportionately reduced due to multiplication by the ARFs (Sivapalan and Blöschl, 1998). This reduction is much sharper for short duration events because short duration events are usually limited in spatial extent. Some of the empirical expressions for ARFs can be found in Singh (1996).

Sivapalan and Blöschl (1998) present an alternative methodology to derive catchment IDF curves which is based on the spatial correlation structure of rainfall. Their method derives the parent distribution of catchment average rainfall intensity from that of point rainfall intensity. The parameters of the two parent distributions are related through a variance reduction factor which is a function of the spatial correlation structure of the rainfall and catchment area. Sivapalan and Blöschl (1998) assume the parent distribution of point rainfall to be exponential and transform it to extreme value distribution of the Gumbel type. The parameters of the extreme rainfall distribution are then matched (for the particular case of zero catchment area) with those of empirical point IDF curves which have also been fitted to the Gumbel distribution. This match allows the derivation of catchment IDF curves for catchments of any given size and for rainfall of any spatial correlation structure. The objective of the methodology is to distinguish between the scaling behavior of the parent and extreme value distributions of the rainfall process. The main control on the catchment IDF curves was concluded to be the rainfall spatial correlation length, not the rainfall duration as commonly used in empirical

determination of ARFs. The results were applied to two storms in Austria, one convective storm and one synoptic scale storm and the results were compared with the empirical ARFs.

The assumption made for the analysis was that the correlation structure of the rainfall does not change with return period. The approach has no means to take into account the partial coverage of rainfall over a catchment. Therefore, it is only appropriate for rainfall systems which are large relative to catchment area.

2.3 Scaling of Peak Flows

Stream flow is a reflection of the volume of water supplied to a basin in various forms of precipitation such as rain and snow, and the hydrological retention and transport processes in the basin. The stream flow rate at a particular point in time, such as annual peak flow, integrates all the hydrologic processes and storages upstream of that point. The peak flow in a basin of given size is affected by the characteristics of the storm and other flood generating mechanisms, basin morphology, basin geology, land use and miscellaneous factors such as antecedent conditions.

Basin area is one of the most important controls on the hydrological processes and subsequently the stream flow exhibits strong correlation with the basin area. Power laws relating peak flow to basin scale have been shown to be valid for a number of regions.

Let $Q(A;T)$ be the T -year return period flood for a basin of area A . Empirical data indicate a dependence of Q on A and T of the type

$$Q(A;T) = kA^{\theta(T)} \quad (2.9)$$

where k is a constant and $\theta(T)$ is an exponent which depends on the climatic conditions, the basin characteristics and the return period. Studies have shown that θ usually ranges from 0.6 to 0.9 (Gupta and Dawdy 1995). It is important to use the representative basin area when using (2.9). Villani (2000) investigated the effect of contributing area on the exponent of $Q \sim A^\theta$. Contributing area is the area contributing directly to surface runoff. Any area not contributing directly to surface runoff should be subtracted from the total drainage area. Villani studied a basin in Campania, Italy by comparing the relationship between the mean annual flood and the total area to that of the mean annual flood and the actual contributing area (which was a fraction of the total basin area). For the case of contributing area case, Villani found a lower scaling exponent θ and higher linear correlation coefficient for the fitted regression for (2.9).

The theory of statistical simple scaling and multiscaling predict that flood peaks are log-log linear with respect to drainage areas. If the growth of the scaling exponents with the order of moment is linear then the flood peaks obey simple scaling; otherwise the flood peaks follow multiscaling. In contrast to the simple scaling case where there is a linear growth in slopes, in the multiscaling case the scaling behavior is determined by a spectrum of exponents (see figure 2.1).

Storms that produce floods in large drainage basins are usually dispersed and nonuniformly distributed. The highest peak flows in large basins are most often produced by storms that span large areas, while high peak flows in small drainage

basins are commonly the result of intense storms that extend over limited areas. The amount of runoff resulting from the rainfall depends on the spatial distribution of the rainfall. If the rainfall is concentrated over a particular part of the basin, then the runoff is higher than if the rainfall is uniformly distributed throughout the basin. This is because infiltration capacity is exceeded more rapidly for intense and concentrated storms than for uniformly distributed storms. Therefore, the peak flow increases as the ratio of maximum rainfall at any point to the mean rainfall in the basin increases.

Pitlick (1994) studied the flood frequency curves for five regions in the Western USA characterized by diverse climate but similar physiography. Pitlick (1994) suggested that the variation in flood frequency distribution reflects largely the variability in precipitation amount and intensity rather than differences in physiography. Floods tend to be more variable in regions where more of the annual precipitation is concentrated into single storm events, as is typical of semi-arid regions. Pitlick argued that in regions characterized by snowmelt runoff, or in humid regions where runoff and floods are produced by frontal storms, precipitation is spread out over periods of several days or even weeks.

Other studies have also shown that the governing climatic conditions have a large influence on the relationship between annual flood and drainage basin area. As floods generated in the arid or semi-arid regions are a result of rainfall covering a limited portion of the drainage basin, the flood is attenuated by infiltration and other losses. On the other hand, in humid regions, floods are almost proportional to the rainfall. In areas where snowmelt or rainfall over snow contributes to the floods, large discharges are to

be expected.

Gupta and Dawdy (1995) studied the scaling between peak flows and basin area for three States in the U.S. These states have been subdivided in smaller regions by the United States Geological Survey (USGS) and the flood generating mechanisms in each region has been investigated and documented by the USGS. Their analysis showed that there is evidence of both simple and multiscaling in regional floods. The value of the exponent varied from region to region as a reflection of the differences in other characteristics of these regions. The analysis of Gupta and Dawdy (1995) showed that the runoff is almost directly related to the drainage area (with θ about 0.9) for regions in New Mexico where floods are produced by snowmelt runoff. Results from Utah state regions with snowmelt generated floods also showed high scaling exponent of peak flow. They hypothesized that snowmelt generated floods exhibit simple scaling and rainfall generated floods exhibit multiscaling. They argue that multiscaling structure in floods inherits from rainfall.

Using an artificially constructed basin and HEC-1 lumped rainfall-runoff model with input from a random rainfall set, kinematic wave routing was used to route the flows. Then, fixing recurring frequency, ratios of flood discharge quantiles were related to ratios of corresponding drainage areas. In the second set of analyses, different quantiles corresponding to different return periods were computed, and the exponents of drainage area ratios for different sub-basins were computed in a manner similar to the first set of analyses. Results showed that exponents increase with the return period which supported their theoretical result. This experiment by Gupta and Dawdy (1995)

suggests that behavior of flood exponents in small basins is determined by basin response rather than precipitation input.

Dubreuil (1986) reviewed the relationships between geophysical factors and hydrological characteristics in the tropics. Dubreuil (1986) showed that the exponent θ is about 0.5 in the arid and semi-arid areas and 0.8 in areas with higher rainfall. Dubreuil (1986) noted that the relationship between Q and A varies markedly with the drainage area and identified four different scales within which the relationship of $Q \sim A^\theta$ was expected to remain stable. The scales were: hillslope, characterized by homogeneity; small watershed, likely to be affected by a small single storm; medium watershed, where runoff mechanism and transport is important and large watersheds where runoff may be composed of separate events with possibly different origins.

Pilgrim et al. (1982) investigated the hydrological relationships between small and large catchments using data for eastern Australia. Annual rainfall-runoff relations were developed for 22 catchments in four regions of New South Wales. These relations were derived by assuming a constant nonlinear relation for every point on a catchment making allowance for the non-uniform distribution of rainfall over the catchment.

Pilgrim et al. (1982) computed the loss, defined as the difference between the line of equal runoff and rainfall (with no loss) and the rainfall-runoff curve at high rainfall values, where it became almost parallel to the line of equality. The result of interest for our purpose is that the median loss rate did not vary significantly with the area.

Runoff rates are also sensitive to soils and topography (Kirkby, 1978). Peak rates of runoff from hillslope and small watersheds may vary over several orders of magnitude depending on the mechanism of runoff production. Kirkby (1976) suggested that with increasing drainage area, the travel time of runoff on hillslope becomes negligible in comparison with the travel time through the channel network.

A related area of research to flood scaling is the regional flood frequency analysis (RFFA). Regionalization is carried out to estimate the magnitude of flood peaks for sites where at-site data are either unavailable or too short to allow for a reliable frequency estimate. For sites with available data, the joint use of data measured at a site and regional data from a number of stations in a region provides additional information. Traditionally regional flood frequency modeling has been carried out by methods such as index flood and quantile regression. Both of these methods lack sound physical and theoretical backgrounds. The key assumption in the index flood method is that the distribution of floods at different sites in a region is the same except for a scale or index flood parameter, which reflects rainfall and runoff characteristics of the basin. The index flood is usually taken as the mean flood. Eagleson (1970), among others, has emphasized the importance of physically based flood frequency models. With the current progress in identification and validation of scaling theories for spatial hydrologic processes such as rainfall, runoff and flood peaks, there is an increasing interest in applying scaling theories to regional flood frequency. Scaling theories have the potential of application to ungaged catchments which remains as one of the most important hydrologic problems to be solved. The simple scaling concept corresponds to the index

flood method of regional flood analysis. Thus, the index flood method can be justified if the flood series exhibits simple scaling.

Scaling of flows, that is the log-log linearity of flows with area, is only meaningful for a homogenous area. Identification of homogeneous area is itself a major area of research. USGS uses quantile regression approach for flood frequency studies for different states. Each state is divided in regions based on features such as topography and land use; then adjustments are made based on goodness of fit of the quantile regression equations in these areas. A recent study of homogeneous regions in Australia which compared a number of current techniques for identifying homogeneous regions has indicated that geographical proximity alone may not be a reasonable indicator of hydrologic similarity (Bates et al. 1998). Preliminary data analysis of flood peaks from more than a 1000 gaging stations in 18 regions of the US has indicated that both simple and multiscaling of peak flows exists and smaller and larger basins tend to show different scaling behavior. This shows that the precise nature of scaling in spatial runoff over successively larger scales is still unclear. There is a need for a physical underpinning for the scaling models of flood peaks so that there is a broad theoretical framework for their application and extension to basins with varying climatological and physiographic characteristics.

The scaling literature on flood peaks can be divided in two approaches: scaling theories based on moment analysis (Smith 1992; Gupta et al. 1994a, 1995; Gupta et al., 1994b) and physically based flood frequency models (Sivapalan 1987, 1997). In the first approach, used by Gupta and Waymire (1990) and Smith (1992) among others, the scaling behavior of the floods is assessed by the variation of the conventional statistical moments with the

basin area. On the other hand, Sivapalan et al. (1987, 1997) have used similarity analysis and physically based flood frequency models to study the process controls and the effect of rainfall characteristics and basin properties on the flood frequency.

Gupta and Waymire (1990) studied the multiscaling behavior of runoff by using empirical moment analysis of a data set of river flow averages from Pennsylvania. They showed that the spatial river flows exhibit a departure from simple scaling as the growth of slopes with respect to order of moments was nonlinear and concave. The spatial variability in these processes increases with a decrease in spatial scale. Gupta and Waymire suggested that this multiscaling behavior is a consequence of the cascading down of some large-scale flux to successively smaller scales.

Gupta and Dawdy (1994a and 1994b) discuss the relation between flood quantiles and the return period for the log-normal multiscaling model. They argue that a physical implication of this observation is that the scaling exponent appearing in the multiscaling representation of peak flows remain the same within a given homogenous region but can vary among different regions. Gupta and Dawdy (1994a) used a log-normal multiscaling model and the notion of a critical basin area with the result that spatial variability in $Q(A)$ increases with the drainage area until a critical drainage area and after that the variability in $Q(A)$ decreases with the drainage area. According to their multiscaling theory, there are two different equations to describe the quantiles $q_p(A_i)$ (for the i -th station with a drainage area A_i and with exceedance probability p for large basins and for small basins.

Gupta et al. (1994a, 1995) addressed the issue of providing a physical interpretation of multiscaling theory by linking their multiscaling theory to the dimensionless parameters derived by Sivapalan (1990). Sivapalan et al. (1990) developed a dimensionless flood frequency model by extending a partial area runoff generation model to a Geomorphologic Unit Hydrograph (GUH) based model to form a generalized GUH. They identified five dimensionless parameters which were shown to be related to return period. They also found that slope of the relation between return period and peak is flatter for large basins than that of smaller basins. Empirical verification of the theory was not presented by Sivapalan et al.

In a study to represent basin scale in flood peak distributions, Smith (1992) performed a moment-based analysis using a lognormal cascade model. The model was developed from the multiplicative cascade modeling framework developed by Gupta and Waymire (1990) for spatial hydrologic processes. Smith used the lognormal model to study the scale properties of annual flood peaks from 104 stations in the central Appalachian region of Maryland and Virginia. Smith showed that coefficient of variation of floods does not increase monotonically with drainage area but shows a decline after a certain critical or threshold area. Simple scaling corresponds to a constant CV over a region, that is, the index flood method of regional flood frequency analysis.

In another attempt to explain the behavior of CV of flood peaks with drainage area of the basin, Blöschl and Sivapalan (1997) developed a model which would explain the process controls on regional flood frequency. They used data from 489 catchments in Austria to show the scatter in CV against drainage area and proceeded to develop a

derived flood frequency model. Catchment IDF curves were used to specify catchment-average rainfall intensity as a function of storm duration and return period. A correlation structure was decided for the rainfall. The runoff model consisted of multiplying rainfall intensity by a runoff coefficient to get the effective storm rainfall. The parameters were calibrated. Then by using this model, Bloschl and Sivapalan studied the interaction of storm duration and catchment response time. They argued that the interplay of duration and the catchment response time and the dependence of storm intensity on duration results in a lower CV for runoff than that of precipitation. Bloschl and Sivapalan (1997) also investigated the effect of nonlinearity in runoff generation and showed that nonlinear runoff processes are an important mechanism for increasing CV. Bloschl and Sivapalan (1997) conclude that much of the variability of CV between catchments is due to runoff processes rather than to rainfall variability. They found the CV of rain to be in the range of 0.23 to 0.43. They also concluded that catchment area is not the most important control on regional CV thus implying that the explanation of the relationship between CV of runoff and catchment scale suggested in the literature is too simplistic. Contrary to the findings of Gupta and Dawdy (1995), Bloschl and Sivapalan find that CVs do not necessarily increase with catchment scale and that both rainfall and runoff processes are important at small scale. Bloschl and Sivapalan (1997) agree with the conclusion drawn by Gupta and Dawdy (1995) that at large catchment scales, CV is mainly controlled by precipitation.

Robinson and Sivapalan (1997) studied the implications of temporal scales and hydrological regimes for flood frequency scaling. Robinson and Sivapalan (1997) investigated the interactions among storm, within-storm, between-storm and seasonal

variabilities of rainfall and catchment response time and how these interactions can help identify different hydrological regimes. They assumed a multiscaling spatial structure for rainfall and used a linear theoretical rainfall-runoff to propose five hydrological regimes ranging from very fast to very slow. Robinson and Sivapalan (1997) then studied how the interactions between the time scales in the rainfall and in the runoff response influence the flood peak response for each class of regime. Robinson and Sivapalan (1997) found that slow regimes have lower CV and faster regimes have higher CV. Robinson and Sivapalan (1997) illustrated that the interaction between rainfall duration and time to peak flow is a major factor in producing the empirically observed differences in CV values for peak flows between large and small basins. They also found that the scaling exponent in the relationship between mean annual flood and catchment size, for a linear runoff response, is higher for slow catchments and lower for fast catchments, and in both cases it remains constant with catchment area. One important result of this paper is that the combined effects of within-storm patterns, multiple storms, and seasonality have an important control on the observed scaling behavior in empirical flood frequency curves, each being dominant over a certain range of basin size.

A few studies have tried to link the scaling of rainfall to that of floods. Among these studies, Gupta et al. (1994a, 1994b, 1995, 1996) and Tessier et al. (1996) are notable. As discussed above, Gupta et al. (1995) performed a simple rainfall-runoff experiment with a lumped model to study the variation of exponents of flood quantiles with catchment size.

Tessier et al. (1996) empirically investigate the scaling properties of daily rainfall and river flows and determine the statistical relations between the rainfall and runoff.

Tessier et al. (1996) carried out multifractal analysis of daily river flow data using 30 small basin (40 to 200 km²) distributed in different regions in France. In each basin, they used daily rainfall series recorded by a single rain gage. Spectral analysis of the river flow series and daily rainfall series showed a break in scaling at about 16 days. They used the double trace moment (DTM) method to perform moment analysis on daily river flow and rainfall series.

The results of DTM showed that there is a break in scaling for rainfall at 16 days. For DTM analysis on rainfall (1-16 days) they obtained $\alpha = 0.7 \pm 0.2$, $C_1 = 0.4 \pm 0.1$ and $H = -0.1 \pm 0.1$ where $0 \leq \alpha \leq 2$ is the multifractal index, which quantifies the distance of the process from monofractality ($\alpha = 0$ is the monofractal β model and $\alpha = 2$ for the lognormal model); C_1 is the so-called codimension of the mean of the process, and H is a scaling exponent. For river flows (1-16 days) they obtained $\alpha = 1.45 \pm 0.25$, $C_1 = 0.2 \pm 0.1$, and $H = 0.4 \pm 0.3$ with no break in the double-trace moments. The α for rain is considerably lower than the α of river flows because the DTM is particularly sensitive to low values or zeros found in rainfall series. This is a drawback of this technique and this is one reason why an approach such as that of Schmitt et al. (1998), who used separate models for exterior and interior rainfall, is useful. Tessier et al. (1996) comment that for timescales of 1 to 16 days the rainfall and river flows belong to two different multifractal classes (different α and C_1) but still compatible with quantities preserved by cascade process.

Tessier et al. (1996) checked the multifractal parameters described above for possible systematic variations with regional climate types, size of the basins, and the geology of the region but found no such systematic variation. Therefore, they claimed that the measured properties are general. They also extended the multifractal model to take into account the requirement that the series are causal. Using the exponents given above, they performed causal multifractal time series simulations and show how a linear scaling transfer function can be used to relate the low-frequency rainfall series to the corresponding river flow series. Limitations of their approach include the sensitivity of the approach to low or zero values and neglecting the annual cycle.

The results of Tessier et al (1996) are in contrast with those of Gupta et al. (1994b). Gupta et al. (1994b) assumed that river flow followed a multiplicative process ($H = 0$) and fitted log-Levy multiscaling model to the flows. Gupta et al. (1994b) found that α in the range of 1.5 to 2 provided good fits but were unable to estimate α from the data and chose the lognormal model, which is the same model used by Smith (1992).

Gupta et al. (1996) used a random cascade model of spatial rainfall intensities and the Peano basin as an idealized model of a river basin to calculate the statistical scaling exponents of peak river flows. The maximum contributing set approximately determines the magnitudes of peak flows in a self-similar manner in different sub-basins of the Peano basin. For an instantaneously applied random, spatially uniform rainfall, the Hausdorff dimension of the maximum contributing set appears as the statistical simple scaling exponent of peak flows. This result is generalized to an instantaneously applied cascade rainfall, and it is shown to give rise to statistical multiscaling in peak flows. The

multiscaling exponent of peak flows is interpreted as a Hausdorff dimension of a fractal set supporting rainfall intensity on the maximum contributing set of the Peano basin. Although interesting from academic point of view, the study is limited in scope as it is not based on realistic basin networks and lacks theoretical generalization.

Gupta and Waymire (1998) extended their work on Peano basins to study the effect of rainfall duration on the scaling exponent of peak flows. They argue, through the derived equations for the Peano basin, that for durations less than the concentration time, a fraction of the area contributes to flow and the exponent of the peak flow θ is lower, for example 0.6. When the rainfall duration exceeds the time of concentration of a basin, then the entire basin contributes to the peak flow and the peak flow is almost directly proportional to the drainage area.

The paucity of theoretical and empirical studies on the connections between rainfall and flood scaling indicates that there is a need to have a consistent and unified theory for scaling of floods based on scaling of rainfall. This theory would need to take into account the spatial variability of rainfall, behavior of extreme rainfall scaling and the effect of basin characteristics on the scaling exponents of peak flows. A step in this direction would be to use theory to establish the relation of scaling of rainfall and scaling of IDFs and to use data analysis to investigate the relation of scaling of IDFs and scaling exhibited by flood peaks.

CHAPTER 3

Analysis and Modeling of Temporal Rainfall

3.1 Objective

The focus of this chapter is the probabilistic structure of temporal rainfall. In section 2.1.1, we reviewed literature related to scaling of rainfall in time. The scale invariance approach can represent the rainfall structure within a range of scales with parsimonious parameterization.

There are various aspects of scaling of rainfall. In this chapter, we investigate the scaling properties of occurrence of rainfall, scaling behavior of the dry period distribution, scaling of storms and the connection to relation of rainfall intensity with duration. We follow the approach of Schmitt et al. (1998). Finally, we propose a new model for distribution of dry periods and discuss its applications to estimate the critical dry duration.

3.2 Approach

Schmitt et al. (1998) have presented a stochastic model for rainfall which includes an alternating renewal model for storm arrivals. We carry out data analysis to test the assumptions and results presented by Schmitt et al. (1998). We investigate if scale invariance applies to occurrence of rainfall and study the distribution of durations of dry periods. Dry periods can occur both inside storms or in dry periods only.

The literature survey shows that judgement has been used to estimate the critical dry duration (Robinson and Sivapalan, 1997; Menabde and Sivapalan, in press). Motivated by previous work (Schmitt, 1998; Hawk, 1992) and the need for a model of dry period durations, we propose a new model for the distribution of durations of dry periods and verify it by data analysis.

3.3 Data

We analyze the hourly rainfall data for rainfall gaging stations distributed in New England, U. S. The data used in this study are based on the National Climatic Data Center database. Figure 3.1 shows the location of selected gaging stations. Table 3.1 provides a summary of the stations and their location. These stations are located in Connecticut, Massachusetts and Rhode Island. The length of the hourly rainfall series varies from station to station; the average length is about 29 years. These stations are checked for completeness and accuracy. Only those stations are considered for analysis which had less than 10% missing values. Only those years are used which had 99% or more complete data. The 1% or less missing data in a year was assumed to be zero. However, for most of the analysis, we selected stations and years with no missing data.

Most of our analysis uses the data from station 3456 (see table 3.1) in Hartford, Connecticut. This station has 40 years of complete data, from 1955 to 1994. Figure 3.2 shows the time series of rainfall intensity for 1956 at station 3456.

The gage is located at Bradley International Airport, about 3 miles west of the Connecticut River on a slight rise of ground in a broad portion of the Connecticut River

Valley between north-south mountain ranges whose heights do not exceed 1,200 feet. The station is in the northern temperate climate zone. The prevailing west to east movement of air brings the majority of weather systems into Connecticut from the west. The average wintertime position of the Polar Front boundary between cold, dry polar air and warm, moist tropical air is just south of New England, which helps to explain the extensive winter storm activity and day to day variability of local weather. In summer, the Polar Front has an average position along the New England-Canada border with this station in a warm and pleasant atmosphere.

The location of Hartford, relative to continent and ocean, is also significant. Rapid weather changes result when storms move northward along the mid-Atlantic coast, frequently producing strong and persistent northeast winds associated with storms known locally as coastal or northeasters. Seasonally, weather characteristics vary from the cold and dry continental-polar air of winter to the warm and humid maritime air of summer. Summer thunderstorms develop in the Berkshire Mountains to the west and northwest and move over to the Connecticut Valley.

Table 3.1: List of rain gage station locations and available data

Station#	Name	State	Total Years	Useful Years	Latitude	Longitude
806	BRIDGEPORT WSO AP	CT	48	45	41.17	73.13
1093	CANDLEWOOD LAKE	CT	28	23	41.48	73.47
3451	HARTFORD BRAINARD FLD	CT	49	30	41.73	72.65
3456	HARTFORD WSO AP	CT	42	40	41.93	72.68
3857	JEWETT CITY	CT	48	35	41.63	71.90
4488	MANSFIELD HOLLOW LAKE	CT	44	37	41.75	72.18
5018	MOODUS RESERVOIR	CT	29	24	41.50	72.43
5273	NEW HAVEN AIRPORT	CT	22	19	41.27	72.88
5445	NORFOLK 2 SW	CT	48	14	41.97	73.22
6942	ROCKVILLE	CT	48	28	41.87	72.43
8138	STORRS	CT	48	13	41.80	72.25
8330	THOMASTON DAM	CT	35	22	41.70	73.05
9388	WEST THOMPSON LAKE	CT	31	19	41.95	71.90
408	BARRE FALLS DAM	MA	38	27	42.43	72.03
510	BECKET 2 SW	MA	17	10	42.32	73.12
575	BELLINGHAM	MA	18	8	42.10	71.48
666	BIRCH HILL DAM	MA	48	43	42.63	72.12
736	BLUE HILL WSO	MA	48	44	42.22	71.12
770	BOSTON WSO AP	MA	48	45	42.37	71.03
840	BRIDGEWATER M C I	MA	40	29	41.95	70.95
998	BUFFUMVILLE LAKE	MA	38	19	42.12	71.90
1097	CAMBRIDGE	MA	10	7	42.38	71.12
3821	HYANNIS	MA	48	35	41.67	70.30
3985	KNIGHTVILLE DAM	MA	48	38	42.28	72.87
4246	LITTLEVILLE LAKE	MA	31	22	42.27	72.88
4667	MENDON	MA	31	21	42.10	71.57
5159	NANTUCKET FAA AP	MA	22	20	41.25	70.07
5246	NEW BEDFORD	MA	48	42	41.63	70.93
6322	PETERSHAM 3 N	MA	42	29	42.53	72.18
6414	PITTSFIELD	MA	23	19	42.43	73.28
6681	PROVINCETOWN	MA	42	23	42.05	70.18
6977	ROCKPORT 1 ESE	MA	36	25	42.65	70.60
8159	STERLING 2 NNW	MA	25	18	42.45	71.80
8843	WASHINGTON 2	MA	23	20	42.37	73.15
9093	WEST BRIMFIELD	MA	48	22	42.17	72.27
9923	WORCESTER WSO AP	MA	43	35	42.27	71.87
896	BLOCK ISLAND STATE AP	RI	48	42	41.17	71.58
6698	PROVIDENCE WSO AP	RI	48	45	41.73	71.43

3.4 Analysis

First, we compile the main statistics of the rainfall data series. Figure 3.3 shows selected statistics of the rainfall for the annual series at station 3456. This includes the number of rainy events, mean intensity and variance of aggregated events for different durations against duration of events. Rainy events are taken as all the periods when there is rainfall; the rainy event durations ranged from 1 hour to 42 hours for the data series at Hartford.

The analysis shows that a few years were subject to exceptionally intense storms. The data set was matched with the storm data archives of National Oceanic and Atmospheric Administration to ensure accuracy and to obtain further background information about the causes of the storms.

We perform an analysis to detect any influential rainy events for all the stations which exhibited particularly intense storms. This analysis is carried out by aggregating rainfall over a set of durations ranging from 1 hour to 15 days. For each aggregation level, we first compute the average maximum annual rainfall for the complete series. For example, for Hartford station, we get a mean maximum of 3.23 in for 24 hour aggregation. Then we use a sliding window to extract those storm events where the ratio of the aggregated rainfall to the corresponding mean maximum annual rainfall is equal to or greater than 2.5. For example, for Hartford station, the 24 hour aggregated maximum rainfall for year 1955 is 12.1 in. Therefore the ratio is computed as $12.05/3.23 = 3.73$, which is greater than 2.5 so this is classified as an influential event. For station 3456, we identify the dates of events where the ratio of the aggregated rainfall to the average rainfall over the

aggregation exceeded 2.5. The analysis shows that year 1955 can be regarded as an influential year. These intense events correspond to the Hurricane Diane in August 1955 which caused major flooding in Connecticut (Platt, 1999). Results of the above mentioned analysis for the Hartford station are given in Table 3.2.

Table 3.2: Analysis of influential storms at Hartford station

Event		Ratio of event		Event date		
Aggregation	Rain	rainfall		Year	Month	Date
Duration (Hr)	(in)	to mean rainfall				
9	6.8	2.82		1955	8	19
12	8.4	3.12		1955	8	19
18	9.5	3.15		1955	8	19
24	12.1	3.73		1955	8	19
36	14.0	4.04		1955	8	19
48	14.2	3.93		1955	8	19
72	14.4	3.67		1955	8	19
96	14.4	3.48		1955	8	19
120	14.4	3.21		1955	8	23
240	19.0	3.33		1955	8	19
360	21.3	3.23		1955	8	19

Figure 3.4 shows the coefficient of variation (CV) against durations for the Hartford station. For each duration or aggregation level, we compute the mean and the standard deviation of rainfall intensity; CV is then given by the ratio of standard deviation to the mean . Figure 3.4 shows the CV for two cases: open circles show the complete data series and + shows the series without the year 1955. Note that the CV is considerably higher for longer durations for the case with 1955 data. For the series with 1955 data, the maximum CV is about 0.58. This is the effect of the heavy and persistent storms occurring in year 1955 (see table 3.2). The data series without year 1955 data has a

maximum CV of about 0.43 and a standard deviation of 0.055. The data series with year 1955 has a standard deviation of 0.11. This analysis clearly shows that year 1955 considerably influences the analysis. As the higher moments are sensitive to such dominating events, all of the analysis in chapter 4 is carried out without the 1955 data.

Since New England region has distinct seasons, we also investigated the seasonal characteristics of the rainfall time series. The work of Olsson et al. (1996) and Svensson et al. (1996) shows that seasonality effect is important in assessing the scaling behavior. To investigate the seasonality effects, we divided the annual data into four seasons as described below:

Season 1: Spring - March, April and May

Season 2: Summer - June, July and August

Season 3: Fall - September, October and November

Season 4: Winter - December, January and February

Events are centered based on their duration and a month/season is assigned to each event. Our investigation shows that most storms occur in summer season when convective type rainfall is dominant; the short intense bursts of rainfall in summer often cause flooding in Connecticut.

In chapter 2, we discussed a stochastic model of rainfall, proposed by Schmitt et al. (1998). The model combines a two state alternating renewal process for modeling dry durations with a multifractal model for internal rainfall modeling. Schmitt et al. (1998)

use the empirical distribution of rainy and dry residence times to produce succession of rainy and dry events. A multifractal model is used to model the variability of rainfall within rainy events. In this chapter, we limit the discussion to the modeling of temporal rainfall i.e., modeling of rainy and dry durations.

The approach used by Schmitt et al. (1998) has the advantage of modeling the interior rainfall independently from the external rainfall. While the interior rainfall might be multifractal at micro-meso scales, the exterior rainfall process is probably not scaling at all.

The data used by Schmitt et al. is a 29 year long, 10 minute rainfall sequence in Uccle, Belgium. We give a detailed description of the approach used by Schmitt et al. (1998), discuss the assumptions they have made, discuss the validity of those assumptions and compare our results with the results obtained by Schmitt et al. (1998). Based on our analysis, we suggest possible improvements in the model.

Schmitt et. al (1998) analyze the scaling properties of occurrence and nonoccurrence of rainfall. They follow the finding of Hubert and Carbonnel (1989), who showed that occurrence and nonoccurrence of rainfall is scaling according to

$$N_{wet(\tau)} = N_{wet(\tau_1)} \left(\frac{\tau}{\tau_1} \right)^{-D}, \quad (3.1)$$

where $N_{wet(\tau)}$ is the average number of rainy events at timescale τ ; $N_{wet(\tau_1)}$ is the average

number of rainy events at timescale τ_1 , which is the largest scale for which the scale invariance holds; and D_s is the fractal dimension of the rainy set. Schmitt et al. verify the scaling of occurrence of rainfall for their data and obtain a D_s of 0.55 for timescales between 10 minute and 3.5 days. Olsson et al. (1993) have performed similar analysis on a rainfall time series in Sweden and found a D_s of 0.37 for timescales between 45 minute and 1 week. A discussion of the results by Olsson was provided in chapter 2. For the Hartford station, we performed a box counting analysis for comparison with Schmitt et al. (1998). The rainfall time series is divided into non-overlapping sets of boxes. The box size ranges from 1 hour to 2^n hours where $n = 1, 2, \dots, 9$. Then we count the number of boxes which have at least partial rain and denote it by $N(t)$ where t is the box size (or the duration). In the plot of $\log[N(t)]$ against $\log(t)$, the slope of the linear portion (if any) is termed as fractal dimension of the occurrence of rain. The result of the box counting analysis is shown in figure 3.5.

For the Hartford station, we observe a slight curvature in the initial portion of the box counting curve. A break in scaling occurs at a duration of approximately 4 days. In other words, beyond 4 days, almost 100% of the 'boxes' have rain and the slope of the line becomes 1. From the box counting curve of Hartford station, we can see that for the durations between 1 and 3 hours the slope of the curve is steep (about 0.64) which indicates that if it rains for 1 hour it is likely to continue for longer durations as well. For durations between 8 and 64 hours, the slope is gentler (about 0.44) which shows the intermittency of short duration rain events.

Schmitt et al. (1998) derive the probability of the system to be in dry state and show that

it follows a power law which can be expressed in terms of D_s . Through data analysis, they show that a discrete or continuous β -model is not adequate to represent the residence time probability of rainy events. A β -model is a random cascade model which generates a two-value state variable, one being zero. As an alternative to the β -model, they propose to use the empirical distribution of rainy and dry residence times to reproduce succession of rainy and dry events. For modeling the characteristics of rainy periods, they use a universal multifractal model (Schertzer and Lovejoy, 1987). Time series of the rainfall is obtained by multiplying term-by-term the series generated with the alternating renewal process and the one provided by multifractal model.

There are two major assumptions in the analysis of Schmitt et. al (1998) which need to be verified. One assumption is that the duration of the successive rainy and dry events are independent. The second assumption which is implicit in the analysis is that distribution of intensity is independent of the duration of rainy events. Our analysis of rainfall data from New England shows that the first assumption is reasonable (see figures 3.8, 3.9) but the second assumption is not (see figure 3.3).

The distribution of duration of dry events

We consider the duration of dry events for both the annual series and the four seasons we defined above. To associate rainy and dry events with one of the four seasons, the dry and rainy events are associated with a season. Based on the length of the event, we find the month where the center the event lies and the event is assigned the season according to the definition of the seasons discussed above. Figure 3.6 shows the probability plots of dry and rainy durations for the annual series. Figure 3.7 shows the

probability plots of dry durations for the four seasons. Our data analysis clearly shows (see figure 3.6) that distribution of dry periods does not follow a power law.

One assumption, which is implicit in the work of Schmitt et al. (1998) is that the intensity of rainy events is independent of the duration. On the contrary, it has been shown by many researchers that the rainfall variability within a rainy event depends on the duration. For instance, Pilgrim and Cordery (1975) concluded that rainfall variability increases with duration. Acreman (1990) shows significant correlation between intensity and duration within each precipitation event. Our data analysis also substantiates that duration and depth are not independent. Figure 3.3(b) shows the plot of mean intensity against duration in double logarithmic scale. The fitted linear line has a slope of 0.24. This shows some dependence of intensity on duration. Bloschl and Sivapalan (1997) found a slope of 0.08 for their data set and assumed intensity to be independent of the duration. We also carried out an analysis to check if the successive dry and rainy duration are independent. As we can see from figures 3.8 and 3.9, it is reasonable to assume that dry and rainy periods are statistically independent of each other, as they did not show any significant correlation. Acreman (1990) reached similar conclusion for his stochastic model of hourly rainfall in England, U. K.

Lack of consideration of seasonality

Schmitt et. al (1998) carry out the analysis without any consideration for the seasonality. Our data analysis shows a distinct difference between the characteristics of rainfall from one season to another in New England. Table 3.3 gives mean duration of dry and rainy events on annual and seasonal basis for the Hartford station. Note that the decreasing

mean duration in summer agrees with our previous discussion.

Table 3.3: Seasonality and duration of dry and rainy events

Mean duration (hr)	Annual	Spring	Summer	Fall	Winter
Dry Events	43.5	39.8	44.5	46.4	43.6
Rainy Events	3.9	4.1	2.7	3.9	4.9

To summarize the review and discussion of the work done by Schmitt et al. (1998), we found, through box counting approach, that temporal rainfall displays deviation from multifractality. We confirmed that durations of successive rainy and dry events are independent. However, we find that intensity is not independent of duration.

A New Model for the Distribution of Dry Period Durations

We propose a new method based on data analysis and distribution fitting. The distribution of dry periods is shown in figure 3.6 (top plot). First, we considered fitting a mixture of power law and exponential distribution to describe the dry period distribution. However, we found that even though the power law gives a better fit for the initial portion yet it causes a misfit for longer durations. The power law needs to be truncated after a certain duration but it is difficult to determine this truncation point. Without truncation, the power law does not fit the dry distribution well. As an alternative, the dry duration distribution can be fitted with a mixed exponential distribution. The proposed distribution for the dry duration t is:

$$f(t) = pe^{-\lambda_1(t-t_0)} + (1-p)e^{-\lambda_2(t-t_0)} \quad (3.2)$$

where p , λ_1 , λ_2 and t_0 are parameters characterizing the distribution of dry periods. Figure 3.10 shows the relative frequency of dry durations at Hartford along with the fitted curve given by (3.2). The parameters of the distribution are estimated by maximum likelihood method. For this case, the estimated parameters are: $\lambda_1 = 0.68$, $\lambda_2 = 0.0145$, $t_0 = 0.5$ hour and $p = 0.59$. Figure 3.10 shows the relative frequency plot for the data, averaged data and the fitted distribution. The mixed exponential model in (3.2) gives a better overall fit to the empirical distribution of dry periods as compared to the fit with a power law.

For longer dry durations (say between 300-900 hours), there may not exist events with that duration, e.g., in our data set there was no dry duration of 102 hours. Such durations are assigned zero probability, but do not appear in figure 3.10. This is the reason why in figure 3.10 the asterisks, which are averages over duration intervals appear lower than the dots for long durations. Figure 3.11(a) shows the probability of exceedance for empirical and fitted distribution of dry durations. Again the effect of the zeros may give the misleading impression that the fit is not good for durations beyond 400 hours. Figure 3.11(b) shows a zoom of the initial portion of figure 3.11(a) but plotted in arithmetic scale. Figure 3.11(b) shows the normal probability plot for the fit. From figure 3.11(b), it is interesting to note that the distribution of dry periods can also be approximated as composed of three lognormal distribution segments. Another observation from this plot is the sharp change in distribution at durations of approximately 4 hours and 72 hours. These breaks indicate the underlying change in rainfall structure at the corresponding durations; for example, the rainfall generated by

convective and frontal storms has average durations close to these values. Figures 3.12(a) through 3.12(d) show the model fitting for the relative frequency of the seasons using the same parameters as given above.

Separation of Storms

The issue of defining independent storms and interstorm periods is important for many hydrologic modeling applications. This discussion is appropriate here because the modeling of residence time distribution of dry and rainy distribution is closely linked to the issue of interstorm duration. We present a brief review of various approaches to this problem before presenting our own methodology for separating independent storms.

As Acreman (1990) points out, it is difficult to find consensus on an objective definition of a precipitation event. Different criteria that have been used for separating independent storm events include those based on meteorological independence, lack of significant correlation or partial correlation between pairs of storms or from the point of view of a drainage basin, the duration of rainfall to which the basin responds. Some methods seek to determine a certain minimum duration, the critical dry period, for defining statistically independent storms. The significance of a critical dry period is that dry periods below that duration are regarded as 'within-storm' and may be expected to have different distribution than the longer dry durations.

Restrepo and Eagleson (1982) assumed that the arrival times of independent precipitation events is a Poisson process; thus, as an approximation, the dry periods between storms are assumed to be exponentially distributed. The problem with this

approach is that the Poisson process models the arrival rates of storms with zero duration or with insignificant duration compared to dry periods. Their method tests for successively larger critical dry period until a value is found for which all larger dry periods satisfy the necessary (but not sufficient) condition for exponential distribution of dry periods. The model is approximate but simple. Hawk (1992) proposed a stepwise two-phase regression method where then dry period durations is fitted with two separate linear fits on semi-log plot of cumulative probability against dry period durations. The intersection for the best combination of the regression segments is taken as the critical dry duration. This method is sensitive to the large dry period durations and gives unrealistic results unless the data is truncated to ignore the long durations. Moreover, the regression fits are not always good enough to justify this approach.

Robinson and Sivapalan (1997) used 3 years of meteorological records to estimate a minimum dry period such that each isolated event corresponded to an identifiable synoptic event on weather charts. They estimated the critical dry period to be 7 hours. The results of different researchers are summarized in table 3.4.

Table 3.4: Storm separation studies

Study by	Critical dry period used	Criteria used	Geographical location
Grace and Eagleson (1967)	2 hours 3 hours	serial correlation of storm depth	New England Arizona
Huff (1967)	6 hours	judgement	Illinois
Koutsoyiannis et al (1993)	7 hours	exponential distribution	Greece
Cordova et al (1985)	12 hours	unspecified	Spain

Robinson et al.(1992)	2 hours	judgement	South East US
Sivapalan et al. (1997)	7 hours	weather maps	Australia

The definitions result in different results and the selection of a critical dry period which divides a storm and dry period has been subjective. We carried out a sensitivity analysis of the rainfall characteristics to critical dry period. Using 40 years of hourly precipitation data at Hartford, we extracted storms based on increasingly large critical dry periods. Increasing the threshold above one hour means that a dry period equal or less than the critical duration, bounded on left and right by rainfall will be included as a within-storm period and not a separate dry period. Obviously, this would result in a decrease in average intensity of the storms as compared with the rainy events considered before.

We compute the percentage of rainfall contributed from extracted independent storms based on different critical dry periods. The results are shown in table 3.5.

Table 3.5: Statistics related to separation of storms

Critical dry period used (hr)	Number of extracted storms in 40 years	Contributed rain (in) / number of storms	% of rain contributed by storms
1	7391	23.8	100
2	4202	40.9	96.3
3	3103	53.2	92.4
4	2642	60.9	90.2
5	2347	66.3	87.1
6	2121	71.6	85.1
7	1950	76.6	83.7

The review of the approaches used to determine interstorm durations and critical dry period shows that there is a need for a better method to find critical dry duration. All the above described approaches to estimate critical dry periods are deterministic. However, a better approach to separate statistically independent storms would be to use a stochastic model which assigns a certain probability for a duration to be in the rainy or dry state.

One could hypothesize that the transition in shape of the distribution indicates the shift from within-storm dry periods to interstorm dry periods. Referring to figure 3.10, we can see that the proposed mixed exponential model shows a change in distribution after a certain duration.

In order to illustrate this point, consider the two exponential distribution in (3.2) individually with the same parameters as given above. Figure 3.13 shows the probability density function of the two distributions plotted separately against durations. We hypothesize that the first distribution (open circles) represents dry durations outside storms and the second distribution (filled circles) represents the dry durations within rainfall events. The duration corresponding to the intersection of the two curves is 5.74 hours. There is equal probability that this duration of 5.74 hours belongs to either of the two populations. Hawk (1992) has used the same approach, although she does not use an exponential model for the dry duration distribution. This plot also shows how the relative probabilities change with the choice of a critical dry period; for example, for durations beyond 5.74 hours, the probability that the duration comes from a dry duration outside storms decreases rapidly.

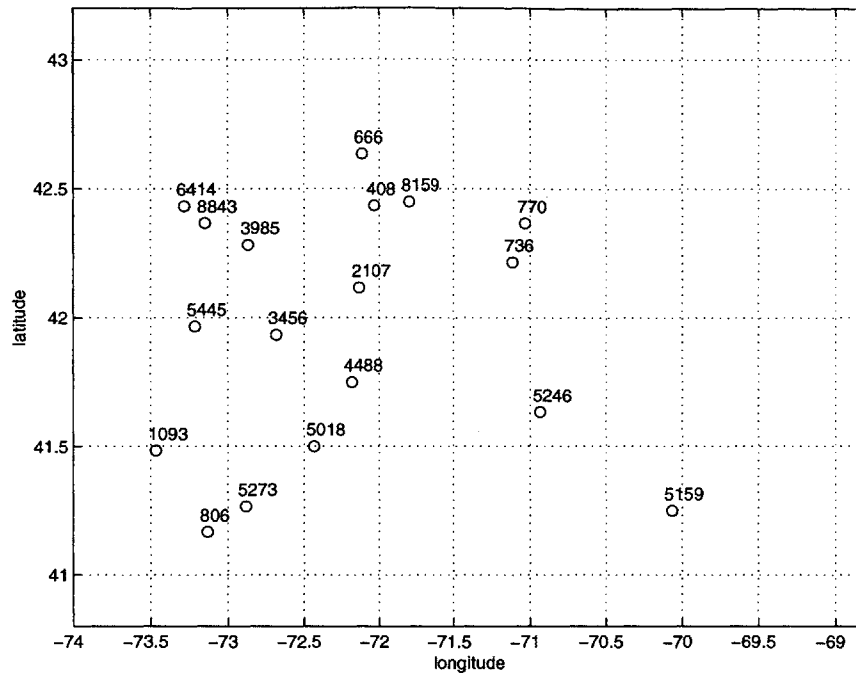


Figure 3.1. Location of selected rain gages in New England region.

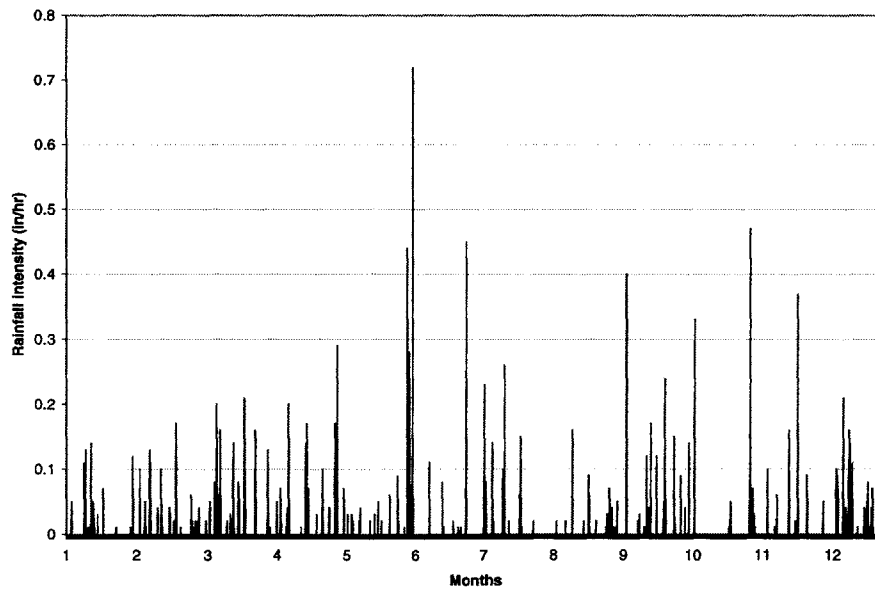


Figure 3.2. Rainfall intensity time series for Hartford, 1956.

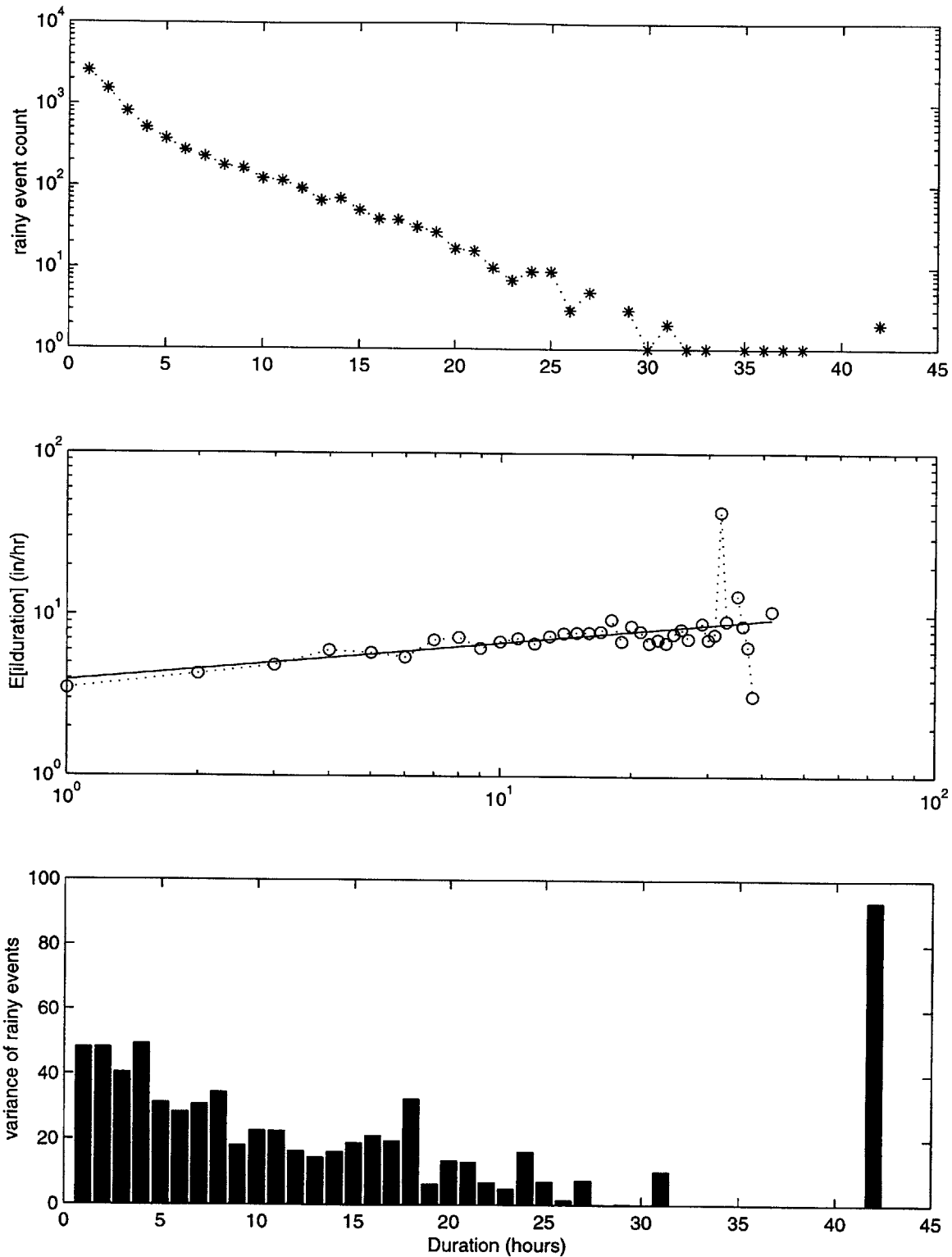


Figure 3.3. Statistics of rainfall for annual series, Hartford station. Top: number of rainy events; Center: expected value of intensity against duration for annual series. The fitted regression has a slope of 0.24; Bottom: variance of aggregated rainfall event for the range of durations.

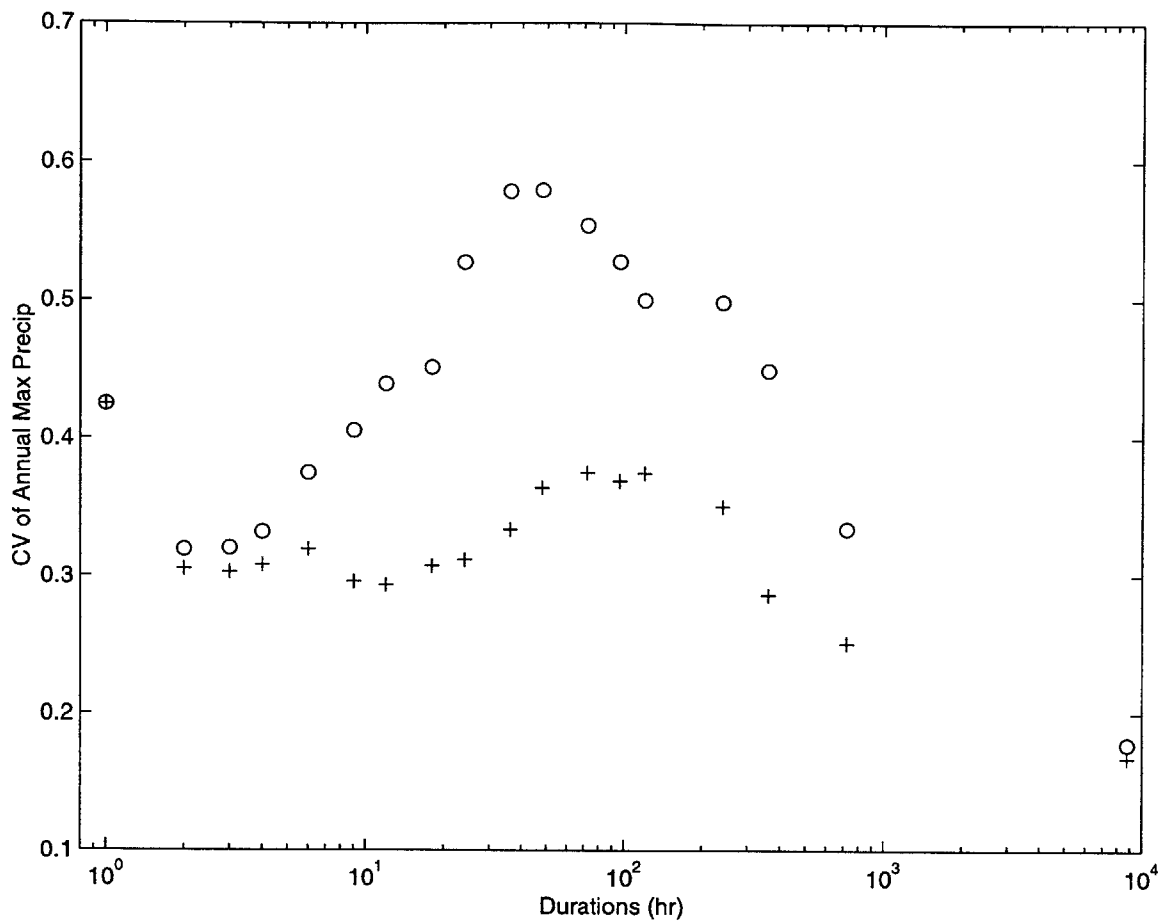


Figure 3.4. Coefficient of variation against duration for Hartford station: circles show the series with year 1955 and + shows the series without 1955.

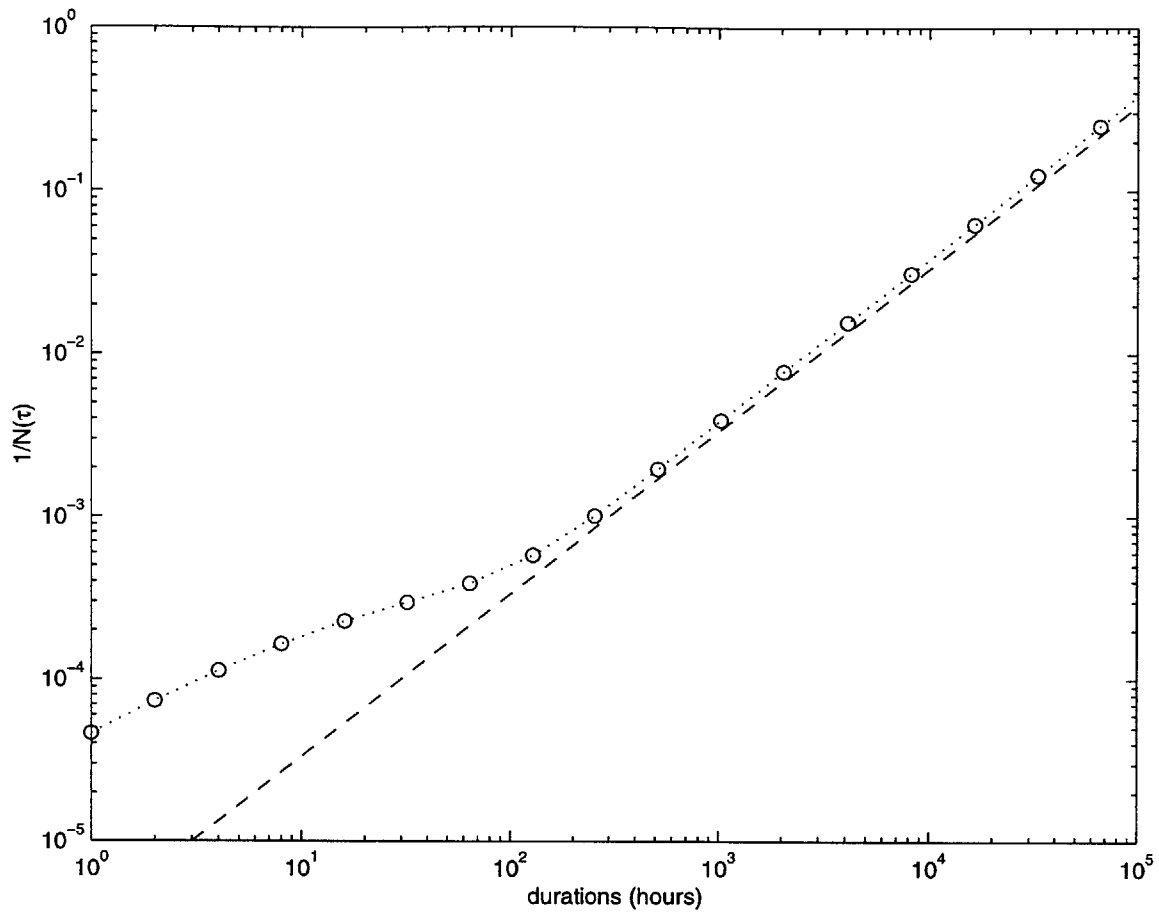


Figure 3.5. Box counting analysis for Hartford station. The dashed line shows the unit slope and is shown for reference.

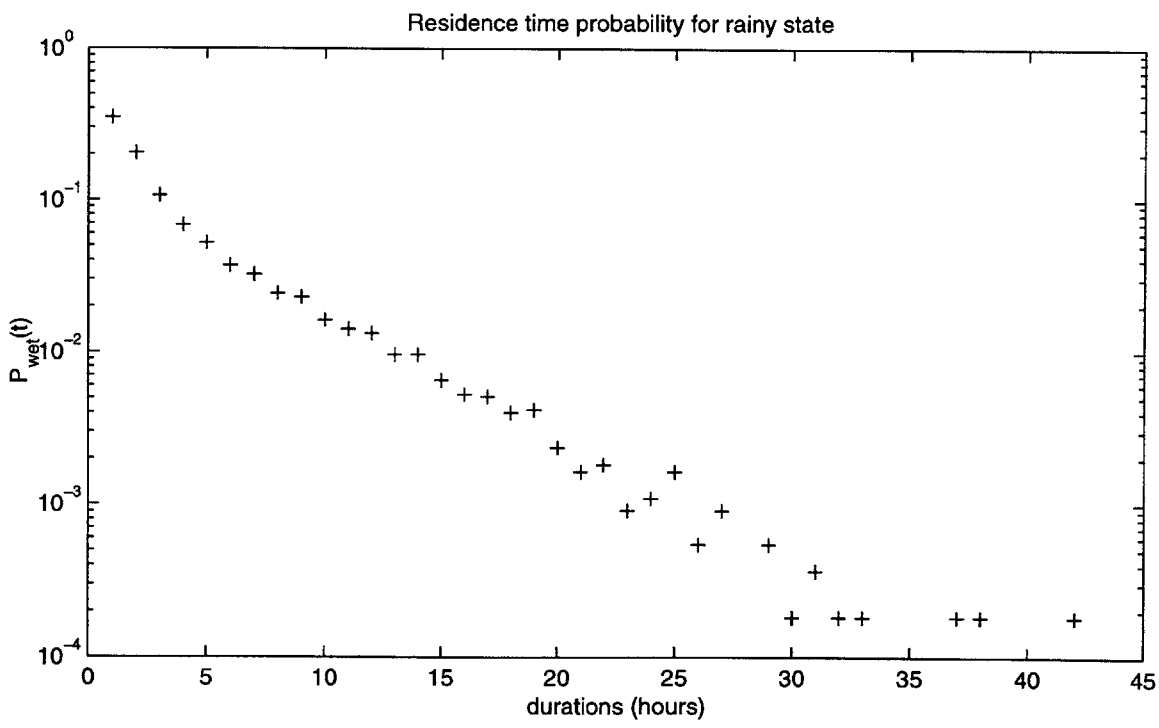
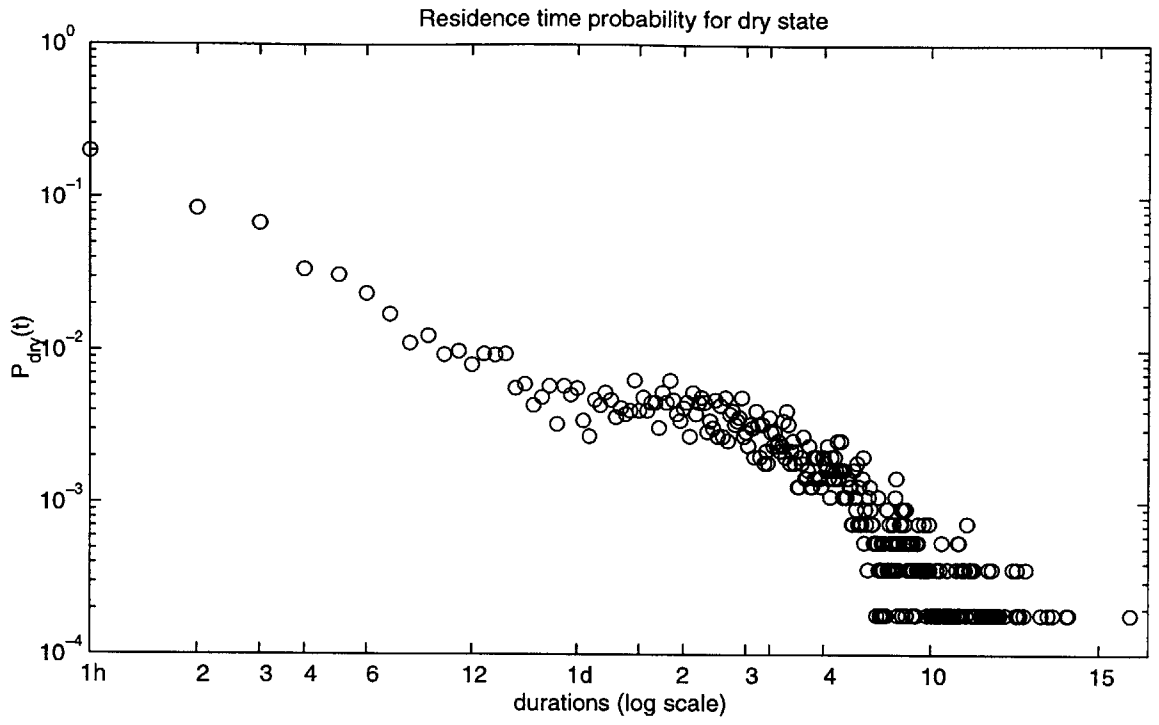


Figure 3.6. Probability of dry and rainy durations for the annual series.

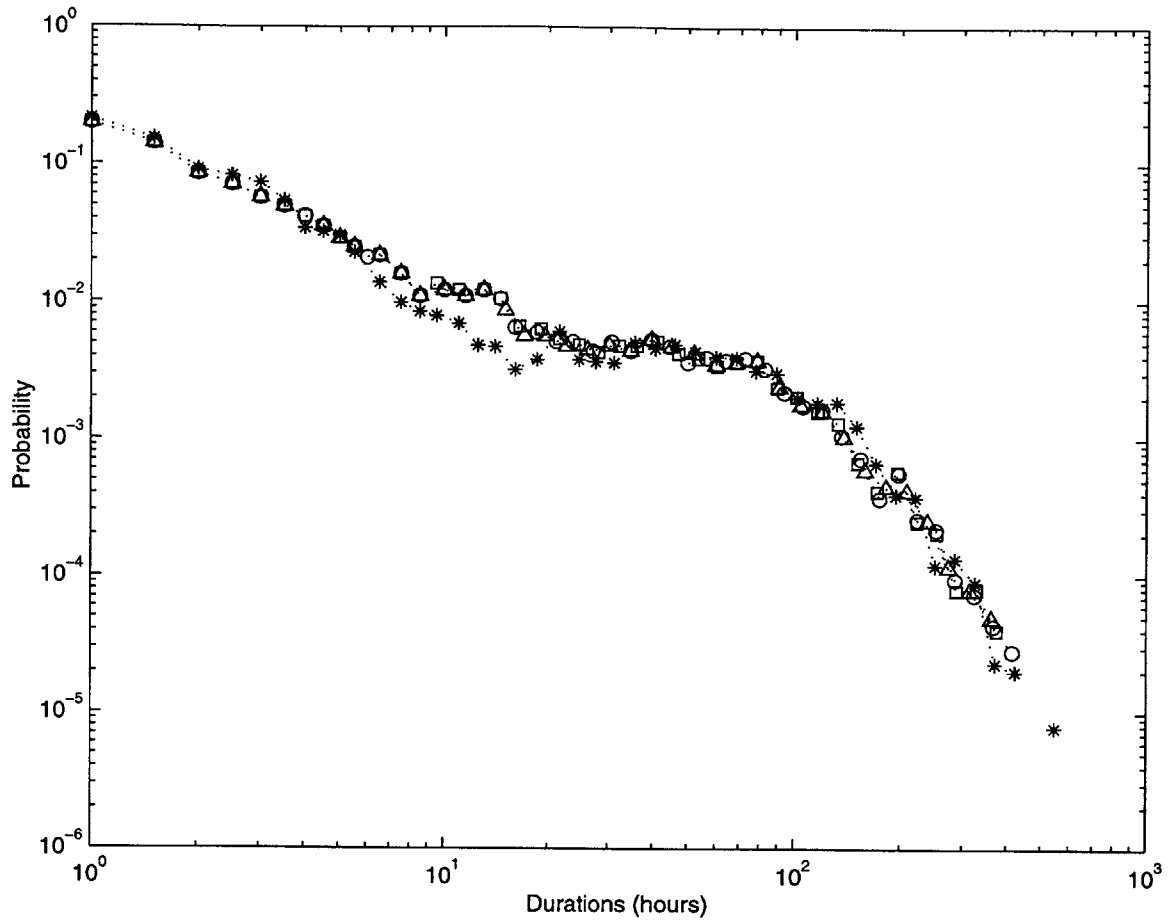


Figure 3.7. Averaged probabilities of dry durations for seasons: S1 (March, April, May) shown by circles, S2 (June, July, August) shown by triangle, S3 (September, October, November) shown by squares, S4 (December, January, February) shown by asterisks.

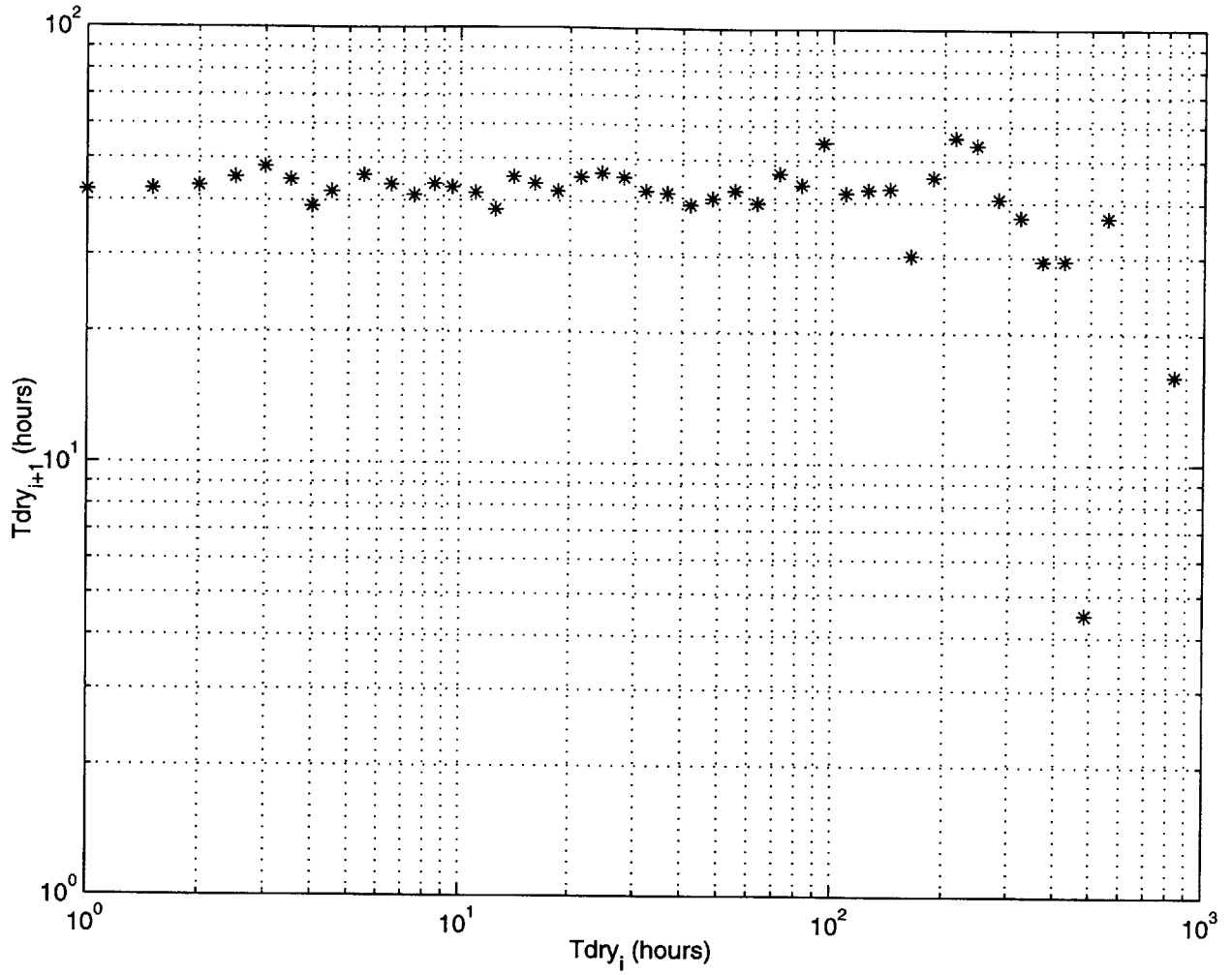


Figure 3.8. Independence of successive dry periods. T_{dry_i} and $T_{dry_{i+1}}$ represent successive mean dry period durations in the series.

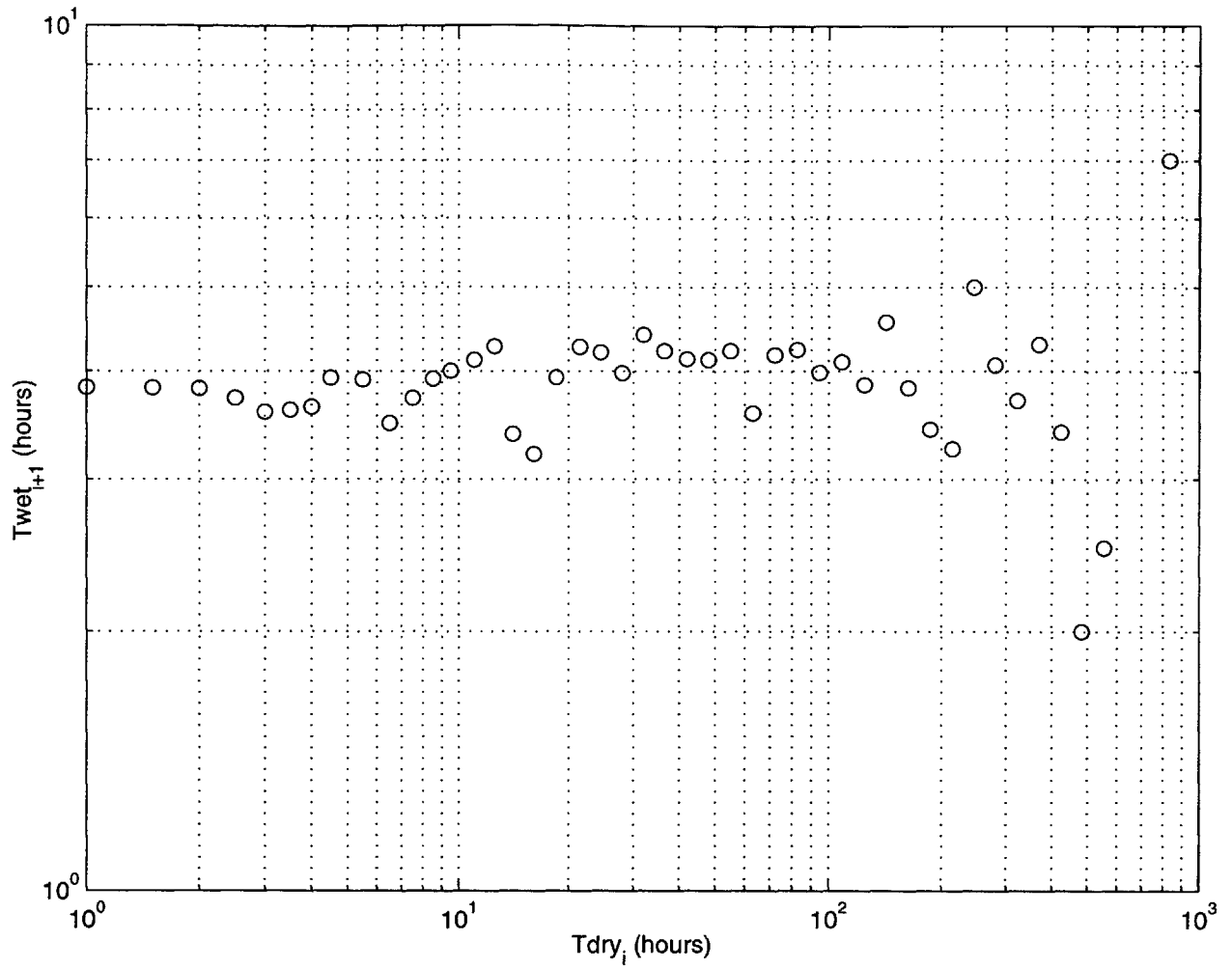


Figure 3.9(a). Independence of successive dry and rainy periods. $Tdry_i$ and $Twet_{i+1}$ represent successive mean dry and rainy period durations in the series.

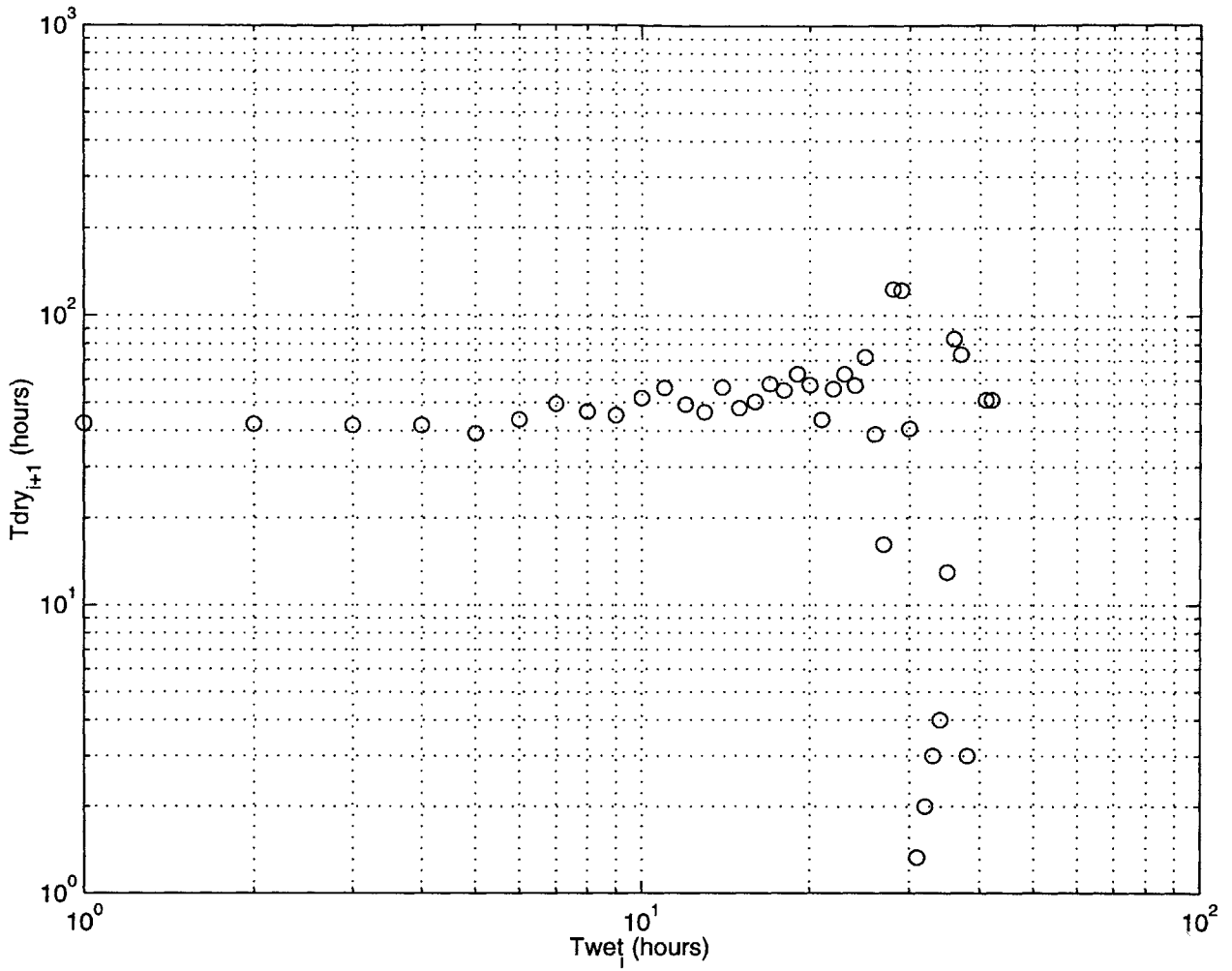


Figure 3.9(b). Independence of successive rainy and dry and periods. T_{wet_i} and $T_{dry_{i+1}}$ represent successive mean rainy and dry period durations in the series.

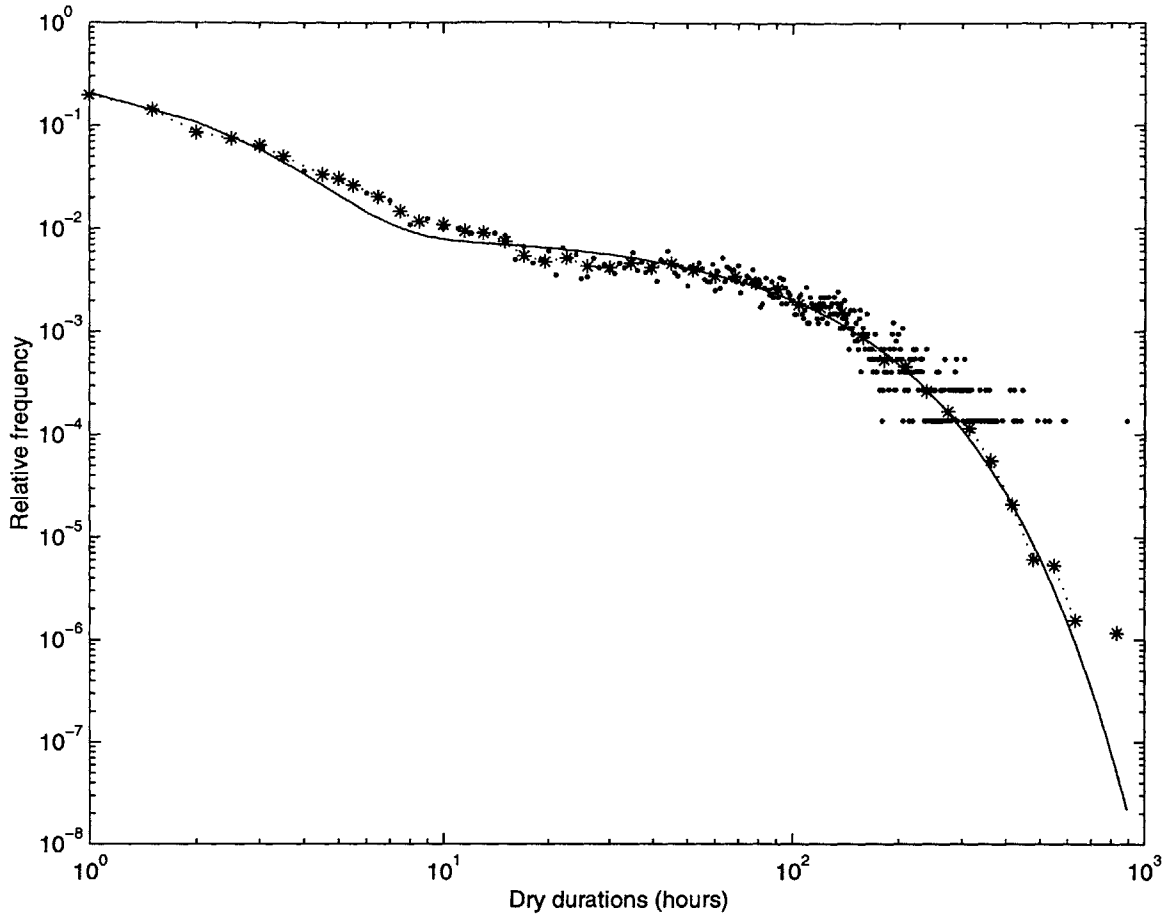


Figure 3.10. Relative frequency plot for mixed exponential model for dry duration distribution of Hartford station. Filled circles represents data, star represents averaged data points in log space and the model fit is shown as continuous line.

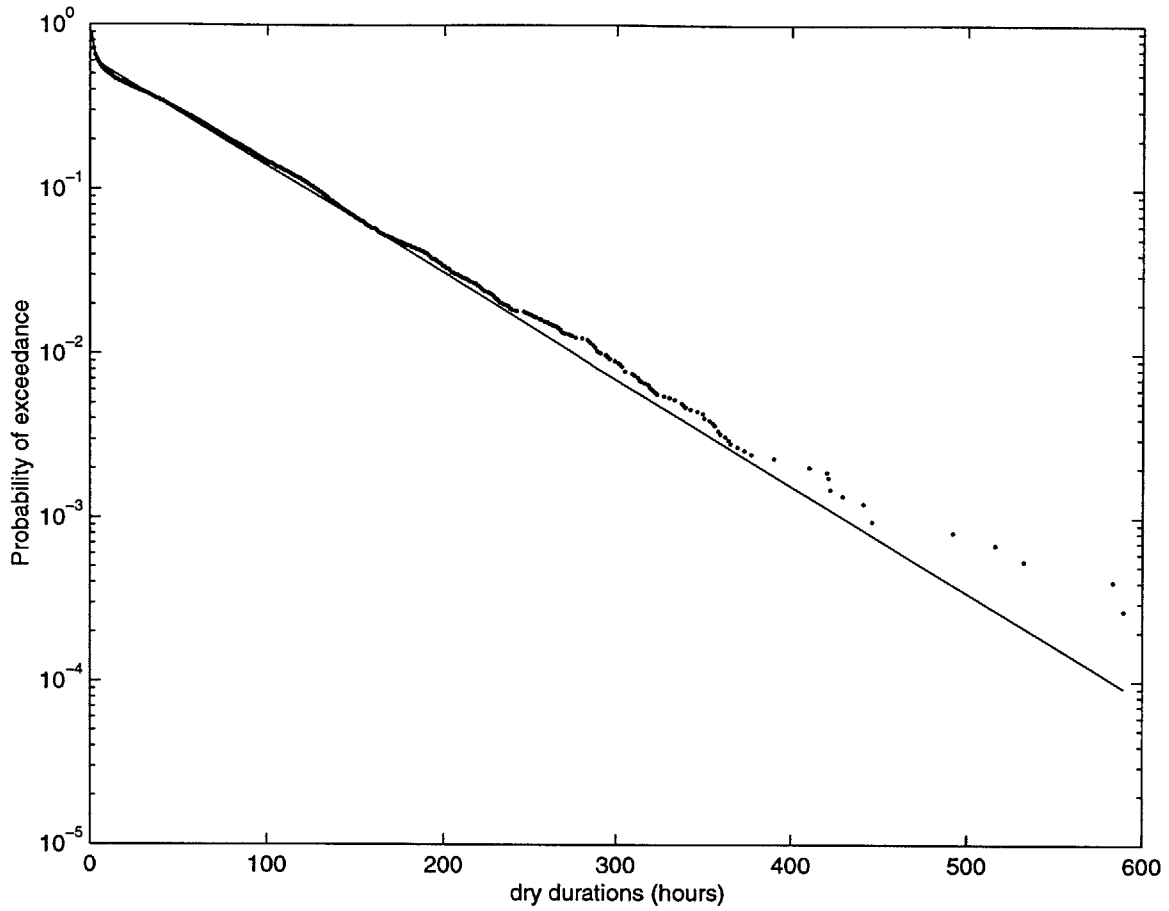


Figure 3.11(a). Probability of exceedance for the empirical dry period durations (filled circles) and the fit of mixed exponential model (continuous line) for the annual series of Hartford station.

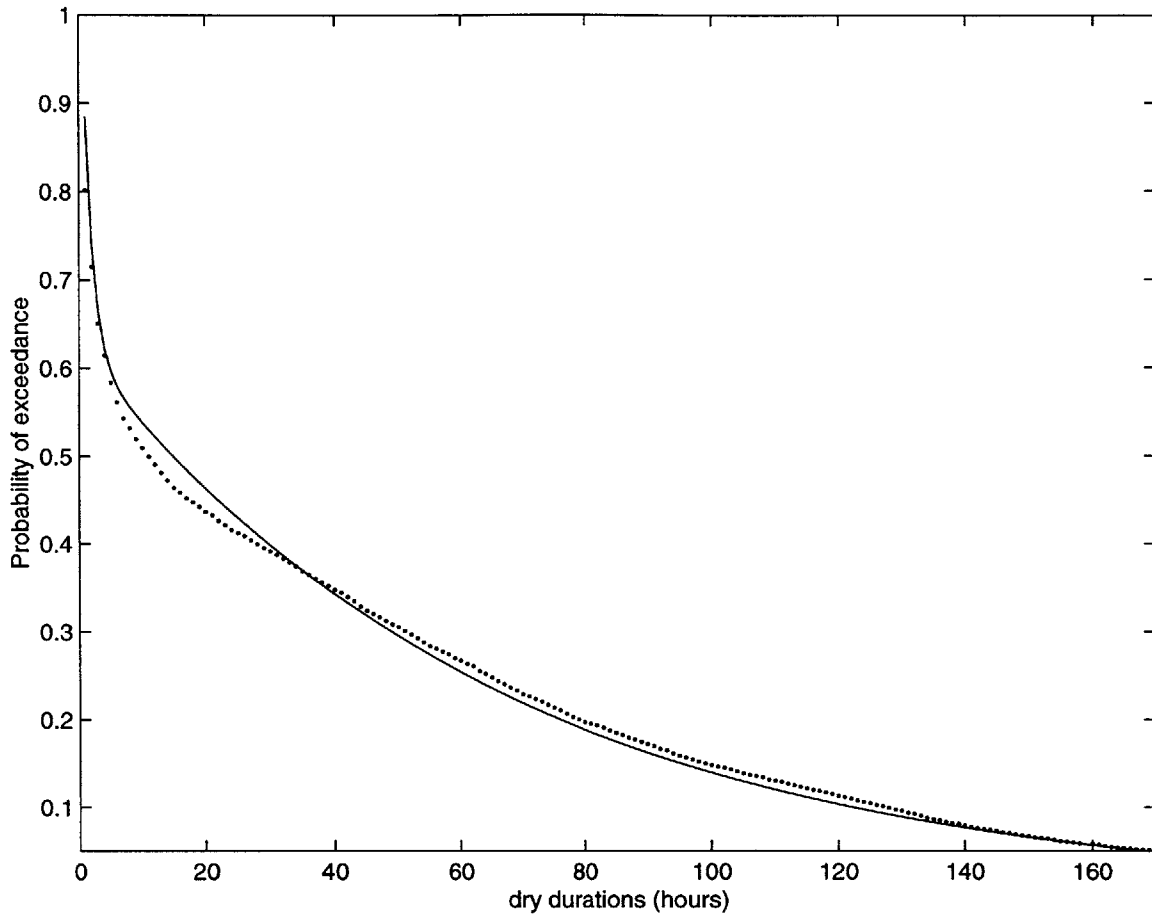


Figure 3.11(b). Initial portion of the plot 3.11(a) plotted on arithmetic scale.

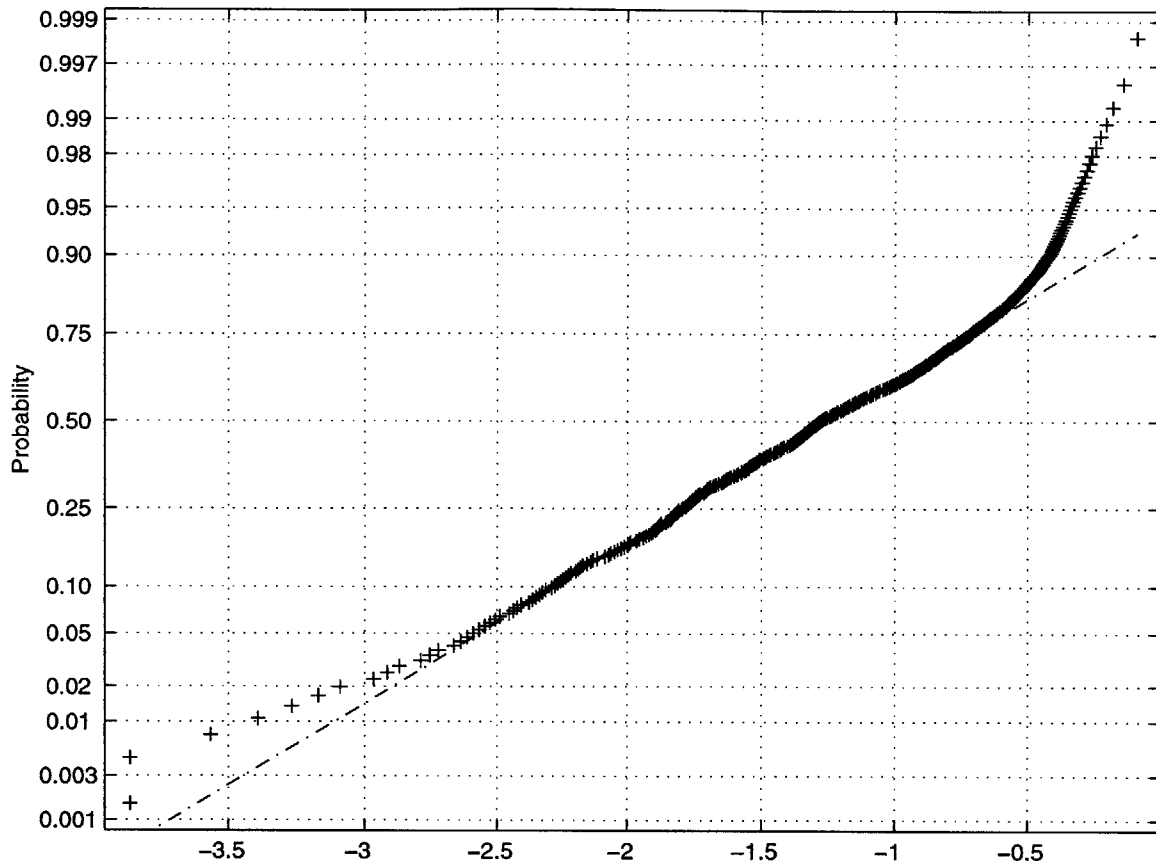


Figure 3.11(c). Normal probability for mixed exponential model for dry duration distribution for the annual series of Hartford station.

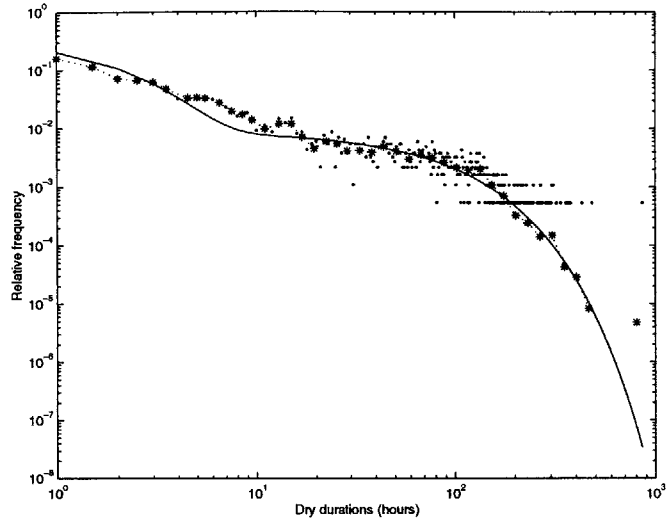


Figure 3.12(a). Model fit for March, April, May.

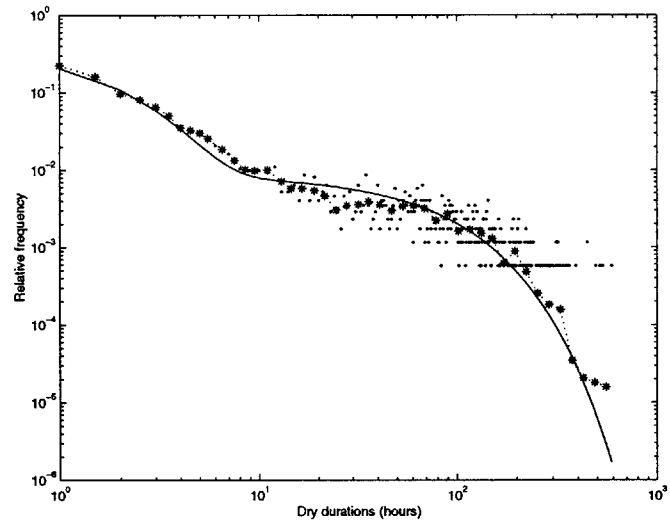


Figure 3.12(b). Model fit for June, July, August.

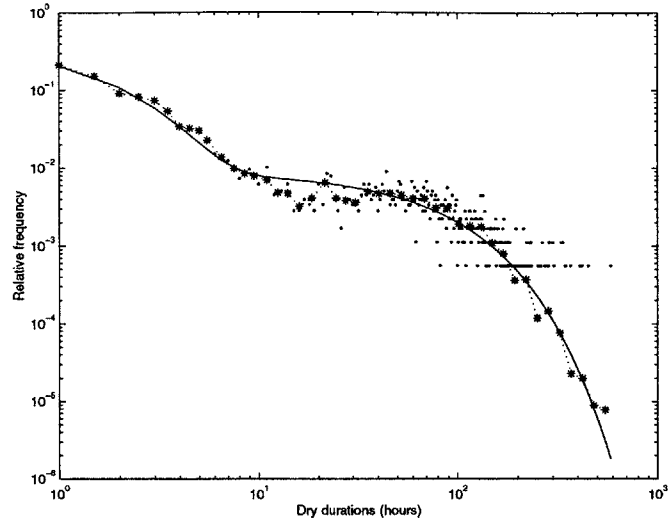


Figure 3.12(c). Model fit for September, October, November.

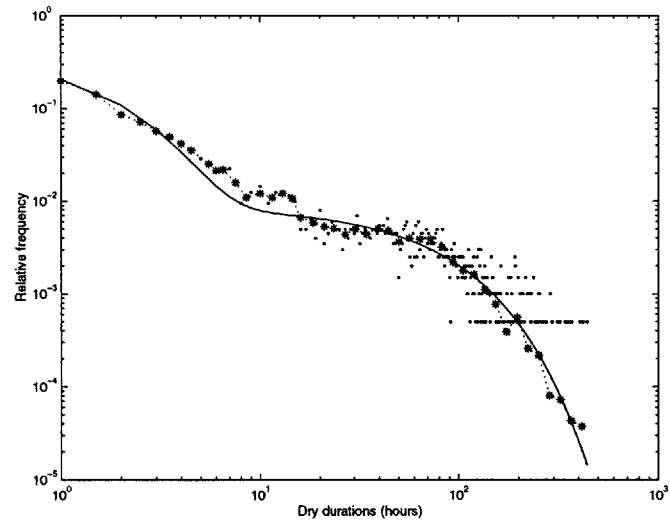


Figure 3.12(d). Model fit for December, January, February.

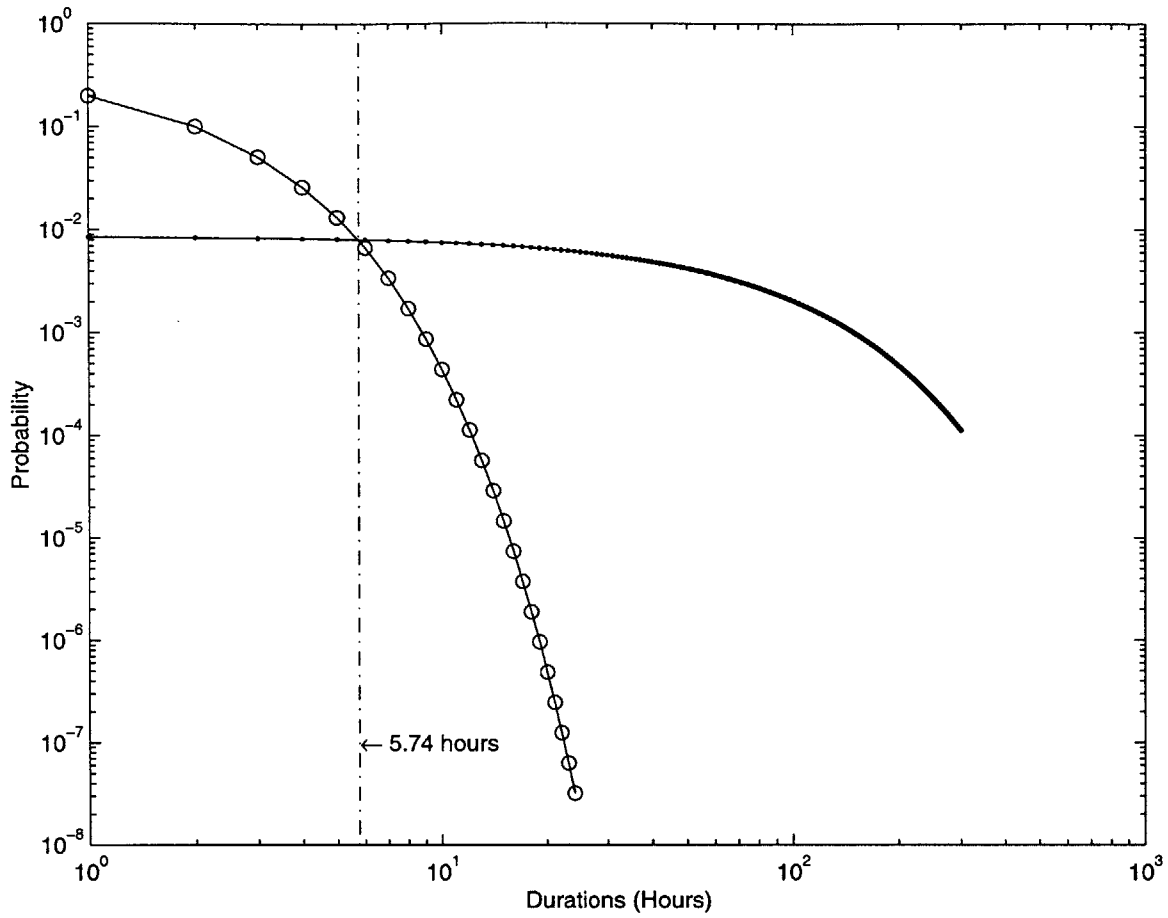


Figure 3.13. Exponential model distribution for within storm (open circles) and outside storm (filled circles). Dotted dashed line shows the duration corresponding to equal probability of a duration to be outside or inside storm.

CHAPTER 4

Scaling of Rainfall and Intensity Duration

Frequency Curves

4.1 Objective and Approach

An important question is whether the extremes of the rainfall scale in a way which is related to the scaling of the averages. The problem is to reconcile the observed multiscaling behavior of temporal rainfall and simple scaling shown by IDFs, and to relate the scaling exponents of rainfall to those of IDFs. The objective of this chapter is to present the analysis of scaling of rainfall and intensity distribution frequency curves (IDFs) and to investigate and verify the relationship between the scaling characteristics of rainfall and IDFs.

Recently, a few studies have investigated the scaling of extreme rainfall and intensity duration frequency curves (IDFs). Burlando and Rosso (1996) presented a lognormal model to derive depth duration curves from extreme rainfall. Benjoudi et al. (1999) have derived the parameters of scaling of IDFs from the codimension function of the rainfall process under the assumption that rainfall time series is multifractal. Veneziano and Furcolo (1999) made the same basic assumptions as Benjoudi et al. (1999), but used a different approach to relate parameters of multiscaling temporal rainfall to those of simple scaling IDFs.

In this chapter, we follow the theoretical framework presented by Veneziano and Furcolo (1999) and use data analysis to investigate the scaling characteristics of intensity duration frequency curves and to verify their results. We test this theory for annual and seasonal series and find that it fits the data very well for all cases. Finally we extend the analysis from point rainfall to spatial rainfall and discuss the results.

4.2 Analysis of Rainfall Scaling

We discussed different approaches and techniques for scaling analysis of rainfall. Results from the analysis of box counting, were discussed in chapter 3. Box counting analysis provides limited information about the scaling characteristics of rainfall (Lovejoy and Schertzer, 1995). Spectral theory is another common preliminary investigation method to examine the scaling behavior and range of scaling of rainfall time series. If scaling holds for a data set, the energy spectrum $E(f)$ has the power law form: $S(f) \propto f^{-\beta}$ where β is spectral exponent.

Figure 4.1 shows the smoothed spectral plot for the Hartford station. The spectrum was averaged over logarithmically spaced frequency intervals. The portion of the double logarithmic plot of $E(f)$ against f which exhibits straight line behavior indicates the range where scale invariance holds. Figure 4.1 shows a good power law between the approximate ranges of 2 hours (Nyquist frequency) and 3~4 days. The slope $\beta = 0.86$ shown in the plot was obtained by regression. This result is in agreement with the box counting analysis in figure 3.5 which also shows a break around 4 days.

The slope and limits of power law exhibited by the power spectrum tend to differ from region to region. To see how this result compares with the other values reported in the literature, we summarize a few results below:

Table 4.1: Results of spectral analysis for rainfall scaling

Data	Study by	Slope β	Scaling Regime
Resolution			Limits
Hourly	Olsson 1995 (Sweden)	0.66	8 min-3 days
Hourly	Schmitt 1998 (Belgium)	0.77	10 min-10 days
Daily	Svensson 1996(China)	0.37	1-32 days
Daily	Svensson 1996 (Sweden)	0.28	1-32 days

The results reported by Svensson are based on a data set for daily regime and therefore, are not directly comparable with the hourly analysis results.

Next, we perform the multiscaling analysis of the averages of the rainfall. The averages are calculated for durations D ranging from 1 hour to 512 hours. Aggregations are made on a non-sliding basis and statistical moments of the averages $E[I_D^q]$, $q = 0.5, 1, 1.5, 2 \dots 4$ are calculated. According to the scaling theory if (1) the statistical moments $E[I_D^q]$ are log-log linear in D , and (2) the slopes of these moments $k(q)$ are nonlinear in q , then rainfall is multiscaling. A plot of the statistical moments is shown in figure 4.2 for the annual series.

The straight lines are the regressions fitted for each of the moment order. The regression was fitted using data points corresponding to durations of 8, 16, 32, 64 and 128 hours. The multifractality is good between 8 and 128 hours. The results of box counting analysis and spectral analysis provide evidence that the scaling limits are in the range of 2 hours to about 4 days. We observe a corresponding break in scaling in the moment analysis after 128 hours. For the summer season, we found that a good fit exists between the range of 4 to 128 hours.

The slopes $k(q)$ of the linear fitted curves to the moments are plotted against the moment order q in the same figure (bottom plot). The results of moment analysis show that rainfall exhibits multiscaling behavior. We repeat the analysis for the four seasons as defined in chapter 3. The results are presented in figures 4.3 through 4.6.

4.3 Scaling of Intensity Distribution Frequency Curves

Intensity distribution frequency curves are important tools for hydrologic design. In this section we discuss a framework for relating IDF scaling to the multifractal properties of rainfall, perform data analysis to verify the validity of the theory described and compare our results with results from the literature.

Willems (1998) investigated the compound IDF relationships of extreme precipitation for two seasons and two storm types in Belgium. Willems used the same data set which was used by Schmitt et al. (1998) and used two-component extreme value distribution to derive equations for IDFs. Willems found out that winter population can be described by one distribution component and that the winter IDFs follows simple scaling. The slope of the IDF for winter was 0.58 which matched well with their theoretical result.

The summer population is described by both components and the summer IDF exhibits multiscaling. The slope of the IDF for summer was about 0.71.

Benjoudi et al (1999) have derived the parameters of IDF scaling from the codimension function of the rainfall process under the assumption that rainfall time series is multifractal. As discussed in section 2.2, the result of Benjoudi et al. (1999) expresses the scaling of IDFs in terms of q_D , which is a multifractal characteristic of rainfall series and on a factor which they assume to be the fractal dimension of the rainfall D_s . Benjoudi et al. (1999) performed data analysis on a 5 year hourly rainfall in Bordeaux, France. They estimated q_D by fitting a regression for the tail portion (seven points) of the log-log plot of probability of exceedance (estimated by Weibull formula) of rainfall intensity. The slope of the fitted regression gave $q_D = 3.5 \pm 0.8$. The fractal dimension of the rainfall occurrence was estimated by box counting to be $D_s = 0.64 \pm 0.08$. The procedure used by Benjoudi et al. (1999) to determine q_D is subjective as to the number of points to be included in the fit and the goodness of the fit.

Veneziano and Furcolo (1999) developed a theory to link the parameters of scaling of IDF to those of the rainfall process. They make the same basic assumptions as Benjoudi et al but use a different approach and reach at different conclusions about the scaling of the IDFs. Below, we describe the theory of Veneziano and Furcolo (1999). In the next section we will verify their theory by data analysis.

Theory

Let I_D be the annual maximum rainfall intensity in a period of duration D and denote by $I_p(D)$ the value exceeded by I_D with probability p . The IDF curves are plots of $I_p(D)$ against D for selected exceedance probabilities p . Denote the average intensity in duration of $[t, t+D]$ as $I'_D(t)$.

The recurrence interval of an extreme event is the average time between occurrences of extreme events. The return period T can be defined in different ways. A common definition of the return period is the average recurrence interval between events equal or greater than a specified magnitude. If $T(D, i)$ is the return period of events with average rainfall intensity i over duration D , then the definition given above corresponds to,

$$T_1(D, i) = \frac{1}{P[I_D > i]} \quad (4.1)$$

Another way to define return period, call it T_2 , is to relate the return period to the marginal exceedance probability $P[I'_D(t) > i]$ as

$$T_2(D, i) = \frac{D}{P[I'_D(t) > i]} \quad (4.2)$$

Let us denote the rainfall intensity corresponding to T_2 and D as $i_2(T_2, D)$.

It has been observed (Burlando and Rosso, 1996; Menabde, 1999) that the distribution of

annual maximum intensity in a period of duration D , I_D , satisfies the simple-scaling relation:

$$I_D = r^H I_{rD} \quad (4.3)$$

with H between 0.6 and 0.8.

Therefore the IDF curves satisfy a power law of the form

$$I_p(D) = g(p)D^{-H} \quad (4.4)$$

where $g(p)$ is some function of p .

In some cases and for small p (Benjoudi et al., 1999),

$$g(p) \propto p^{-\alpha} \quad (4.5)$$

for some α .

Next, consider a multiplicative cascade that starts at level 0 with a uniform unit measure in the unit interval. Denote by b the multiplicity of the cascade, by B the cascade generator, by r an integer power of b and by ε_r the average measure density in a generic cascade tile of length $1/r$. Schertzer and Lovejoy (1987) showed that, for any given γ ,

$$P[\varepsilon_r > r^\gamma] \sim r^{-c(\gamma)} \quad (4.6)$$

where \sim denotes asymptotic equalities as $r \rightarrow \infty$, up to a slowly varying function of r and $c(\gamma)$ is the Legendre transform of the moment scaling function $K(q) = \log_b[B^q]$. The function $c(\gamma)$ may be obtained from the moment scaling function as

$$\gamma(q) = \frac{dK(q)}{dq}$$

$$c(q) = q\gamma(q) - K(q) \quad (4.7)$$

For the scaling analysis of the IDF curves, (4.6) was extended by Veneziano and Furcolo (1999) to obtain the probability $P[\varepsilon_r > ar^\gamma]$ for any given positive number a with the result

$$P[\varepsilon_r > ar^\gamma] = P[\varepsilon_r > r^{\gamma + \log_r a}] \sim a^{-q(\gamma)} r^{-c(\gamma)} \quad (4.8)$$

Next, Veneziano and Furcolo (1999) used the result in (4.8) to obtain the scaling properties of $i_2(T_2, D)$ for large T_2 . I'_D has a unit-mean cascade representation of the type $I'_D = m\varepsilon_{D_o/D}$ where D_o is the outer limit of the scaling regime for rainfall. Substitute

$r = \frac{D_o}{D}$ and $\varepsilon_r = \varepsilon_{D_o/D} = \frac{I'_D}{m}$ in (4.8) to get,

$$P[I'_D > ma \left(\frac{D}{D_o}\right)^{-\gamma}] \sim a^{-q(\gamma)} \left(\frac{D}{D_o}\right)^{-c(\gamma)} \quad (4.9)$$

Equation (4.9) holds for $D \ll D_o$.

Since $i_2(T_2, D)$ satisfies $P[I'_D > i_2] = \frac{D}{T_2}$, the right hand side of (4.9) should be made

equal to $\frac{D}{T_2}$. This happens for

$$\gamma = \gamma_1 \text{ such that } c(\gamma_1) = 1$$

$$a = \left(\frac{T_2}{D_0}\right)^{\frac{1}{q_1}} \quad (4.10)$$

where $q_1 = q(\gamma_1)$. The parameters γ_1 and q_1 are obtained from the moment scaling function $k(q)$ of the rainfall process. From convexity of $k(q)$ and the conditions $k(1) = 0$ and $k(q^*) = q^* - 1$ (see figure 2.2), it follows that $\gamma_1 < 1 < \gamma^*$. With γ_1 and a in (4.10), (4.9) becomes,

$$P[I'_D > m \left(\frac{T_2}{D_0}\right)^{\frac{1}{q_1}} \left(\frac{D}{D_0}\right)^{-\gamma_1}] \sim a \frac{D}{T_2} \quad (4.11)$$

Note that q^* here is the same as q_D discussed earlier.

Hence for $D \ll D_0$, i_2 must scale with T_2 and D as:

$$i_2 \propto T_2^{1/q_1} D^{-\gamma_1} \quad (4.12)$$

As (4.9) was derived for D/D_0 infinitesimal, theoretically (4.12) holds for $D \ll D_0$. This

result has practical implications, particularly for extrapolating the frequency of extreme events. Later, we shall perform data analysis to investigate the accuracy of (4.12) also for large durations.

4.4 Data Analysis for IDF Scaling

In chapter 3, our analysis of major storms at the Hartford station revealed that year 1955 was particularly influential. Since such influential points dominate the moment scaling and IDF analysis, for the data analysis in this chapter, we excluded the year 1955 and only used the data from 1956 to 1994. A similar approach was taken by Svensson (1996).

The first step to obtain IDFs from a data series is to extract the annual maximum rainfall corresponding to a given set of durations. The annual maxima for the whole series are then ranked in descending order. The return period for the length of the time series is calculated based on the definition of the return period, that is, T_1 or T_2 . Then, for the desired return period, the maximum intensity values corresponding to the durations listed above give the IDFs. Figure 4.7 shows the IDFs for Hartford station based on T_1 for return periods of 1, 2, 5, 10, 20 and 40 years. Figure 4.8 shows the same IDFs as in 4.7 but based on T_2 . Theoretically, the results from T_1 and T_2 should be close for large return periods if the extraction of maximum intensities is based on non-overlapping (discrete) duration sets. Comparison of figure 4.7 and figure 4.8 shows that indeed the definitions of return periods are quite close to each other for large return periods. From now on, our analysis will focus on the IDFs defined by T_2 .

The slope and spacing of the IDF curves give information about the scaling

characteristics of these curves. We estimated the slopes of the IDFs curves by fitting regression lines through selected data range. For durations beyond 128 hours, the slopes become flat. This observation is consistent with the break of scale shown in the power spectrum and with our analysis for rainfall moments. Between 8 and 128 hours, the IDFs show good multifractal behavior. Season 2, Summer, is an exception as it shows a good fit from 4 hours onwards. Figure 4.8 shows the IDFs for annual series at Hartford station. This analysis was repeated for the four seasons. See figures 4.9 through 4.12 for IDFs for seasons 1 through 4. The results of IDF analysis are summarized in table 4.2.

Table 4.2: Slopes of the IDF

Return period (years)	Annual	S1	S2	S3	S4
1	0.80	0.75	0.85	0.83	0.79
2	0.80	0.74	0.80	0.80	0.79
5	0.78	0.79	0.79	0.79	0.74
10	0.76	0.81	0.79	0.76	0.76
20	0.73	0.73	0.71	0.80	0.76
40	0.74	0.68	0.64	0.78	0.73
Mean	0.77	0.76	0.76	0.79	0.76

Now that we have investigated the statistical properties of rainfall, scaling analysis of the rainfall and the IDFs based on different definitions of return periods we can test the approach suggested by Veneziano and Furcolo (1999), described in section 4.3.

If (4.12) holds, the slope of the IDFs and the tangent slope γ_1 should coincide. The point of tangency then gives the corresponding moment order q_1 . Figure 4.2 shows the results

of moment scaling analysis for the annual series at Hartford. In the plot of $K(q)$ we have shown the slope of the corresponding IDF's curve as a dashed line for comparison. Note that it is not possible to determine q_1 accurately from the range of the analysis – one can only make an approximate visual estimate. Figures 4.3 through 4.6 show the comparison of IDF's slope and γ_1 for the seasonal cases.

The comparison of results from moment and IDF analysis are summarized in table 4.3. This shows that the IDF slope and γ_1 match very well for the annual and for the seasonal cases.

Table 4.3: Comparison of results of IDF and moment scaling analysis

Rainfall Series	γ_1	IDF Slope
Annual	0.78	0.77
S1	0.80	0.76
S2	0.76	0.76
S3	0.78	0.79
S4	0.80	0.76

Figure 4.13 shows the relation between $\text{mean}[\log(\text{IDF})]$ and return period for annual and seasonal series on a log-log plot. According to (4.12), the slope of this curve should be $1/q_1$. However, we can see from figures 4.3 through 4.6 that q_1 can not be determined within the moment orders (4.0) used in the analysis. If the $k(q)$ plot were to be extrapolated beyond $q = 4$, we would get a $q_1 > 4$. We estimate the slopes of the $\text{mean}[\log(\text{IDF})]$ -return period curves by fitting a regression to the data points. The last point showed a marked deviation from the linear fit. Therefore, we perform the

regression neglecting the last point which results in a better fit. The last point corresponds to return period of 40 years and is not as robust as the smaller return periods. We have summarized the resulting slopes for regression without the last point (table 4.4) and for regression using all points (table 4.5). The resulting values of q_1 are all considerably higher than 4.0 which is in agreement with the moment analysis where we find that $q_1 > 4$.

It is interesting to observe that the mean[log(IDF)]~return period curve bends upward beyond a return period of 20 years. This shows that the higher return periods are sensitive to the curvature of the curve. This characteristic has not been reported elsewhere. This issue is of primary importance because one is interested in extrapolating this curve to higher return periods and therefore deserves further investigation.

Table 4.4: Mean[log(IDF)] against return period, regression without the last point

Rainfall Series	slope of mean[log(IDF)]~ return period	$q_1=1/\text{slope}$
Annual	0.12	8.3
S1	0.11	9.1
S2	0.13	7.7
S3	0.12	8.3
S4	0.08	12.5

Table 4.5: Mean[log(IDF)] against return period, regression using all points

Rainfall Series	slope of mean[log(IDF)]~ return period	$q_1=1/\text{slope}$
Annual	0.14	7.1
S1	0.14	7.1
S2	0.15	6.67
S3	0.13	7.7
S4	0.08	12.5

4.5 Extension to Areal Rainfall

In section 2.1.3 we provided a review of the space-time models of rainfall. In this section we extend our analysis of scaling rainfall and IDFs to space-time rainfall and areal IDFs. Due to the sparse rain gage density and the limited length of the time for which continuous data are available, the analysis has limited scope. However, as we show, we find results which agree with the more detailed studies we presented in chapter 2.

We perform space-time analysis on one year (1962) of hourly data for a set of 7 rain gages near the Hartford station in the New England region. The 7 stations used for the space-time analysis are: 3451, 3456, 4667, 6942, 6698, 8330 and 998; see figure 4.14 for their location. These stations are within a radius of 88 miles from Hartford station. For the space-time analysis, we divide the area covered by these seven stations into three regions of overlapping and increasing spatial extent. Region 1 covers two stations (3451 and 3456) and an area of approximately 600 mi²; region 2 covers four stations (3451, 3456, 6942 and 8330) over an area of 2800 mi²; region 3 includes all seven stations and covers an area of 24000 mi².

In order to carry out the space-time analysis, we need to estimate a response time for each of the three regions described above. This is done by transforming the spatial extent of each region to time scale by using a suitable celerity value. Support for this simplified transformation comes from the recent work of Deidda (2000) who performed space-time multifractal analysis on radar rainfall sequences and showed that space-time rainfall scaling is isotropic within spatial scale from 4 to 256 km and timescales from 15 min to 16 hours.

The response time T can be estimated as L/V where L is the stream length and V is the celerity. For the areas of regions given above, we assume celerity of 5 to 8 ft/sec and L is estimated by Hack's law as $0.5A^{0.5}$. This gives the response time as approximately 3, 7 and 14 hours for the three regions respectively. For each region, we average the rainfall over the number of stations covering that region. Then we perform moment scaling analysis corresponding to the response time of the region. For example, in region 1, we average the rainfall over 3 hour durations and then compute the moments. Results of space-time analysis are show in figure 4.15. Note the curvature of the $k(q)$ curve. Figure 4.16 is the same as figure 4.15 but it shows the estimation of parameter γ_1 . We can see from figure 4.16 that q_1 is about 3.0. Table 4.6 shows the parameters of this analysis and comparison with the point $k(q)$ curve parameter for the Hartford station, as presented in table 4.3. Strictly speaking, this comparison should be between the point rainfall for the year 1962 and not for the point rainfall series of 40 years as shown in table 4.6.

Table 4.6: Comparison of scaling parameters for rainfall space-time analysis

Rainfall Series	γ_1	q_1
Areal average	0.67	3.0
Point Rainfall	0.78	> 4.0

If we assume that rainfall in space-time is a locally stationary process with isotropic multifractality, then it can be shown (Veneziano and Furcolo, 2000) that the theory of point IDFs discussed earlier holds also for spatial IDFs. Therefore, the spatial IDF scaling parameters q_1 and γ_1 can be obtained from the moment scaling function $k(q)$ of spatial rainfall, in the same way as for temporal rainfall. Therefore, the key question is the assumption of isotropic scaling of rainfall in space-time. We discussed this issue in section 2.1.3 where we presented the two opposing views on the isotropic scaling of rainfall in space-time. Marsan et al. (1996) argue that scaling is isotropic in space but not in time. On the other hand, Deidda (2000) has shown by an extensive analysis of GATE rainfall that space-time rainfall scaling is isotropic within spatial scale from 4 to 256 km and timescales from 15 min to 16 hours.

Extension of point IDFs to areal IDFs

Now we discuss the extension of point IDFs to areal IDFs. When point catchment IDFs are used for catchments they are adjusted for the reduction in intensity over the area by the Areal Reduction Factors (ARF). In chapter 2, we discussed the background and the approaches which are used to derive catchment IDFs from point IDFs. It is important to note that the ARF depends on the catchment size, duration of the storm and the return period (Berndtsson et al., 1988). A set of ARF curves for catchments up to 400 mi² is shown in figure 4.17. This was prepared by the National Weather Service from a dense network of rain gages. This curve might be used if no other information about the regional ARF is available. Figure 4.18 shows 100-year and 2-year ARF at Chicago, Illinois. Figure 4.17 shows a comparison of various ARF values used in different regions of the world. This comparison plot shows different ARF values depending on the climate and location; for example, for U.K., the ARF value for a storm of 1 hour duration and 2-year year return period is about 0.44 for an area of 300 km².

Empirical formulas are widely used to determine ARFs. Leclerc and Schaake (1972) have expressed the relation shown in figure 4.17 as

$$K = 1 - \exp(-1.1D^{0.25}) + \exp(-1.1D^{0.25} - 0.01A) \quad (4.13)$$

where K is the ARF, D is the rainfall duration in hours and A is the area in square miles. Many other formulas exist which express the ARF as a function of area and rainfall duration.

Sivapalan and Blöschl (1998) have recently proposed a new method of deriving catchment IDFs (see section 2.2 for the details of the method). They applied their approach to two storm events in Austria: (1) a short, intense convective storm; and (2) a longer, synoptic storm. They found that for the convective storm (assessed to be a storm with return period of 1000 years) the ARFs are fairly low (~ 0.3) within 50 km^2 area. For the larger scale storm (of return period 1000 years) the ARF was about 0.75 at 3000 km^2 (figure 10, Sivapalan and Blöschl, 1998). Sivapalan et al. (1998) found the ARFs to decrease with increasing return period.

For our case, the availability of data for deriving spatial IDFs is limited because of the widely spaced rain gages and the missing data at certain stations. After doing a preliminary analysis, we chose a group of 5 stations where continuous data for 13 years (1955 to 1967) was available. The stations are: 3451, 3456, 5273, 6414 and 806 (see figure 4.14 for location of these stations). Since the original hourly rainfall time series is only 13 years long, we constructed a series from the five stations by pooling all the data into a single time series. Then IDF analysis was carried out on the constructed series. The results of the IDF for the Hartford station is shown in figure 4.20 and the IDF for the constructed series is shown in figure 4.21. The areal IDF is derived by averaging the rainfall intensity from the five stations; see figure 4.22 for the areal IDF. All the IDFs are shown for return periods of 2, 3, 5 and 7 years.

In order to compare the single-station point IDFs with the group of stations areal IDFs, we computed the ratios of the maximum rainfall intensities for different durations and return periods. Figures 4.23 and 4.24 shows the ratios of areal IDFs to point IDFs and the

ratio of areal IDF to constructed series. These ratios provide us with an estimate of the ARFs for this region for the particular duration corresponding to the response time of the areal extent under consideration. Note the peculiarly high ARFs for the return period of 7 years. This is a result of the sparse data set and localized nature of storms; a likely explanation is that an intense event of limited extent was captured at one station but not at the other stations. Figures 4.23 and 4.24 show that ARF decrease with return period for most cases but not all. Our analysis is limited as the rain gages are not located sufficiently close to guarantee averaging to give a representative rainfall.

As discussed earlier, under the assumption of isotropic scaling of rainfall in space-time, the spatial IDF scaling parameters q_1 and γ_1 can be obtained from the moment scaling function $k(q)$ of spatial rainfall in the same way as for temporal rainfall. Further analysis is required to verify this approach.

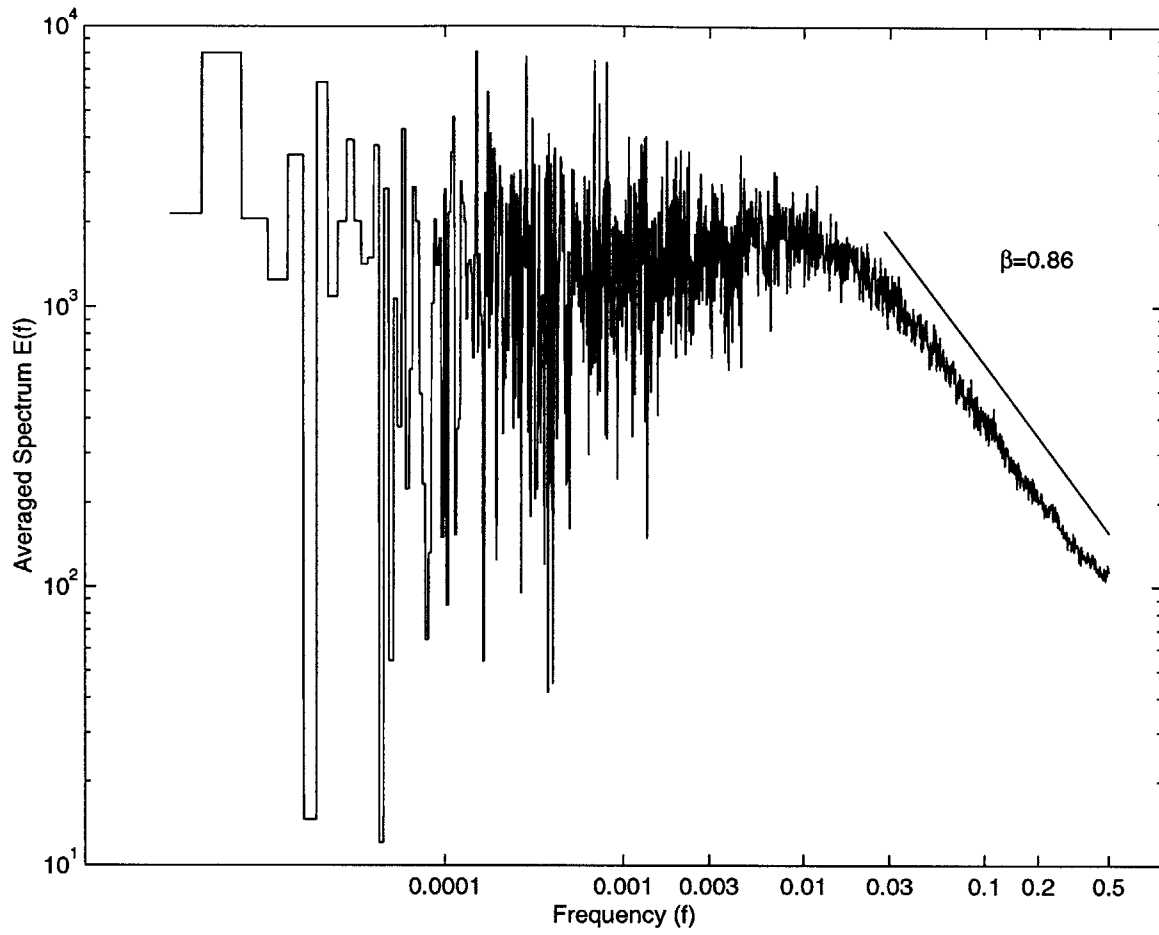


Figure 4.1. Spectral analysis for Hartford.

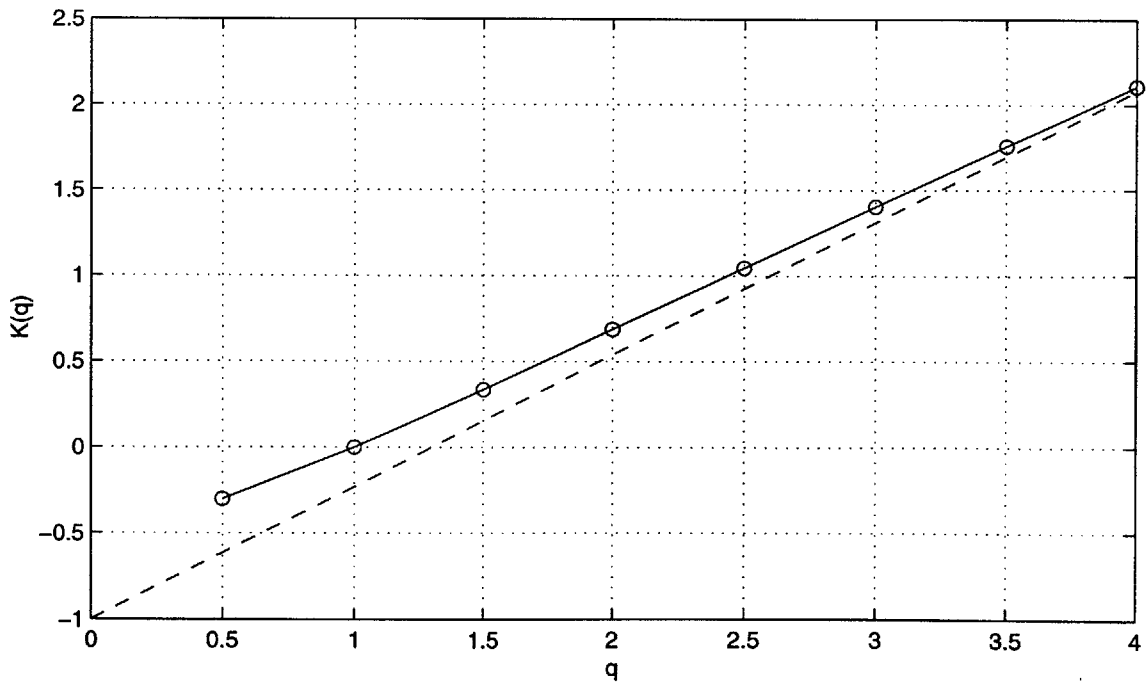
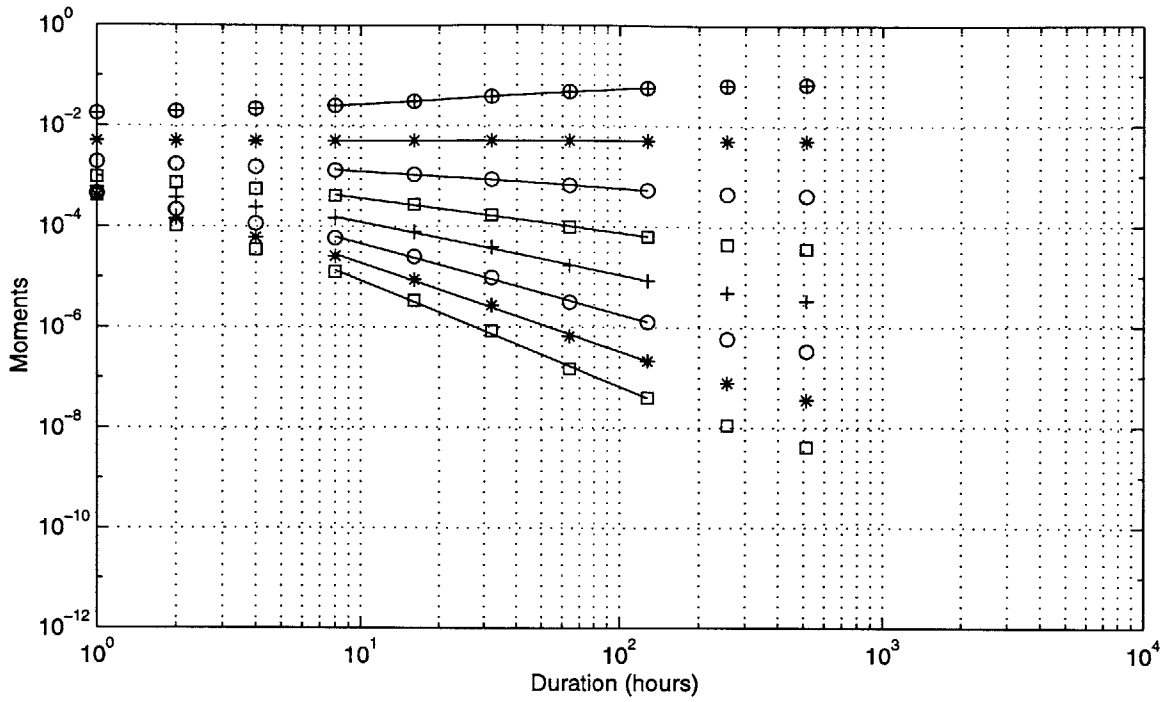


Figure 4.2. Multifractal analysis for annual series at Hartford (regression from 8-128 hrs). The moment order q (from the top) is 0.5 (circle and +), 1 (asterisk), 1.5 (circle), 2 (square), 2.5 (+), 3 (circle) and 3.5 (asterisk) and 4 (square).

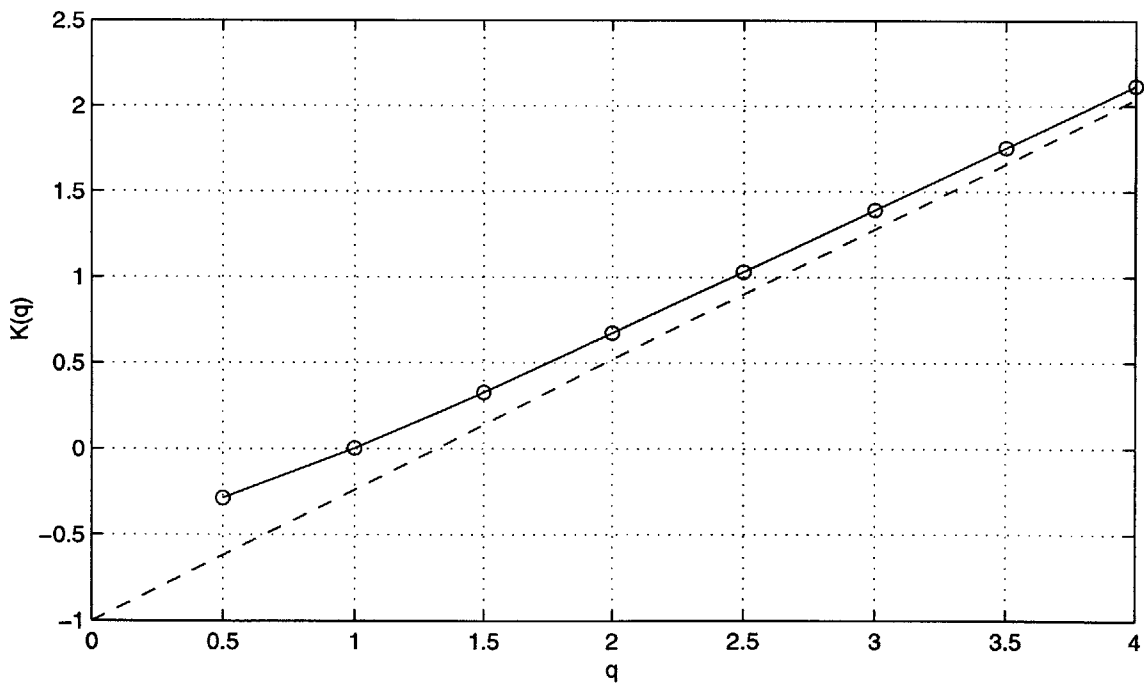
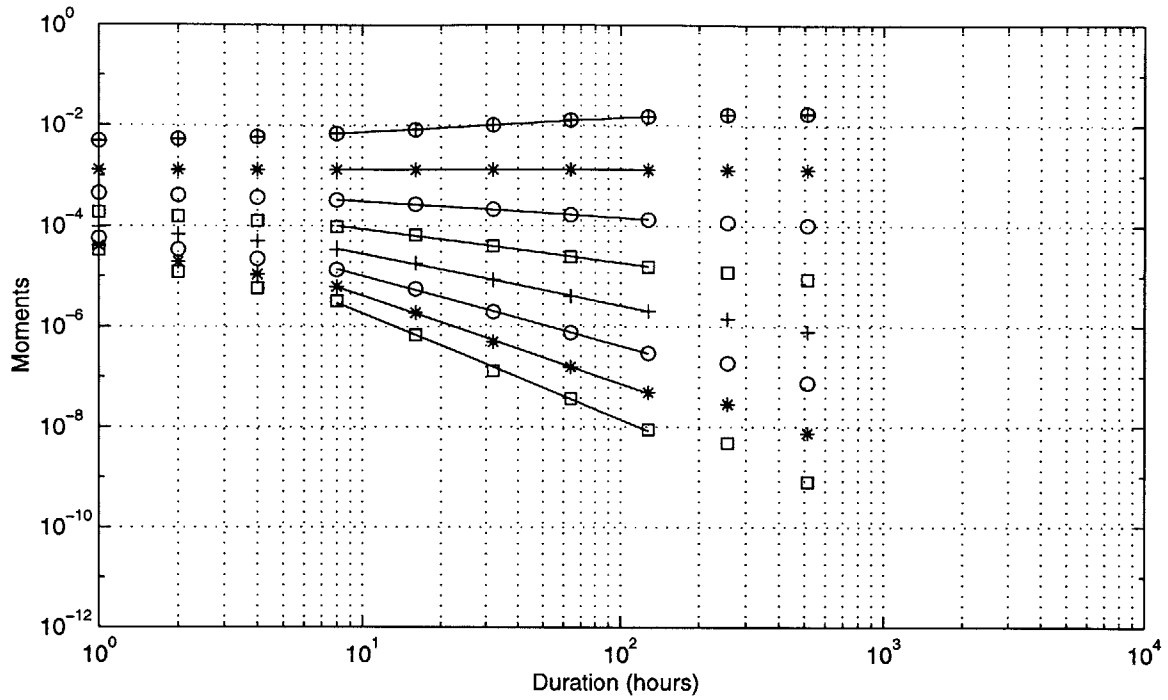


Figure 4.3. Multifractal analysis for season 1 (March, April, May) at Hartford (regression from 8-128 hrs). The moment order q (from the top) is 0.5 (circle and +), 1 (asterisk), 1.5 (circle), 2 (square), 2.5 (+), 3 (circle) and 3.5 (asterisk) and 4 (square).

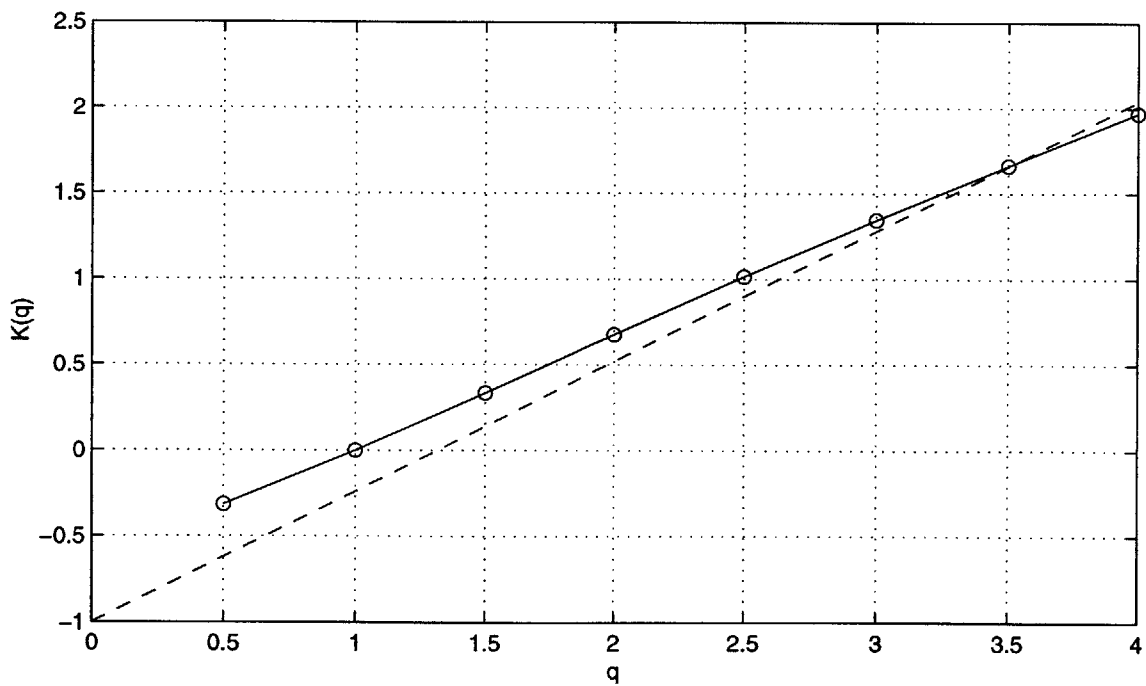
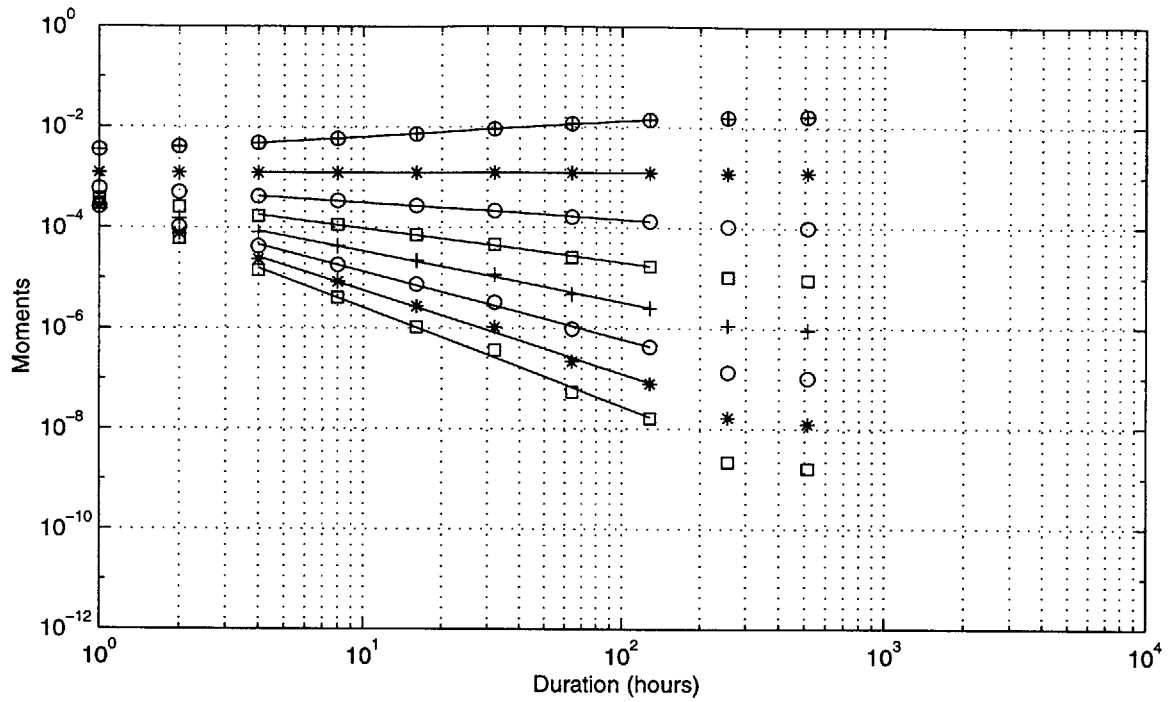


Figure 4.4. Multifractal analysis for season 2 (June, July, August) at Hartford (regression from 4-128 hrs). The moment order q (from the top) is 0.5 (circle and +), 1 (asterisk), 1.5 (circle), 2 (square), 2.5 (+), 3 (circle) and 3.5 (asterisk) and 4 (square).

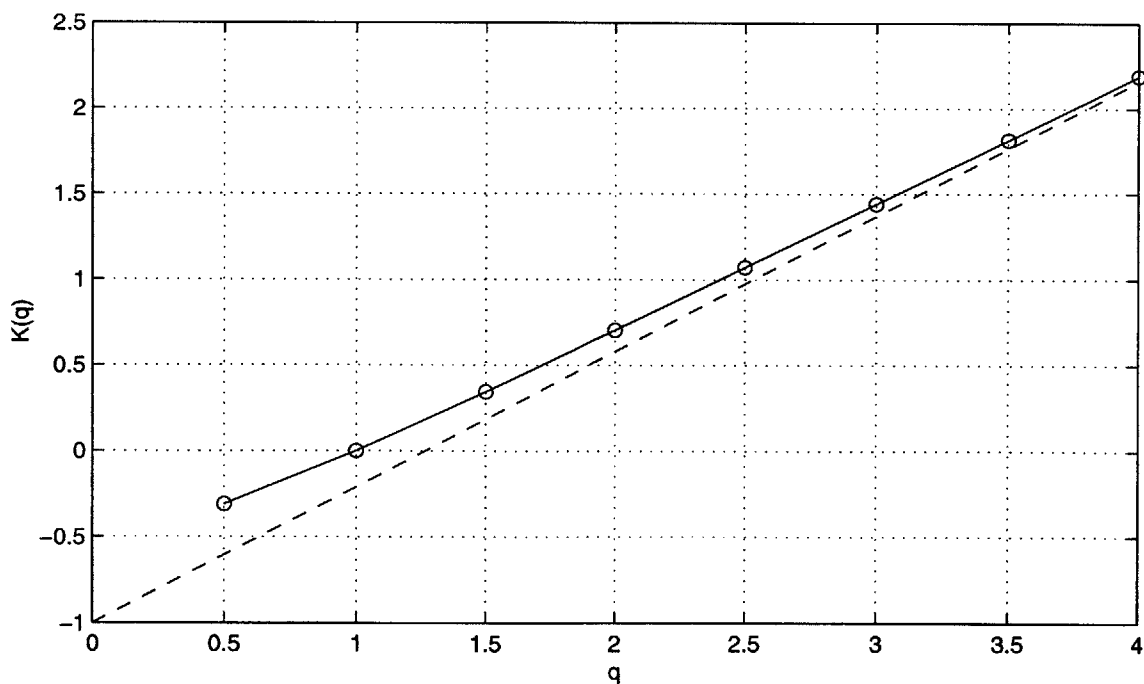
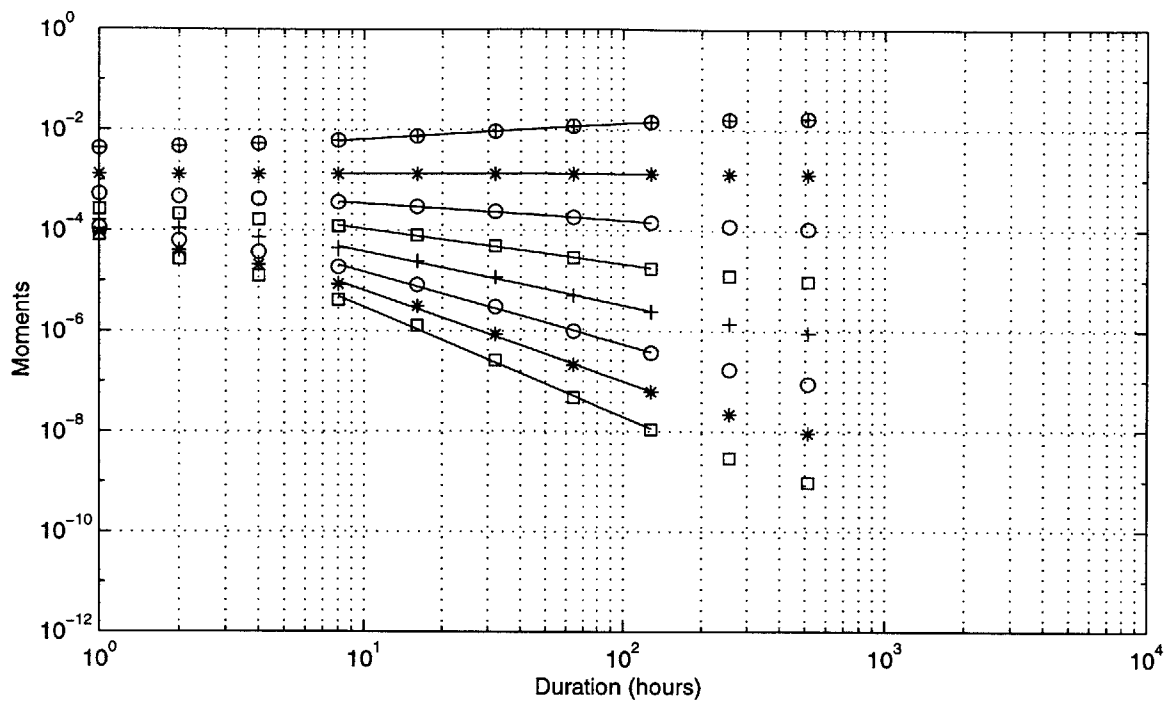


Figure 4.5. Multifractal analysis for season 3 (September, October, November) at Hartford (regression from 8-128 hrs). The moment order q (from the top) is 0.5 (circle and +), 1 (asterisk), 1.5 (circle), 2 (square), 2.5 (+), 3 (circle) and 3.5 (asterisk) and 4 (square).

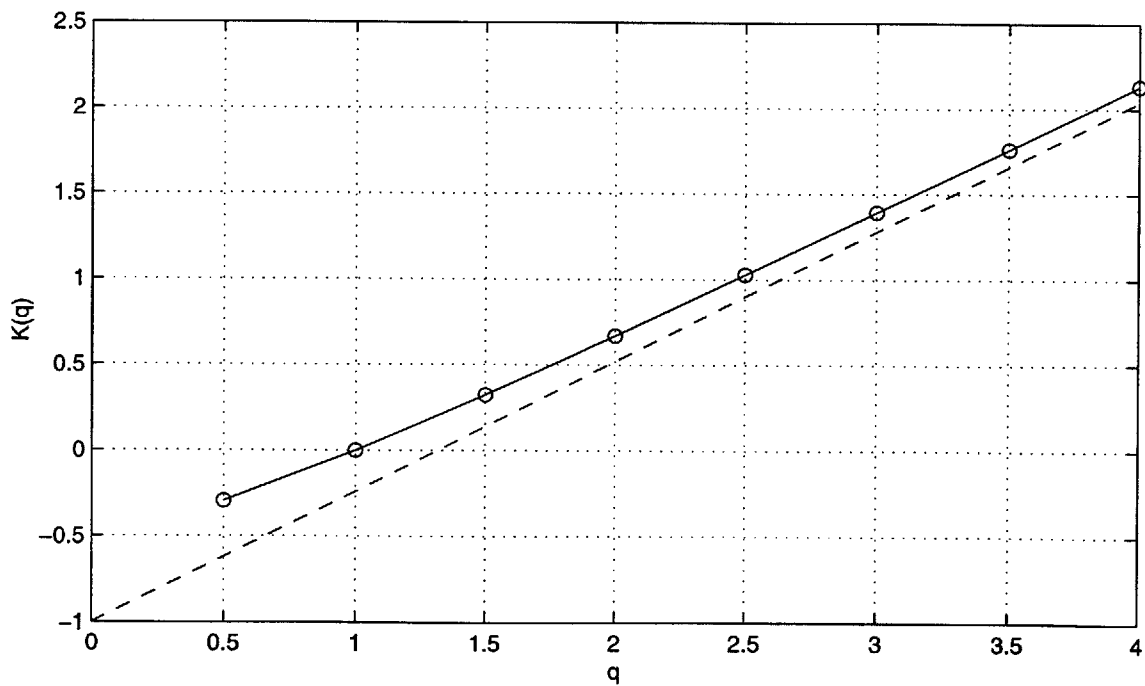
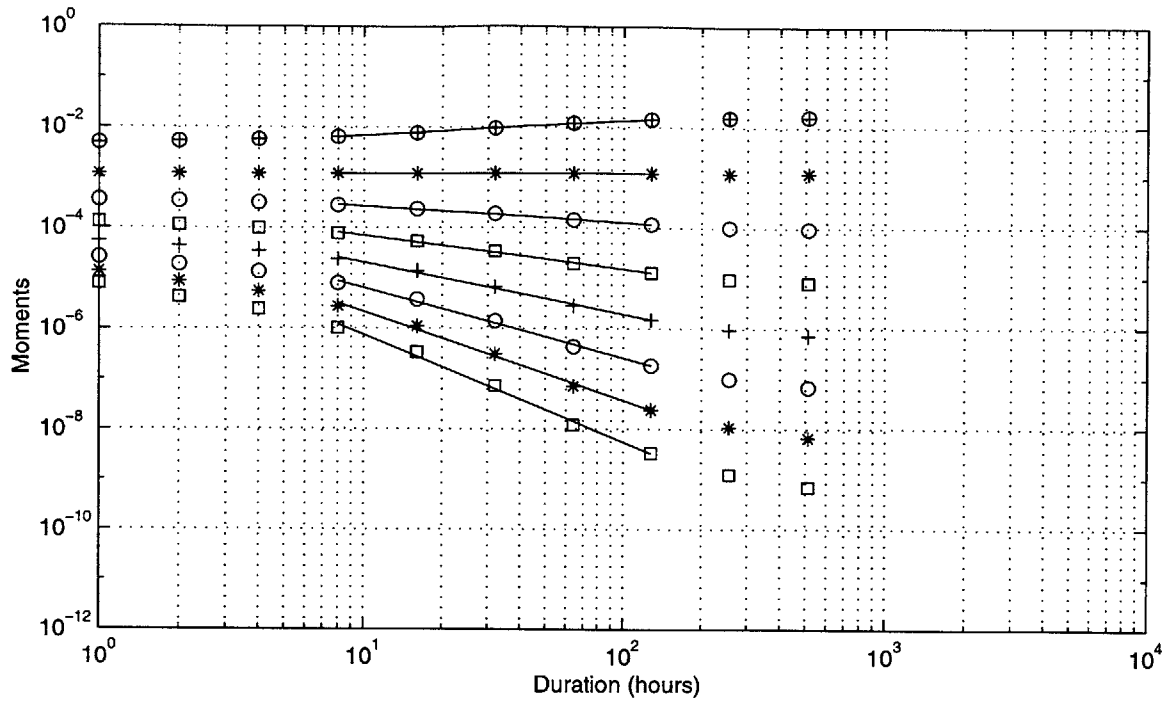


Figure 4.6. Multifractal analysis for season 4 (December, January, February) at Hartford (regression from 8-128 hrs). The moment order q (from the top) is 0.5 (circle and +), 1 (asterisk), 1.5 (circle), 2 (square), 2.5 (+), 3 (circle) and 3.5 (asterisk) and 4 (square).

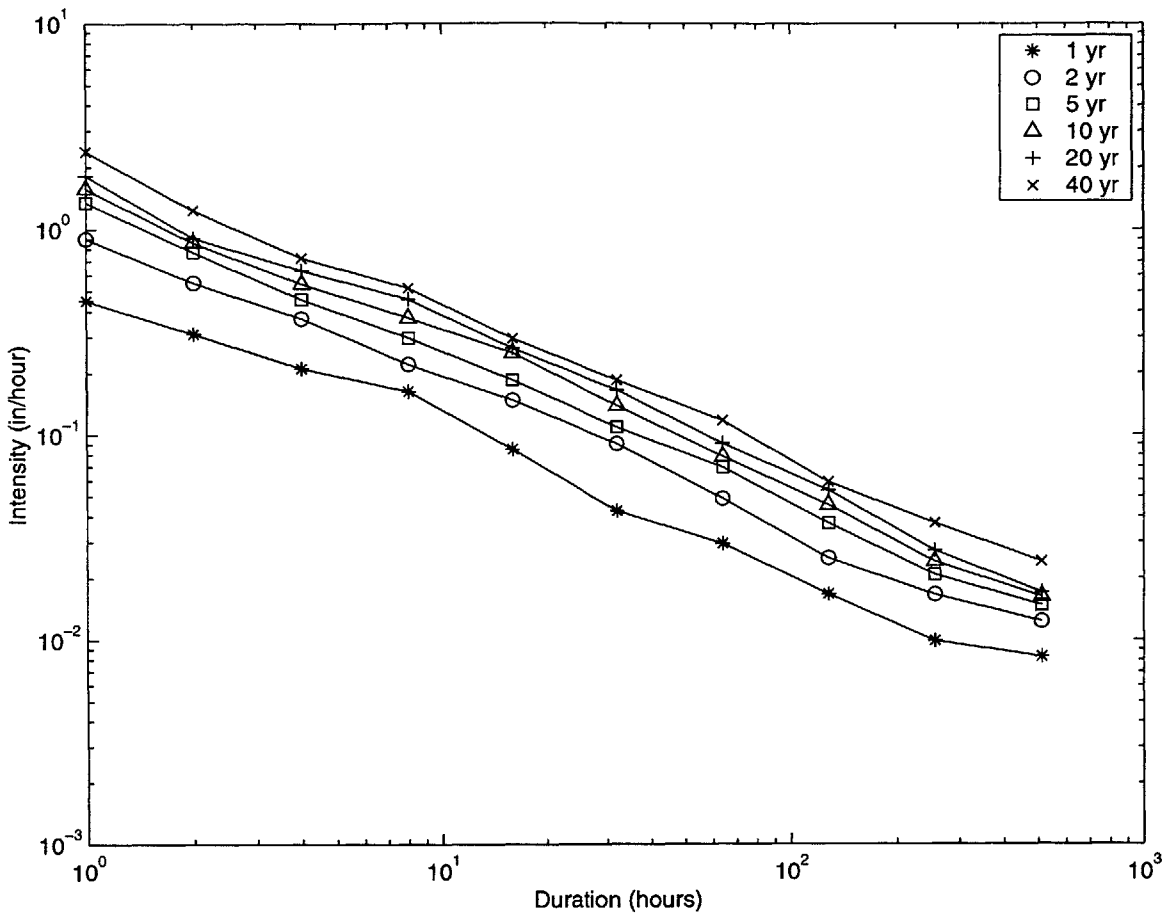


Figure 4.7. Intensity distribution frequency curve for T_1 .

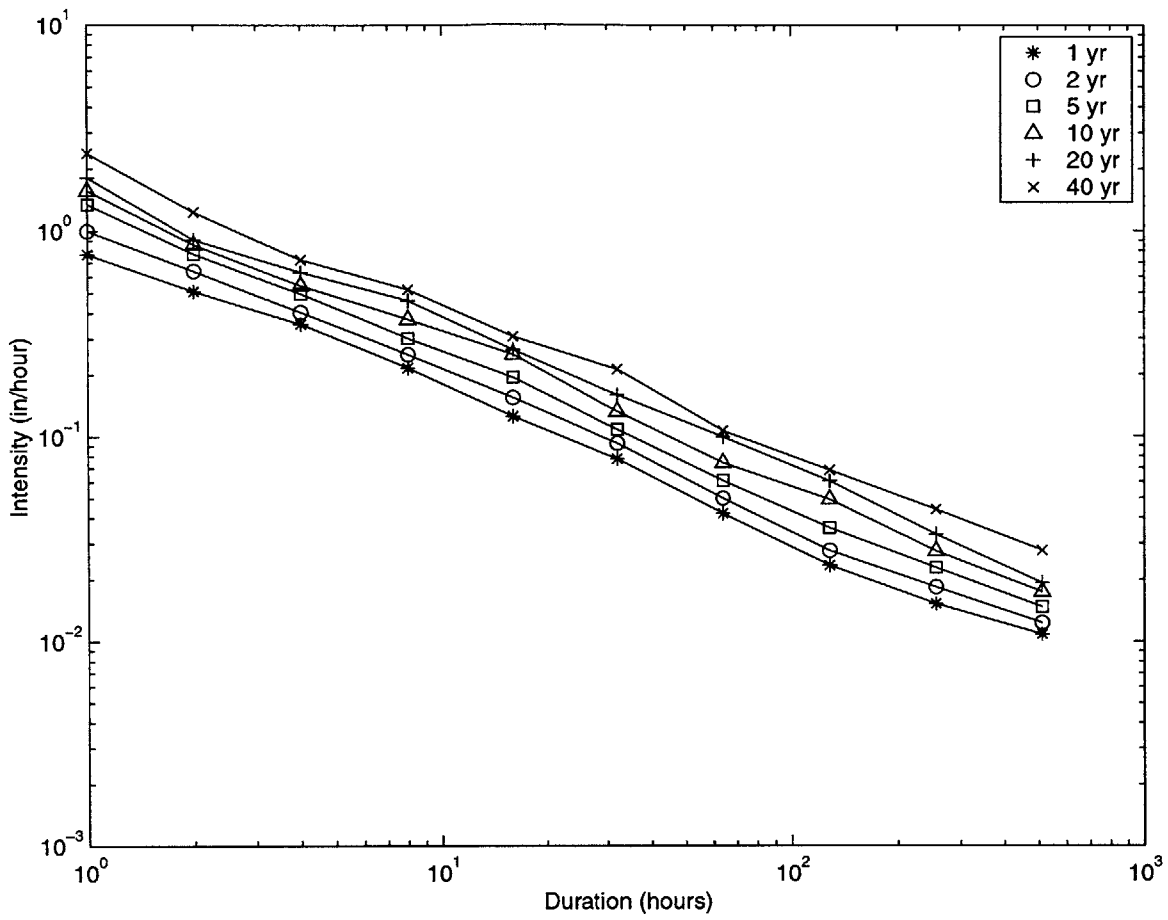


Figure 4.8. Intensity distribution frequency curve for T_2 .

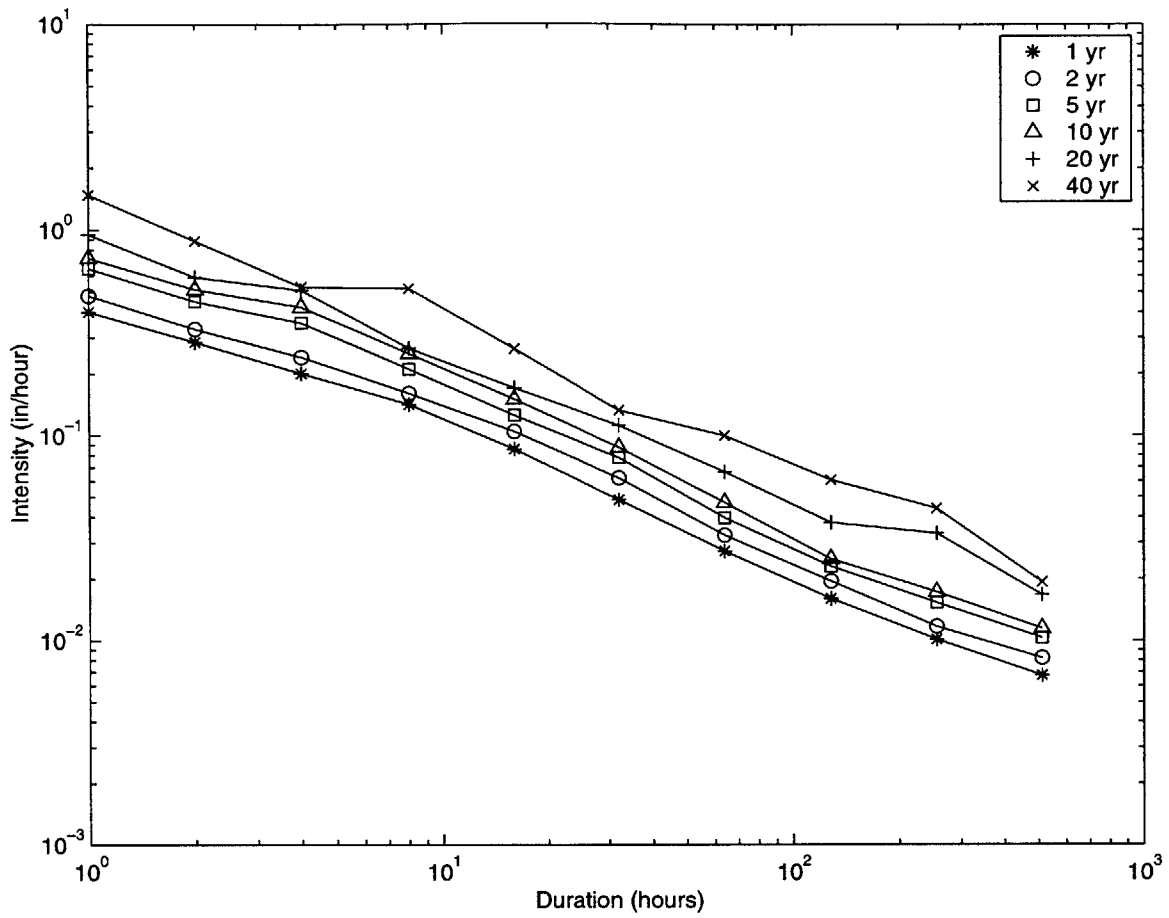


Figure 4.9. Intensity distribution frequency curve for season 1 (March, April, May) at Hartford (regression from 8-128 hrs).

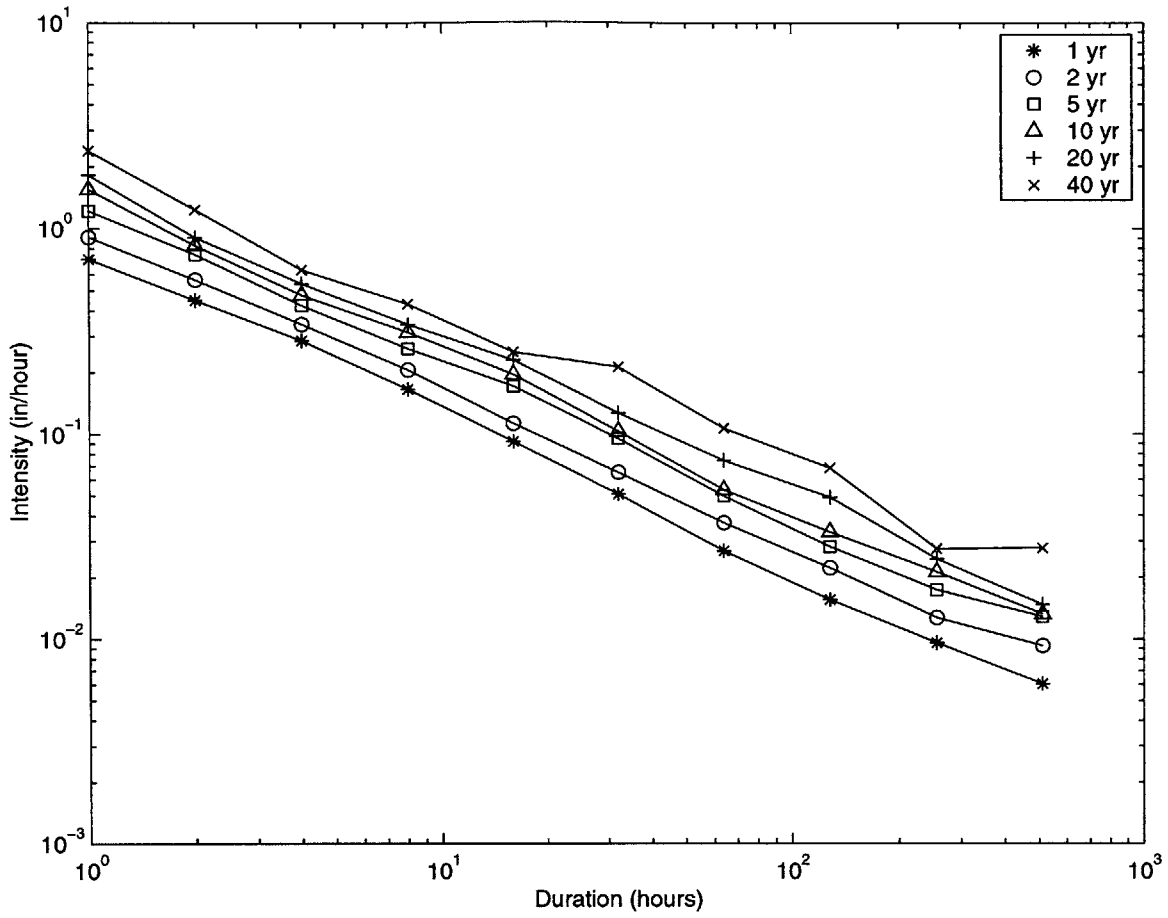


Figure 4.10. Intensity distribution frequency curve for season 2 (June, July, August) at Hartford (regression from 4-128 hrs).

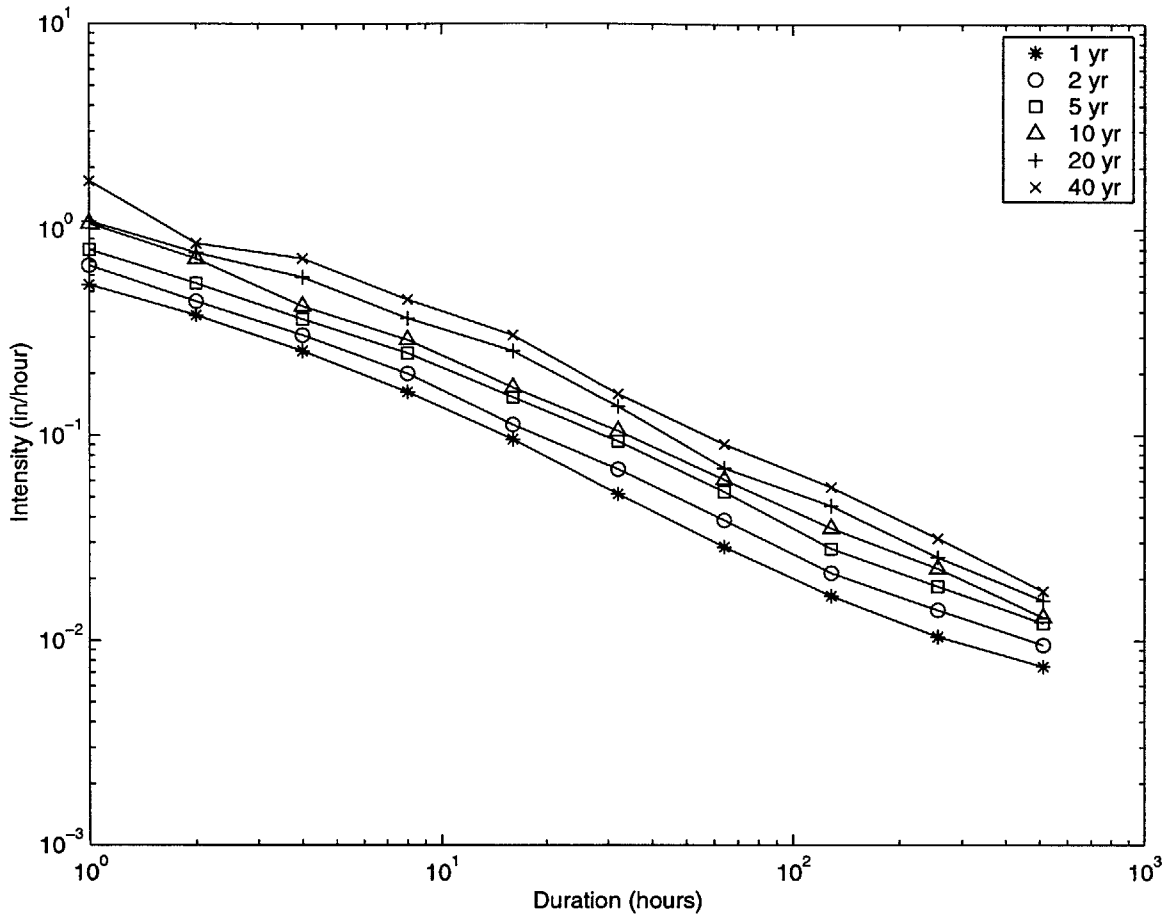


Figure 4.11. Intensity distribution frequency curve for season 3 (September, October, November) at Hartford (regression from 8-128 hrs).

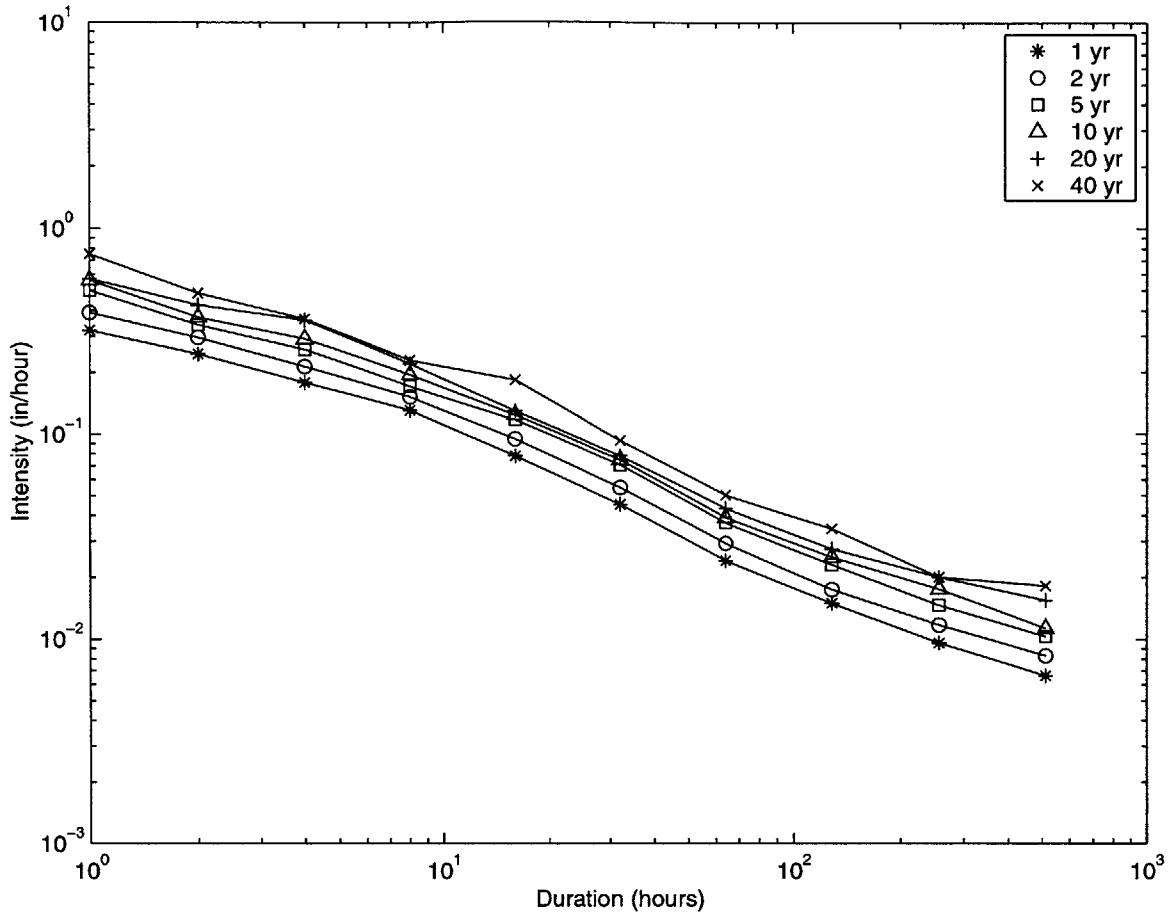


Figure 4.12. Intensity distribution frequency curve for season 4 (December, January, February) at Hartford (regression from 8-128 hrs).

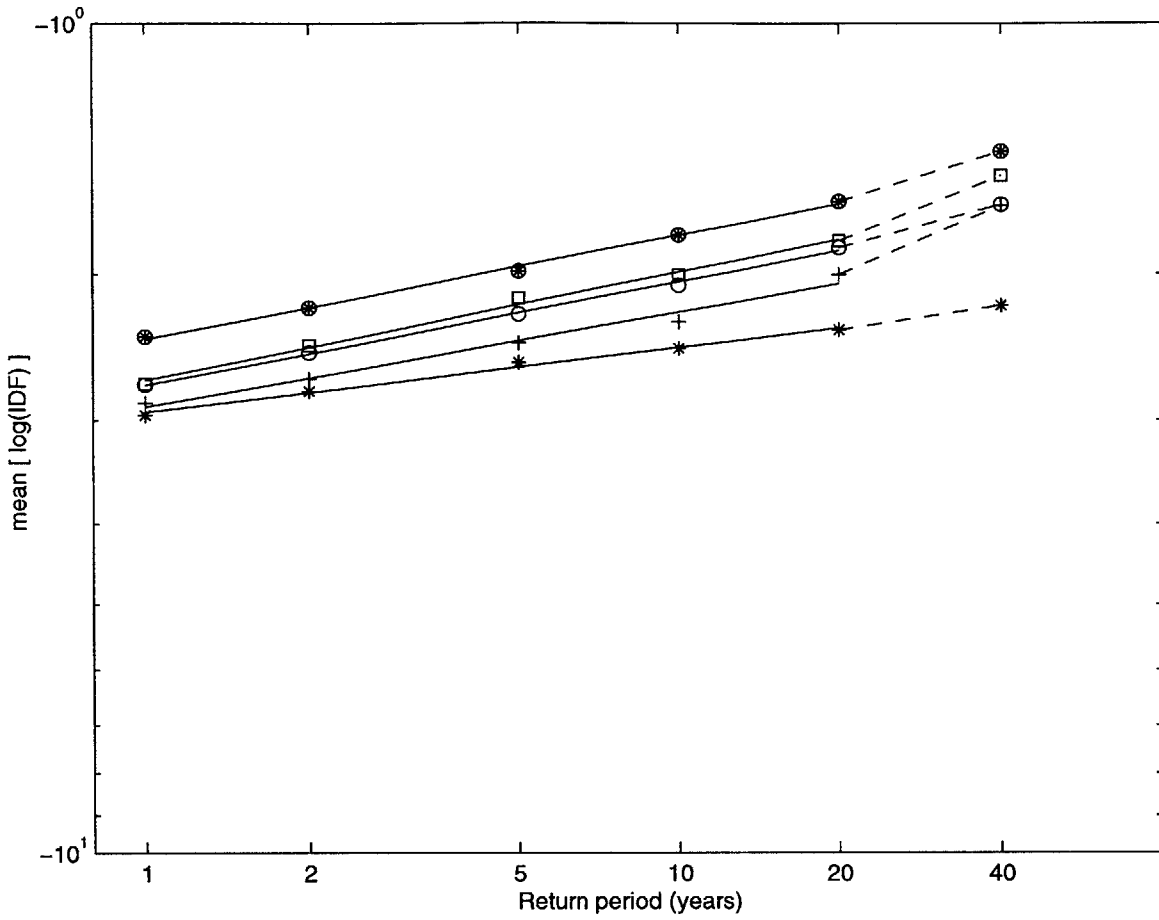


Figure 4.13. Relation between return period and mean of IDF. Circle with asterisk is for annual series (slope=0.12) , season 1 is asterisk (slope=0.11), season 2 is square (slope=0.13), season 3 is dot (slope=0.12) and season 4 is + (slope=0.08).

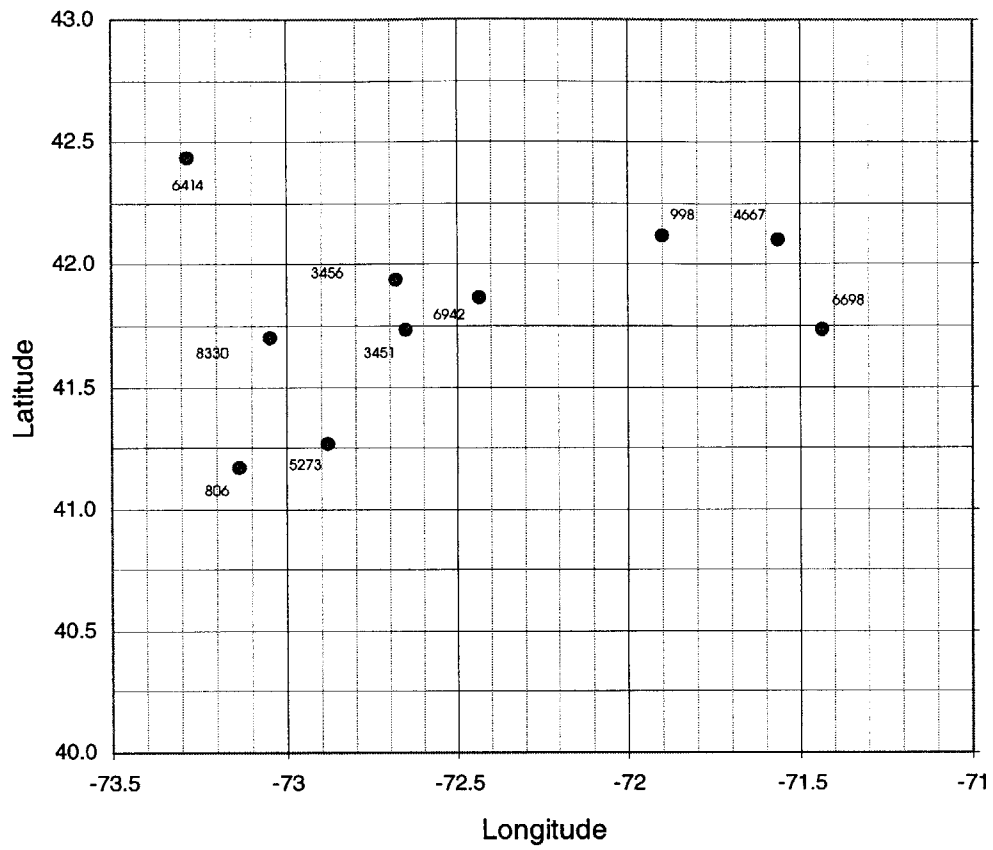


Figure 4.14. Rain gage location for space-time analysis.

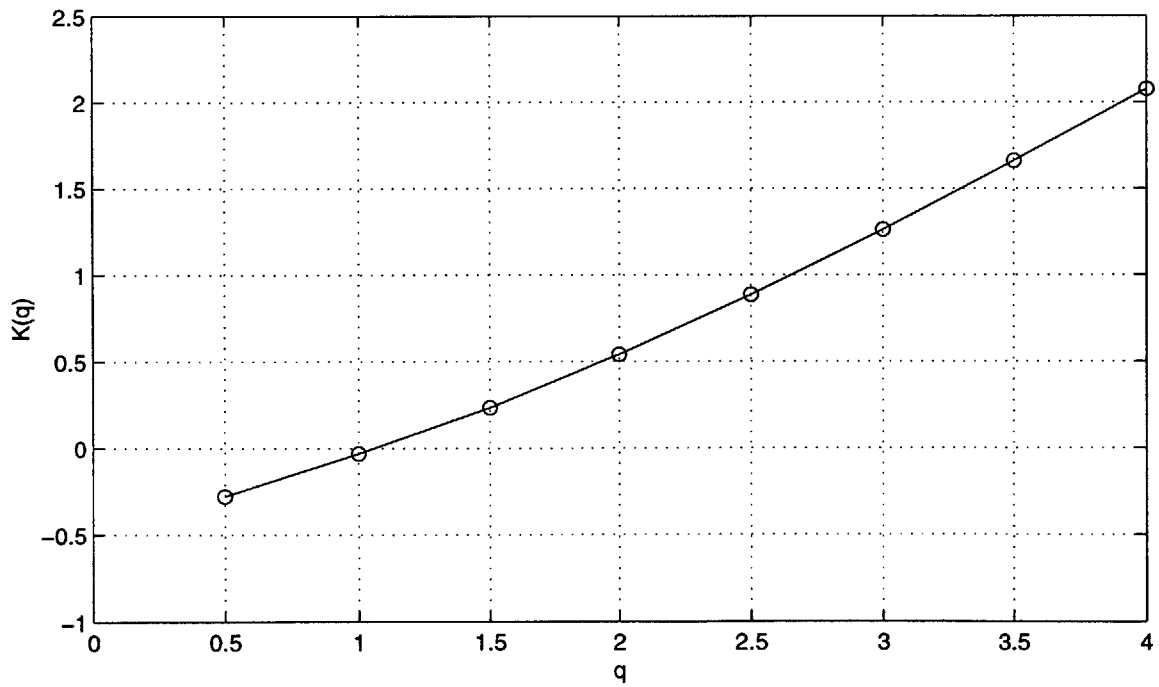
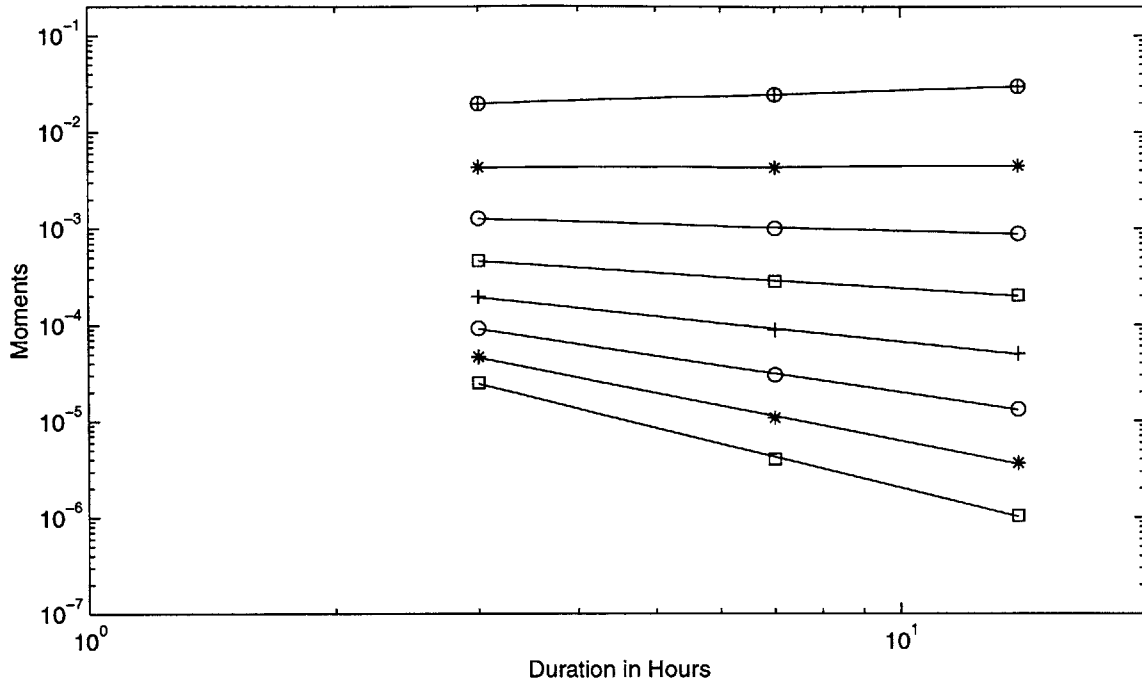


Figure 4.15. Space-time scaling for 7 stations.

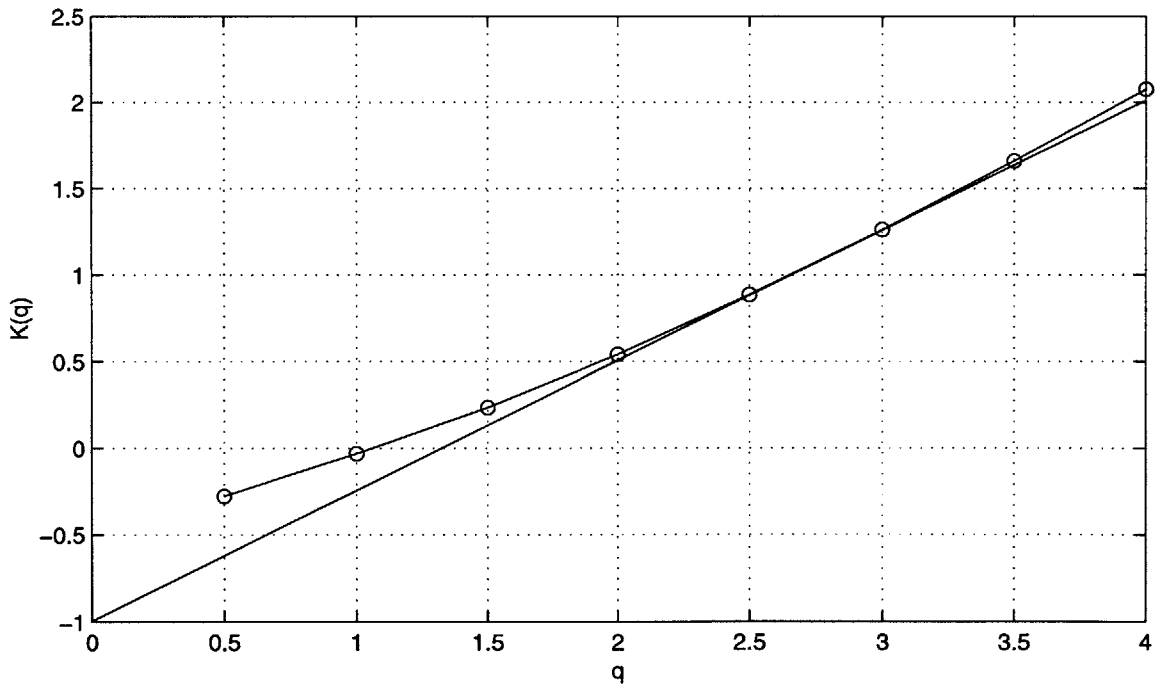
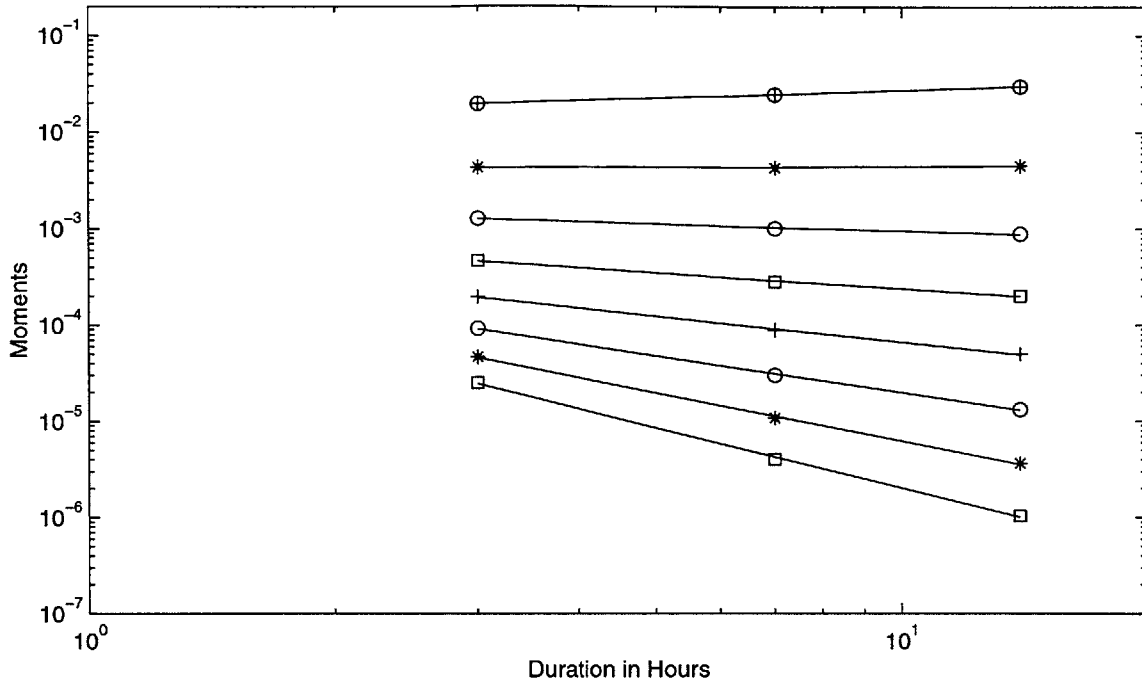


Figure 4.16. Space time scaling for 7 stations (estimate of γ_1).

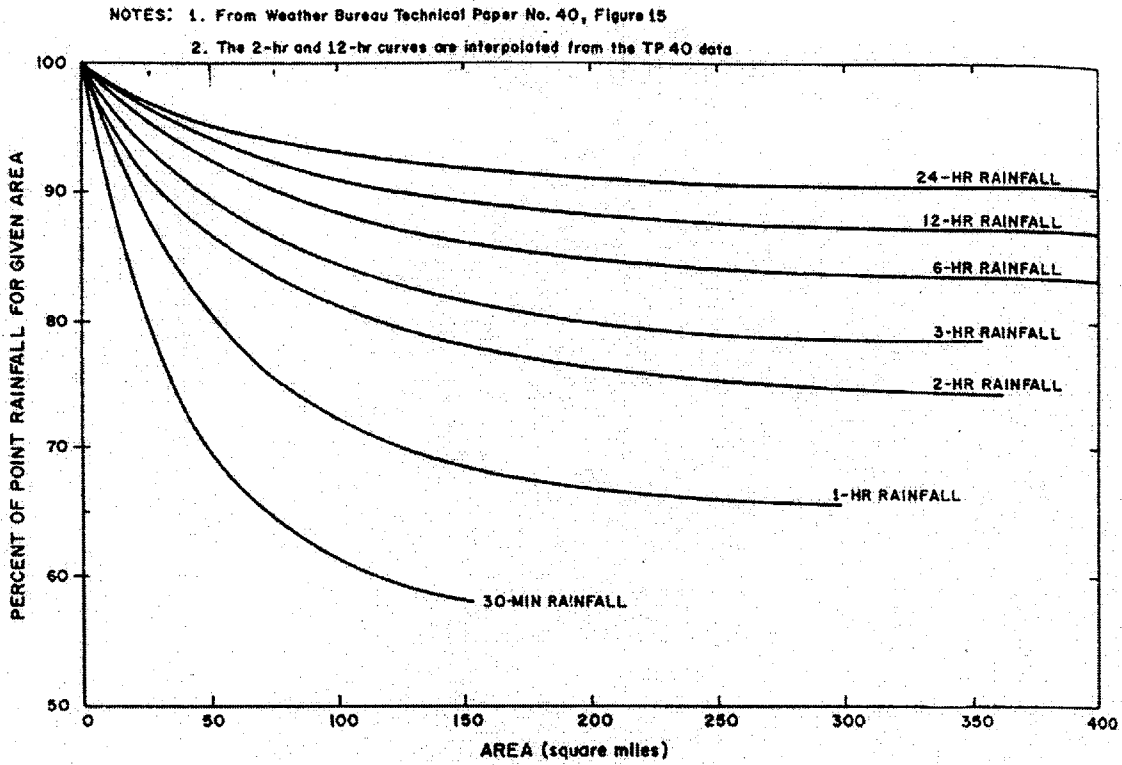


Figure 4.17. ARF based on Weather Bureau Technical Paper No. 40. This set of curve is used unless specific curves derived from regional analysis are available.

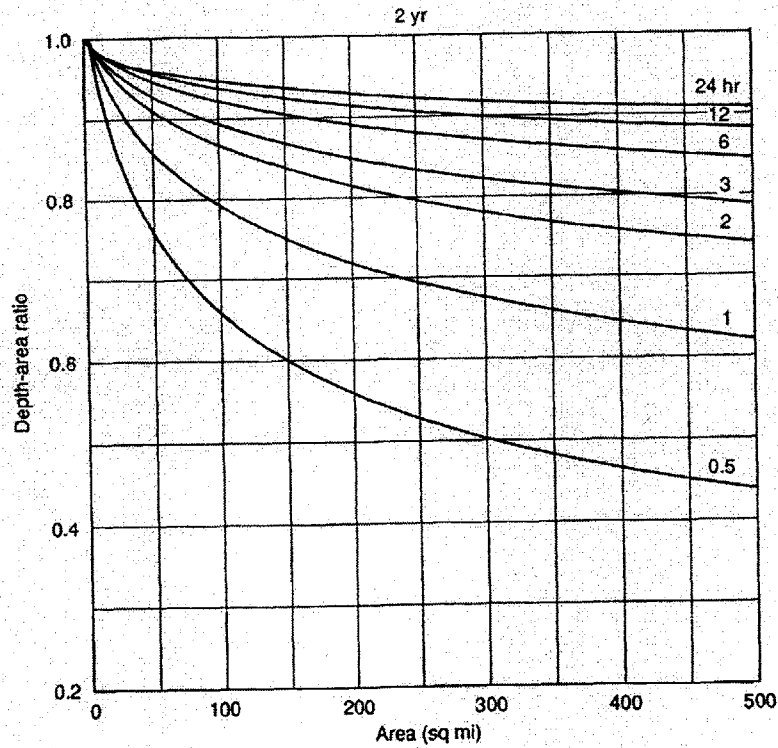
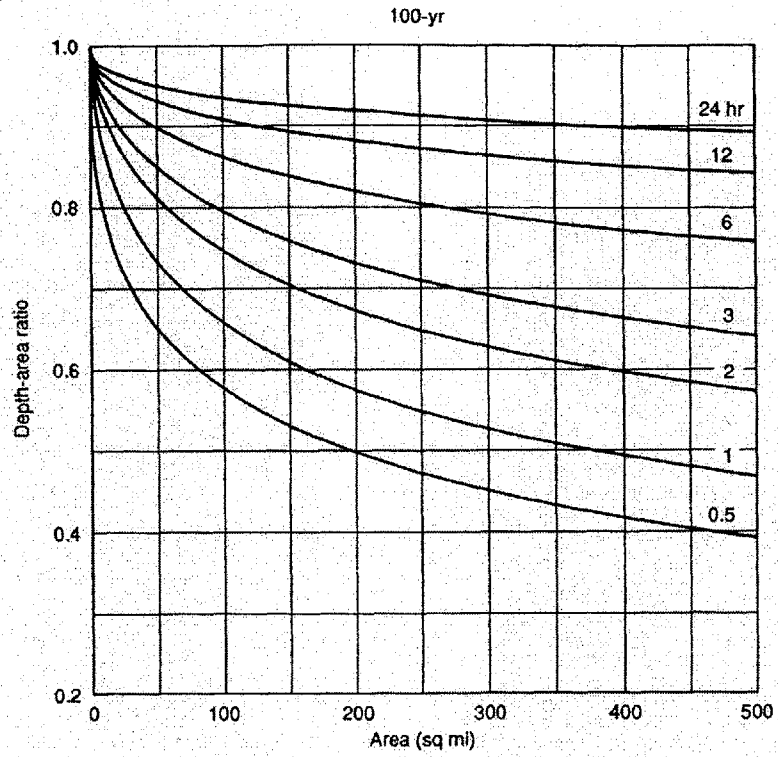


Figure 4.18. ARF for Chicago, Illinois by duration for 100- and 2-year return periods.

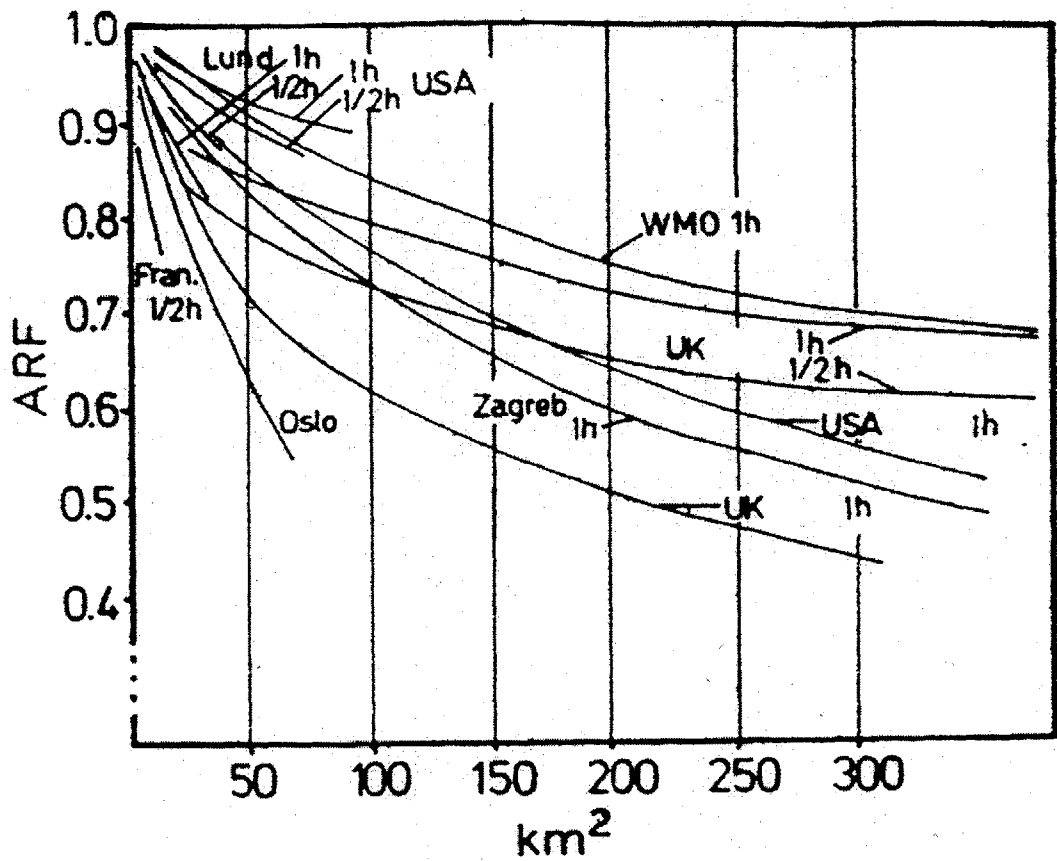


Figure 4.19. Comparison of depth-area relationships for different countries.
 Source: Berndtsson and Niemczynowicz, 1988.

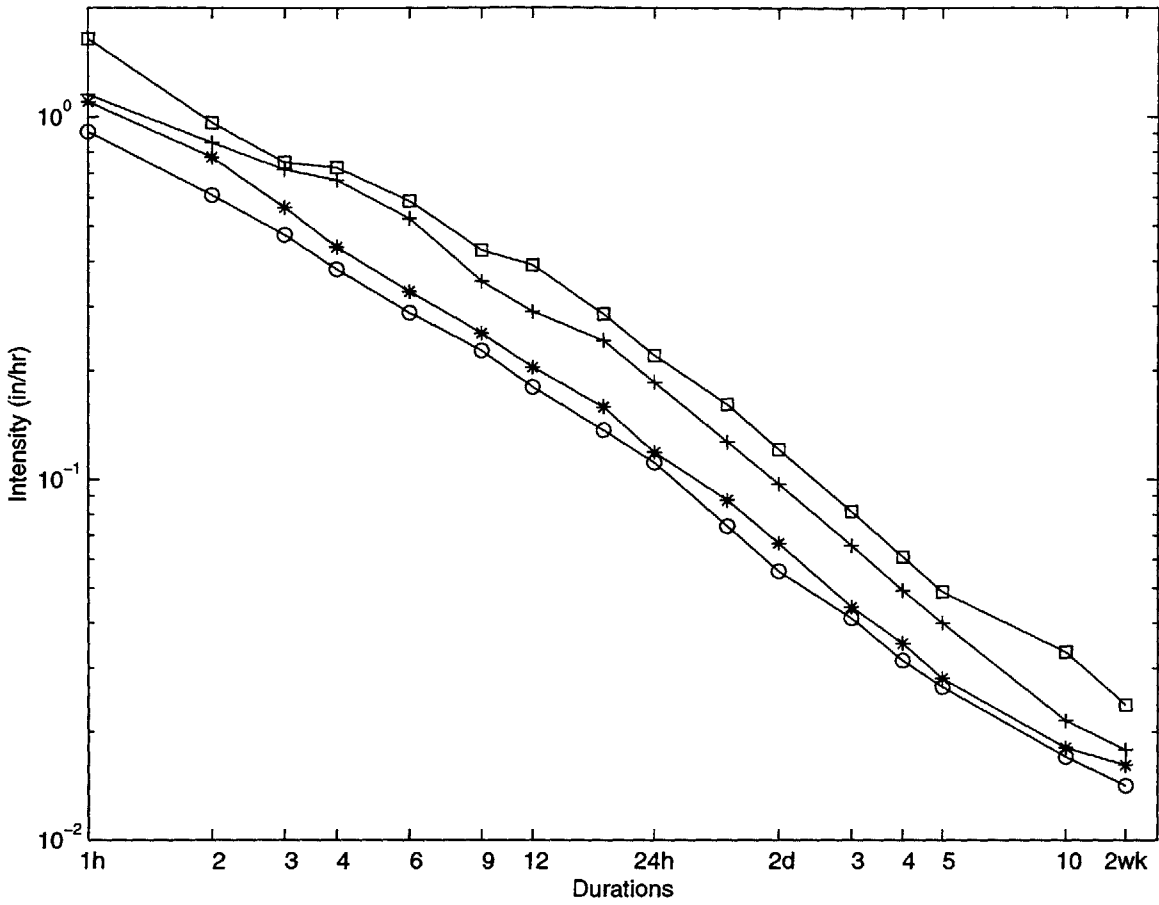


Figure 4.20. Scaling of IDFs for Hartford station, for return periods of 2 (circles), 3 (asterisks), 5 (+) and 7 (squares) years. The average slope is -0.77 for the range between 2 hours and 5 days.

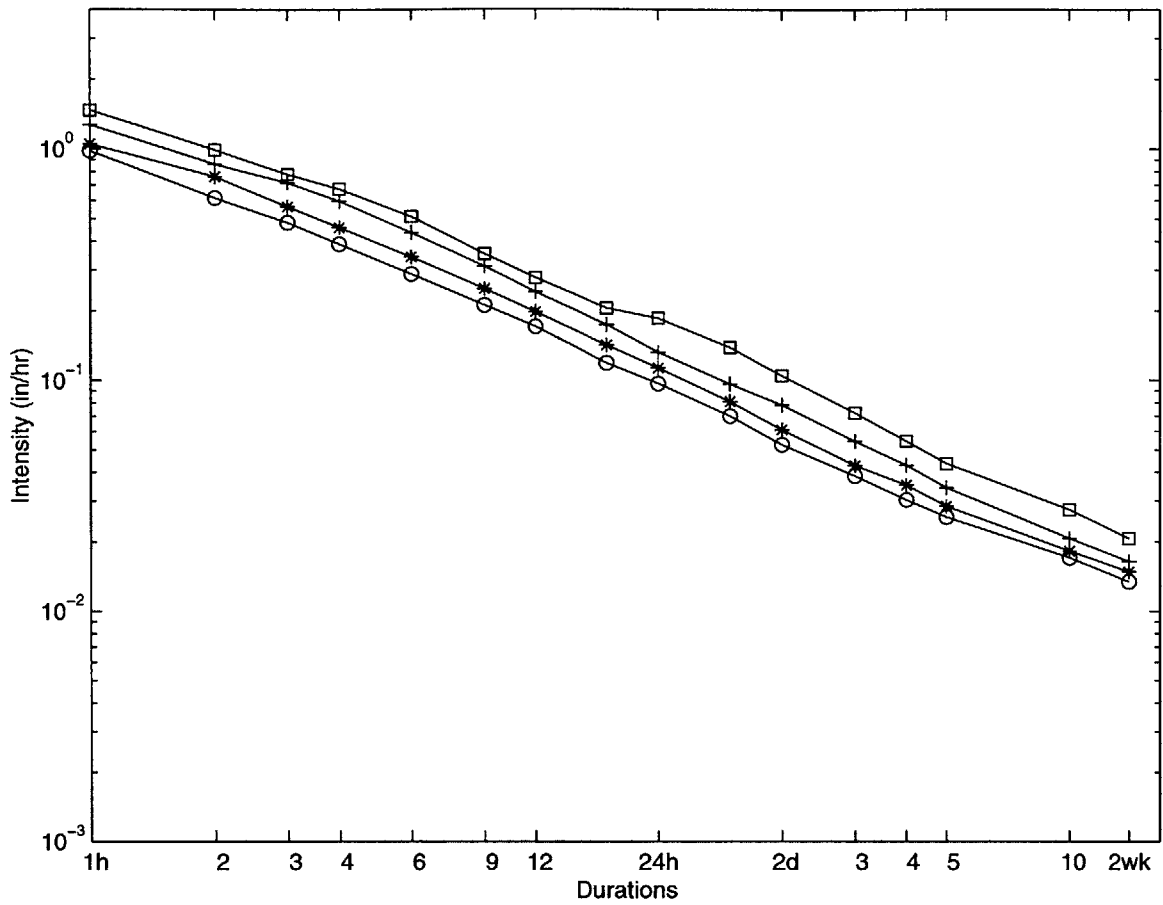


Figure 4.21. Scaling of IDF for the constructed series from 5 stations, for return periods of 2 (circles), 3 (asterisks), 5 (+) and 7 (squares) years. For the range between 2 hours and 5 days, the average slope is -0.79 .

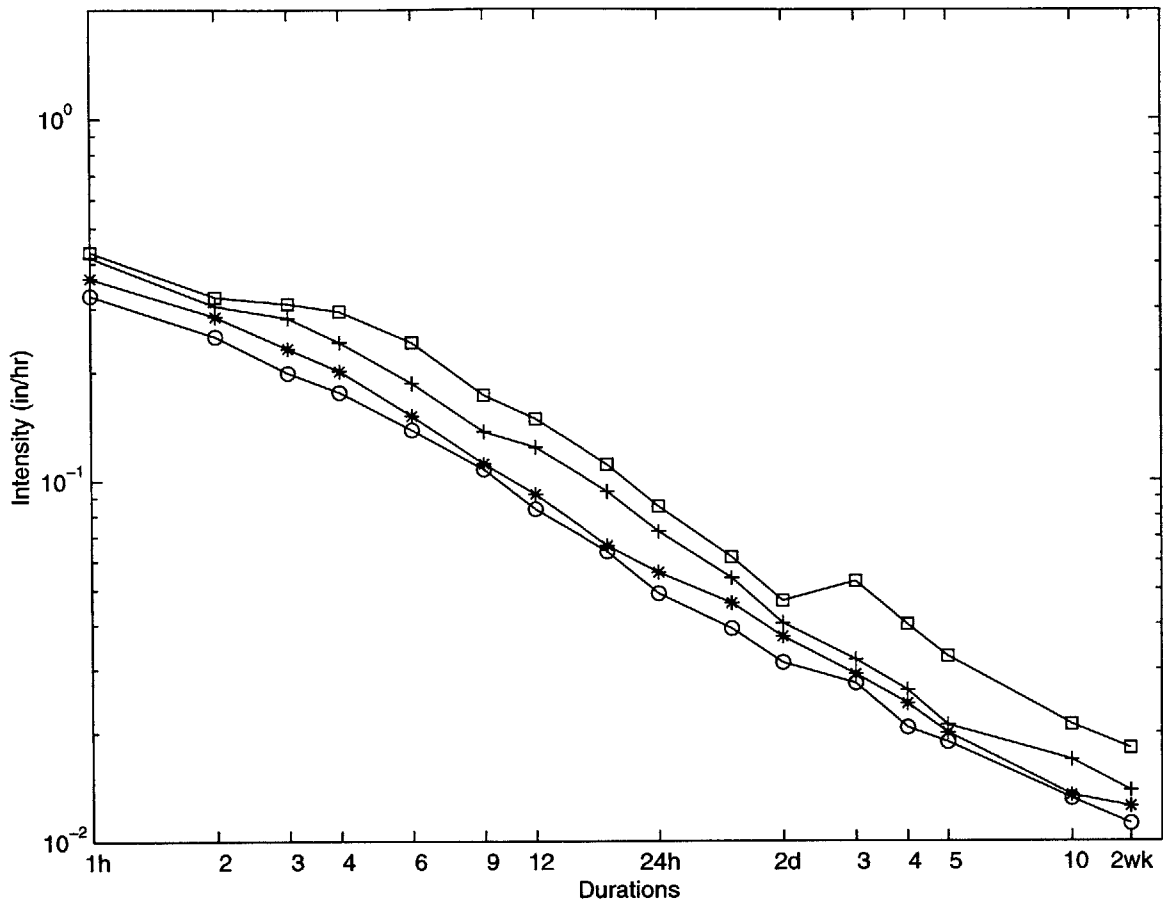


Figure 4.22. Scaling of areal IDF derived from average of 5 stations, for return periods of 2 (circles), 3 (asterisks), 5 (+) and 7 (squares) years. For the range between 2 hours and 5 days, the average slope is -0.65 .

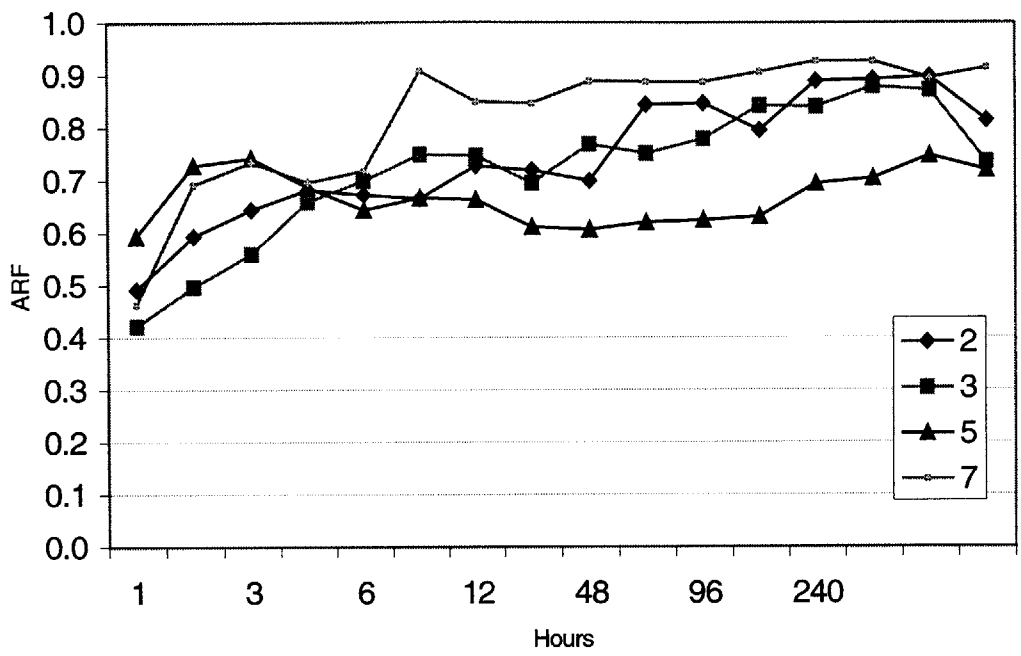


Figure 4.23. ARF for return periods of 2, 3, 5 and 7 years, obtained from the ratio of areal average IDFs (figure 4.22) and the IDF from single station (figure 4.20).

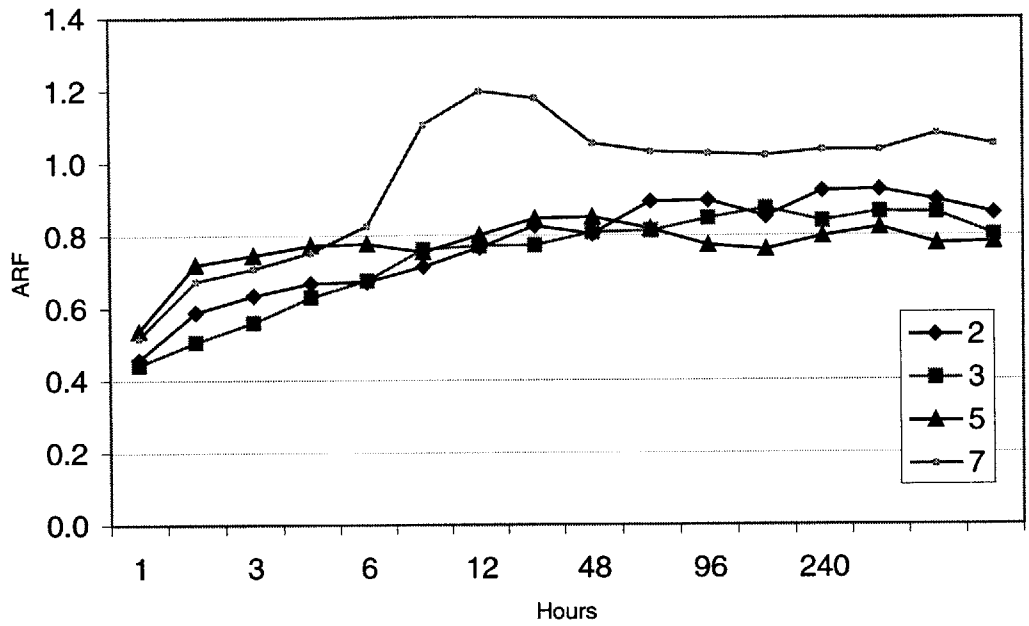


Figure 4.24. ARF for return periods of 2, 3, 5 and 7 years, obtained from the ratio of areal average IDFs (figure 4.22) and the IDF from constructed series of 5 stations (figure 4.21).

CHAPTER 5

Scaling of River Floods

5.1 Objective and Approach

The objective of this chapter is to investigate the relationship between scaling of peak flows and the scaling of rainfall and IDFs. This has practical applications for regional flood frequency analysis and prediction and the estimation of floods at ungaged basins.

We investigate the characteristics of peak flows scaling using a data set of peak annual flows from rivers distributed across the U. S. The United States Geological Survey (USGS), which operates under the Department of the Interior, U.S., operates a network of stream flow gages in the U. S. The USGS uses a classification system for hydrologic regions in the U.S. Such regions are called Hydrologic Units. We investigate the differences found in scaling exponent of flows for different Hydrologic Units and for small and large basins. We compare our results with the quantile regression method used by USGS.

Smith (1992) has observed that the coefficient of variation (CV) of peak annual flow in the Appalachian region varies non-monotonically with drainage area, having a maximum at an area of about 20 mi². A number of studies followed this observation (Gupta et al. 1994b; Robinson and Sivapalan, 1997) with alternative explanations for the

dependence of CV on drainage area and the processes controlling CV. We use our data set to investigate how CV of peak annual flows varies with drainage area for different regions.

We also aim to link the scaling of the IDFs to the scaling of peak flows. For this purpose, we use a variant of empirical rational formula and explain the dependence of the scaling exponent of peak flows on the scaling exponent of IDFs. We focus on the New England region and show that the model results in good fit with the empirical observations.

5.2 Regional Flood Frequency Analysis and Scaling of Peak Flows

Regional flood frequency analysis (RFFA) enables flood quantile estimates for any site in a region to be expressed in terms of flood data at other gaging sites in that region. Regionalization is useful for sites where at-site data are either unavailable or too short to allow for a reliable frequency estimate. For sites with available data, the joint use of data measured at a site and regional data from a number of stations in a region provides additional information. Regional homogeneity can be defined in a number of ways. The definition of regional homogeneity is dependent on which aspects of flood frequency behavior is considered to be homogeneous (Cunnane, 1988). One definition of homogeneity can be in terms of index flood. The USGS uses a quantile regression regionalization method. See section 2.3 for definitions and discussion of the index flood and the quantile regression methods.

The simple scaling concept corresponds to the index flood method of regional flood analysis. Thus, the index flood method can be justified if the annual floods exhibit simple scaling. USGS uses quantile regression approach for flood frequency studies for different states. Each state is divided into regions based on features such as topography and land use; then adjustments are made based on goodness of fit of the quantile regression equations in these areas. A recent study of homogeneous regions in Australia compared a number of current techniques for identifying homogeneous regions (Bates et al., 1998). This study indicated that geographical proximity alone may not be a reasonable indicator of hydrologic similarity. Gupta and Dawdy (1995) performed data analysis for 3 States in the U.S. and concluded that the rainfall generated flood peaks exhibit multiscaling and the snowmelt generated floods show simple scaling. Our preliminary data analysis of flood peaks from more than a thousand gaging stations in 15 regions of the US has indicated that flood peaks exhibit both simple and multiscaling.

5.3 Data

As mentioned earlier, USGS operates a network of stream gages in the U.S. The data for the USGS peak stream flow values was historically stored in the USGS WATSTORE database. Currently the access for data is through the USGS web site (<http://water.usgs.gov>). The web site provides historic and real time stream flow data. The peak flow data is available through National Water Information System (NWIS) page at (<http://waterdata.usgs.gov/nwis-w/US>). It is possible to search and retrieve data for a stream flow station by the station number or station location in a state, county etc. This provides a quick way to get data if one is interested in retrieving data for a small number of stations. However, it is inconvenient to retrieve data manually for a large number of stations. A Java applet and application was developed to retrieve,

process and save peak flow data from the USGS-NWIS web site, based on the preferences of the user (Bhatti, 1998).

The USGS follows the delineation of water resources regions set up by the Water Resource Council (WRC) in 1970. This was done to ensure consistent criteria for names, codes etc of hydrologic regions. The Water Resources Council developed a hierarchical classification of hydrologic drainage basins in the United States. Each hydrologic unit is identified by a unique hydrologic unit code (HUC) consisting of two to eight digits based on the four levels of classification in the hydrologic unit system . The first level of classification consists of 18 water-resources regions in the conterminous U. S.

Subsequent levels include 222 sub-regions, 352 accounting units, and 2150 cataloging units. This division is based on geographic considerations, that is, the drainage divides. These hydrologic regions are listed in table 5.1. In the analysis to follow, we use peak flow data from hydrologic units 1 to 15. We used the Java tool described above to retrieve peak flow data from 15 regions. There was some doubt about whether the flow in regions 16, 17 and 18 was completely free of regulation or not. Therefore we decided not to use the regions 16, 17 or 18.

Figure 5.1 shows the geographical location of these regions. Location of selected stations in region 01, New England, is shown in figure 5.2.

Table 5.1: List of Hydrologic Units

Region	Name
Region 01	New England
Region 02	Mid-Atlantic
Region 03	South Atlantic-Gulf
Region 04	Great Lakes
Region 05	Ohio
Region 06	Tennessee
Region 07	Upper Mississippi
Region 08	Lower Mississippi
Region 09	Souris-Red-Rainy
Region 10	Missouri
Region 11	Arkansas-White-Red
Region 12	Texas-Gulf
Region 13	Rio Grande
Region 14	Upper Colorado
Region 15	Lower Colorado
Region 16	Great Basin
Region 17	Pacific Northwest
Region 18	California

5.4 Analysis

To investigate if peak flows exhibit seasonality, we perform a frequency analysis of the time of occurrence of peak annual flows. Results of this analysis are shown in figure 5.3(a), 5.3(b) and 5.3(c). For example, in regions 2, 3, 5, 6, and 7, most peaks are in March; in regions 1, 4, 8 and 9, most peaks occur in April; in region 11, 12 and 13, May has the highest number of peaks; and for regions 10 and 14 most peak flows occur in June.

Figure 5.4 shows the scaling of moments for hydrologic regions 1 through 6. We can see that the condition of log-log linearity is well satisfied in all the regions. In figure 5.5, we show the plot of scaling exponents against the moment order for the hydrologic regions 1 to 6. The solid lines show the linear growth of the exponent for comparison with the actual growth of exponents. Similarly figure 5.6 shows the moments of peak flows for regions 7 through 12 and figure 5.7 shows the corresponding $k(q)$ plots. Figure 5.8 and 5.9 show the same for regions 13 to 15.

For some regions, for example hydrologic units 5 and 6, the growth of scaling exponents with the moment order is almost linear which indicates that peak flows in these regions exhibit simple scaling with basin area. For many regions, however, the slopes depend in a non-linear way on the moment order. The deviation of slope growth from linearity indicates that the peak flows are multiscaling (Gupta and Waymire, 1990). However, the deviations from linearity are for the most part insignificant. Gupta and Waymire (1990) noted the concave curvature of the slope growth of the multiscaling flows and interpreted it as a decrease in variability of flows with the scale. For our analysis, most of the deviations are also concave. We conclude that both simple and multiscaling can

occur in peak flows. However, the question is to explain the underlying reasons for the difference in scaling behavior in different regions.

The scaling exponents for the first moment of the 15 regions are summarized in table 5.2. The scaling exponents for the first moment range from 0.33 to 0.86. As we discussed in chapter 2, climatic factors have an effect on the scaling exponent (Dubreuil, 1986); for example dry or arid regions having a lower scaling exponent than humid regions. As described by Gupta and Dawdy (1995) and also discussed in section 2.3, we observe that regions with snowmelt generated floods (e.g., regions 1, 2, 13) tend to have higher scaling exponents. However, contrary to the argument of Gupta and Dawdy (1995), we find that there is no evidence that snowmelt generated floods per se cause simple scaling of annual peak flows.

Gupta and Dawdy (1995) studied the scaling between peak flows and basin area for three States in the U.S. These states have been subdivided in smaller regions by the United States Geological Survey (USGS) and the flood generating mechanisms in each region has been investigated and documented by the USGS. Let us consider the cases of New Mexico and Utah to illustrate the difference in scaling exponents from region to region and for comparing our results with those of Gupta and Dawdy (1995).

Region 14 is the Upper Colorado Region which includes parts of Arizona, Colorado, New Mexico, Utah, and Wyoming. Our analysis shows a scaling exponent of 0.60 for region 14. Gupta et al. (1995) analyzed the peak flows in 5 subregions of Utah (as defined by USGS) and found that for the subregions where snowmelt generated floods,

the exponents showed little variability with return period. For a flow with return period of 25 years (close to our average record of peak annual flows), they found exponents of 0.87, 0.73, 0.27, 0.68 and 0.37 in the 5 subregions. The average value of 0.58 is close to our result of 0.60 for the whole region 14.

Table 5.2: Result of moment scaling analysis

Region	Scaling exponent of moment order = 1
Region 01	0.80
Region 02	0.84
Region 03	0.58
Region 04	0.68
Region 05	0.71
Region 06	0.73
Region 07	0.57
Region 08	0.58
Region 09	0.61
Region 10	0.62
Region 11	0.45
Region 12	0.33
Region 13	0.86
Region 14	0.60
Region 15	0.55

Next, we focus on the scaling of peak flows in hydrologic unit 1 which is the New England region. Figure 5.4 shows the scaling of moments in hydrologic unit 1. The scaling exponent of the first moment of annual peak flow with drainage area is 0.8. Let us compare this exponent with the results from quantile regression method of USGS. In this method the USGS divides each state into homogeneous regions and each flow quantile is regressed against a set of basin descriptors which include watershed and climatic characteristics (for example, basin slope, precipitation of certain duration for various recurrence intervals, channel length etc). USGS calls these basin descriptors as the explanatory basin variables. Drainage area is the most important and some time, the only explanatory variable. For example, USGS uses the following equations for Merrimack River basin in Eastern Massachusetts: $Q_{25} = 96.71A^{0.651}$ and $Q_{100} = 143.1A^{0.638}$, where Q_{25} is the peak discharge with recurrence interval of 25 years, Q_{100} is the peak discharge with recurrence interval of 100 years and A is the drainage area (Jennings et al., 1994). In table 5.3, we list the exponents of Q_{25} with drainage area for different basins in New England as reported by USGS (Jennings et al., 1994).

Table 5.3: Scaling exponents from USGS defined basins in New England

Basin/State	Valid for	Scaling exponent
Connecticut	Drainage area >100 mi ²	0.87
Eastern Massachusetts	Drainage area < 260 mi ²	0.65
Central Massachusetts	Drainage area < 260 mi ²	0.78
Western Massachusetts	Drainage area < 260 mi ²	0.97
Maine	-	0.92

It has been argued that the first moment of the peak annual flows and their coefficient of variation are the two most important statistical descriptors of floods. We also investigated the relation between coefficient of variation of peak annual flows with drainage area. As discussed earlier, Smith (1992) had an interesting observation about the non-monotonic variation of CV with basin area. Bloschl and Sivapalan (1997) investigated process controls on CV of peak flows with basin size for 489 catchments in Austria. Robinson and Sivapalan (1997a) refer to the work of Bloschl and Sivapalan (1997) and comment that: "In view of the large amount of scatter in the relationship between $CV[Q]$ and catchment area A , one may choose to remain skeptical of Gupta et al. 's (1994) contention of a systematic relationship between $CV[Q]$ and basin area A ." Bloschl and Sivapalan et al. (1997) concluded that the behavior of CV should be explained by both rainfall and basin characteristics.

The results of our analysis for CV are shown in: figure 5.10 which shows CV of peak flow vs. basin area for all data; figure 5.11(a) which shows CV vs. area for hydrologic units 1-6; figure 5.11(b) which shows CV vs. area for hydrologic units 7-12; figure 5.11(c) which shows CV vs. area for hydrologic units 13-15; and figure 5.12 which shows the CV against peak flow/area. It is clear that a large scatter is present in all the plots. These figures show that CV vs. area plots do not (necessarily) show the type of non-monotonic behavior as Smith (1992) found in Appalachian basins. From figures 5.11(a), 5.11(b) and 5.11(c), we can see that in some regions (e.g., 1, 2, 3, 7) the CV has a maximum around an area of 100 mi². This is different from the maximum of CV at 20 mi² which Smith (1992) and Bloschl and Sivapalan (1997) found. Large areas (larger than 1000 mi²) tend to have low values of CV; intermediate areas (100-1000 mi²) show a large dispersion of CV. Small

areas (less than 100 mi²) tend to have low CV for most regions but not for all. Gupta and Dawdy (1995) have suggested that behavior of flood exponents in small basins is determined by basin response rather than precipitation input.

5.5 Relation Between Scaling of IDF and Scaling of Flows

We started with the objective of developing a unified and consistent framework for scaling of rainfall, IDFs and floods. In chapter 4 we showed how the scaling of the IDF curves is related to the scaling exhibited by rainfall.

We use a modified form of the probabilistic rational formula to study the dependence of flows on rainfall intensity, duration and the time scales of flows. The rational formula can be written as:

$$Q = cIA \quad (5.1)$$

Where c is a runoff coefficient, I is the rainfall intensity in space (which can be obtained by point IDF and ARF) and A is the drainage area. In section 2.3 we discussed that Pilgrim (1982) showed by data analysis that the loss (inverse of runoff coefficient) does not change with drainage area.

From the IDF analysis we can write

$$I \propto D^{-\theta_1} \quad (5.2)$$

where D is the duration which is a function of the drainage area and I is the intensity for the area A . We will discuss more about the approaches to estimate the areal IDF later.

For basins larger than 50 mi^2 , overland flow time is dominated by the channel travel time. Therefore to find the response time of the basin, we need to find the channel travel time as a function of basin area. The travel time in the main channel of length L is given by,

$$D = \int_0^L \frac{dl}{V(l)} \quad (5.3)$$

where $V(l)$ is the celerity in the channel at length l . the length of the main channel is given by Hack's law, that is,

$$L = k_1 A^{0.5} \quad (5.4)$$

where k_1 is a constant and depends on the units used.

Bras (1990, p588) has given relationships between velocity and discharge as,

$$V = KQ^m \quad (5.5)$$

where m is an exponent the value of which varies from 0.1 for semi-arid regions to 0.34 otherwise.

Since we have

$$Q(l|A) = A^{1/2} Q(A^{-1/2}l, 1) \quad (5.6)$$

$$V(l) = l^{2m} V(1) \quad (5.7)$$

Substitute (5.8) into (5.3) to get

$$D = \frac{1}{v(1)} \int_0^L \frac{dl}{l^{2m}} \quad (5.8)$$

Solving (5.9) gives

$$D \propto A^{1/2-m} \quad (5.9)$$

Using (5.10) we can go from a point IDF which is a function of D and return period T, to the areal IDF which is a function of area A, D and T.

In chapter 4, we discussed an approach to estimate the areal IDF scaling. There we discussed that if rainfall scaling is isotropic in space-time then the same procedure can be used to get the scaling for areal IDFs as we used for scaling of temporal rainfall. This method assumes that $m = 0$ in (5.9). If celerity is not constant, i.e., $m \neq 0$, then we can convert the point IDF to areal IDF for the duration obtained from (5.9) using appropriate ARF values. Once we have the spatial IDF then we can assume that the flow is also given by the same A and T as that of rain in space and time and use (5.1) to estimate the flow.

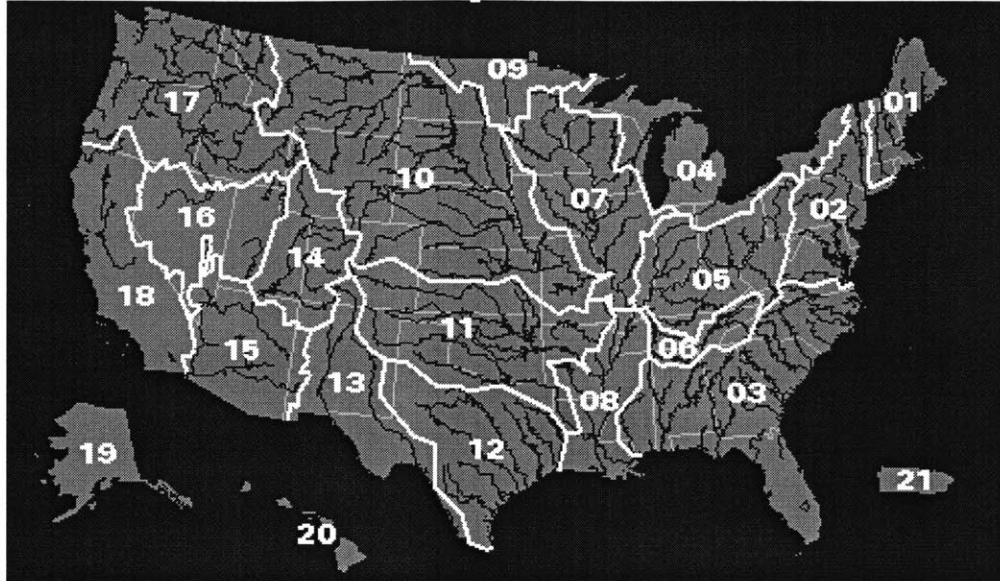


Figure 5.1 Hydrologic Units for the U.S.

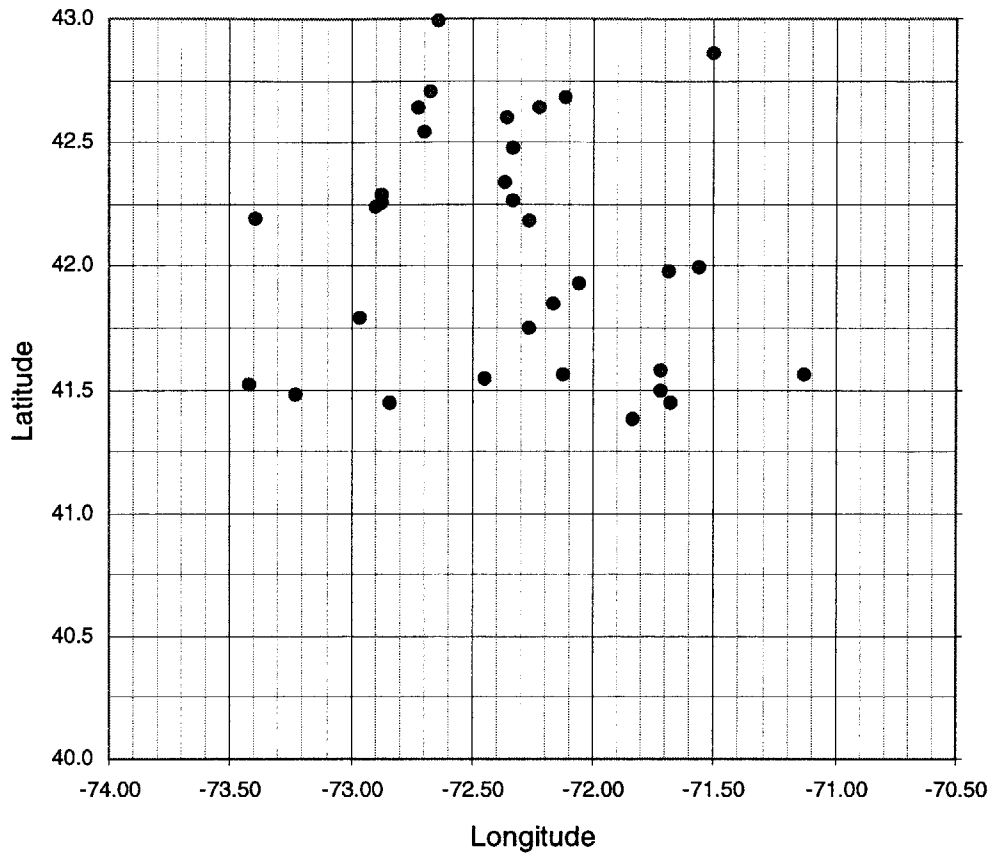


Figure 5.2. Location of selected stream flow gages in New England region.

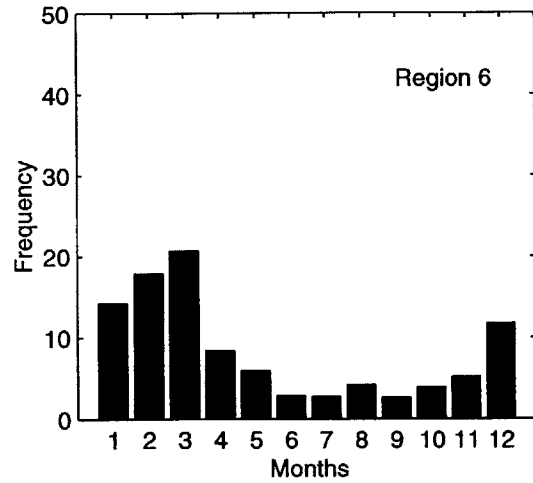
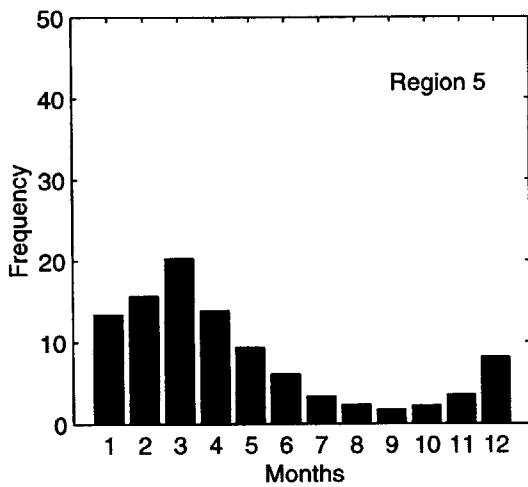
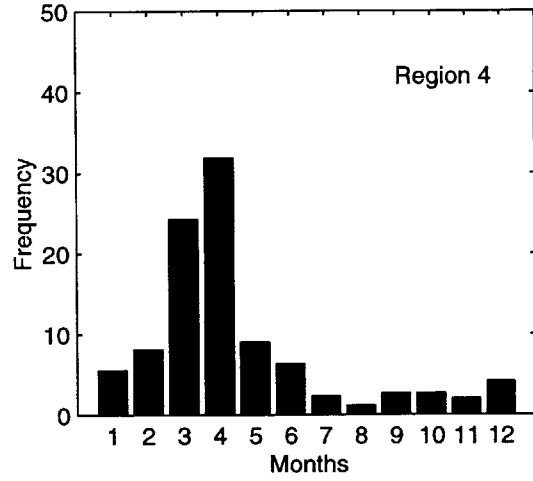
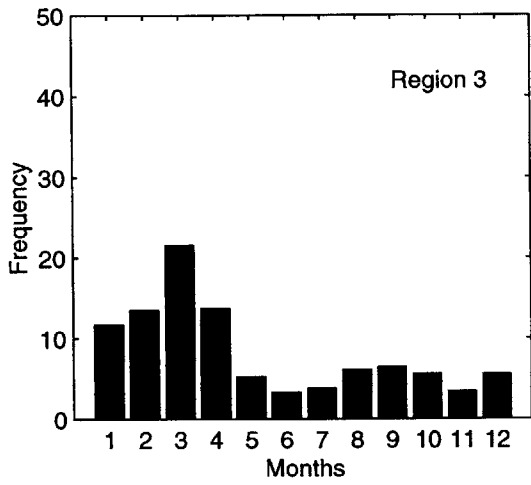
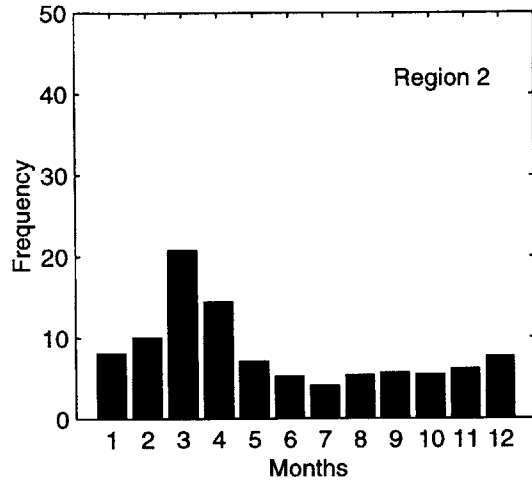
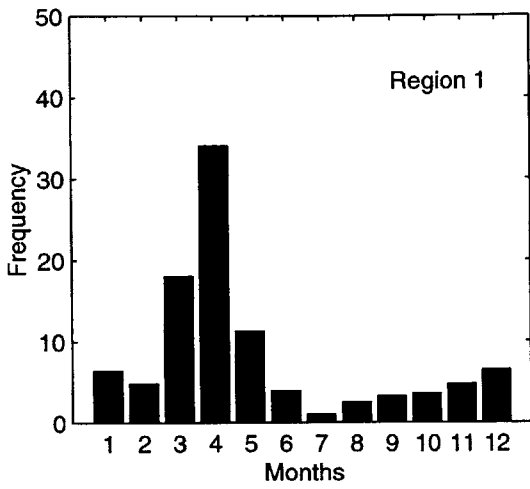


Figure 5.3(a). Monthly frequency of annual flood peaks in hydrologic regions 1 to 6.

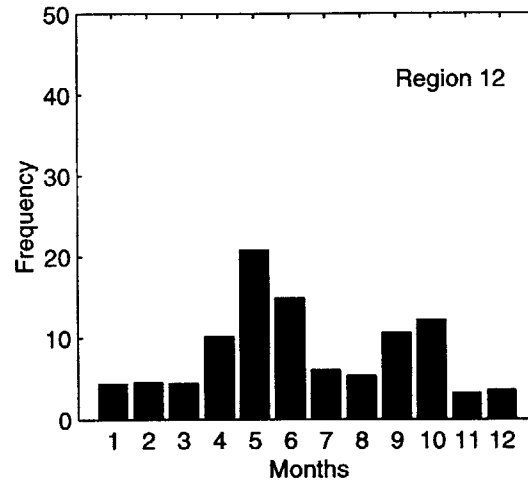
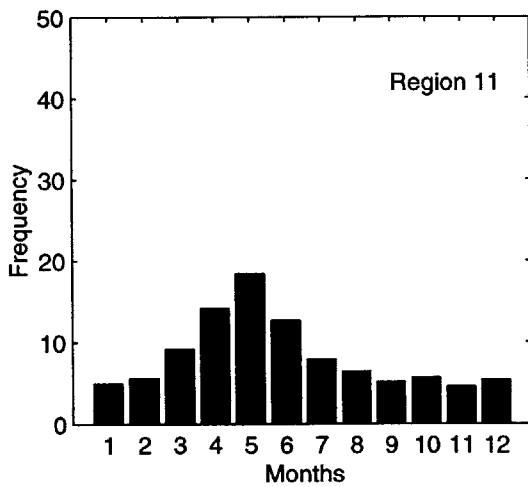
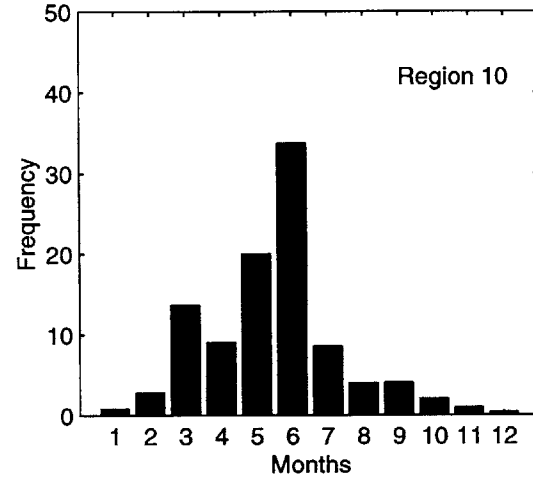
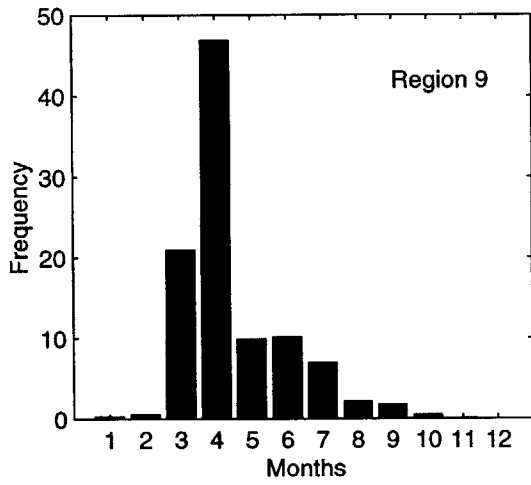
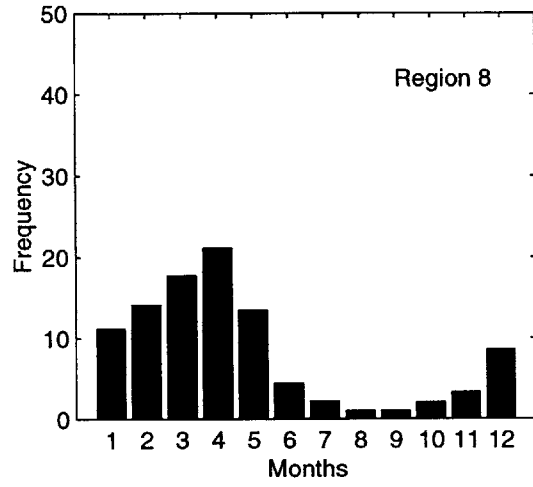
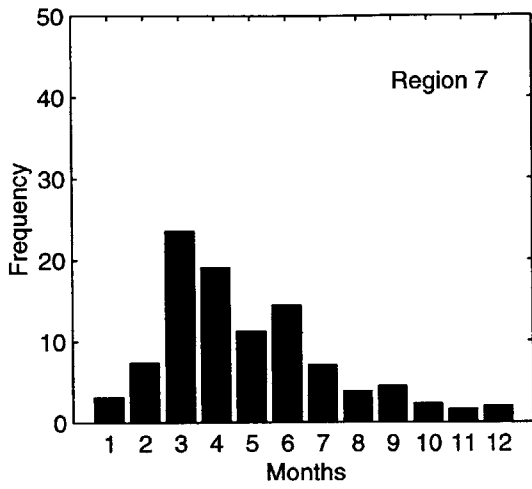


Figure 5.3(b). Monthly frequency of annual flood peaks in hydrologic regions 7 to 12.

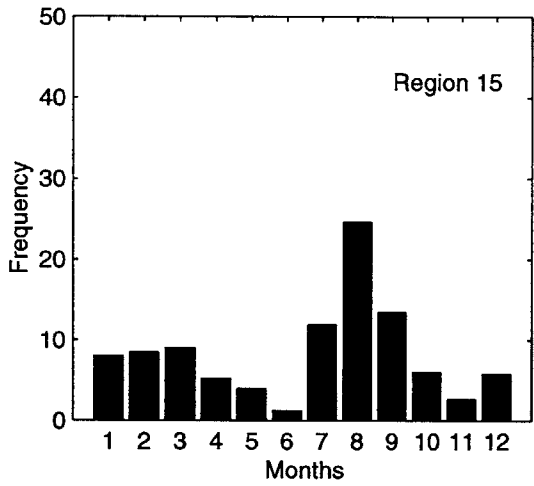
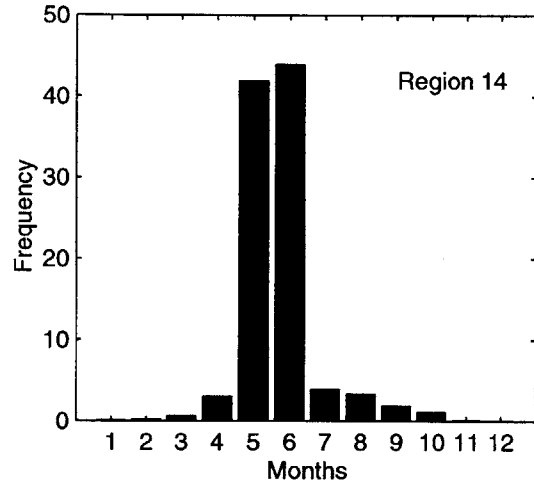
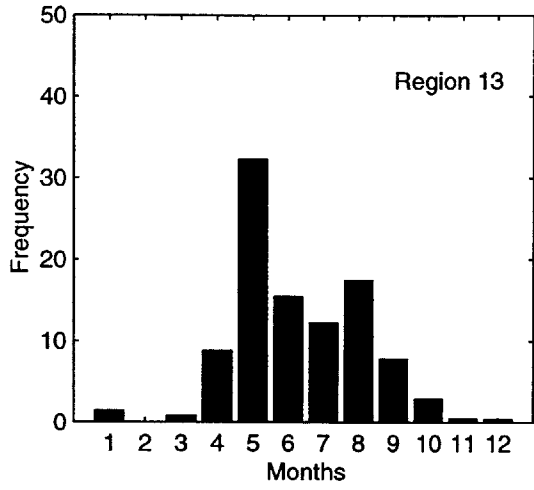


Figure 5.3(c). Monthly frequency of annual flood peaks in hydrologic regions 13 to 15.

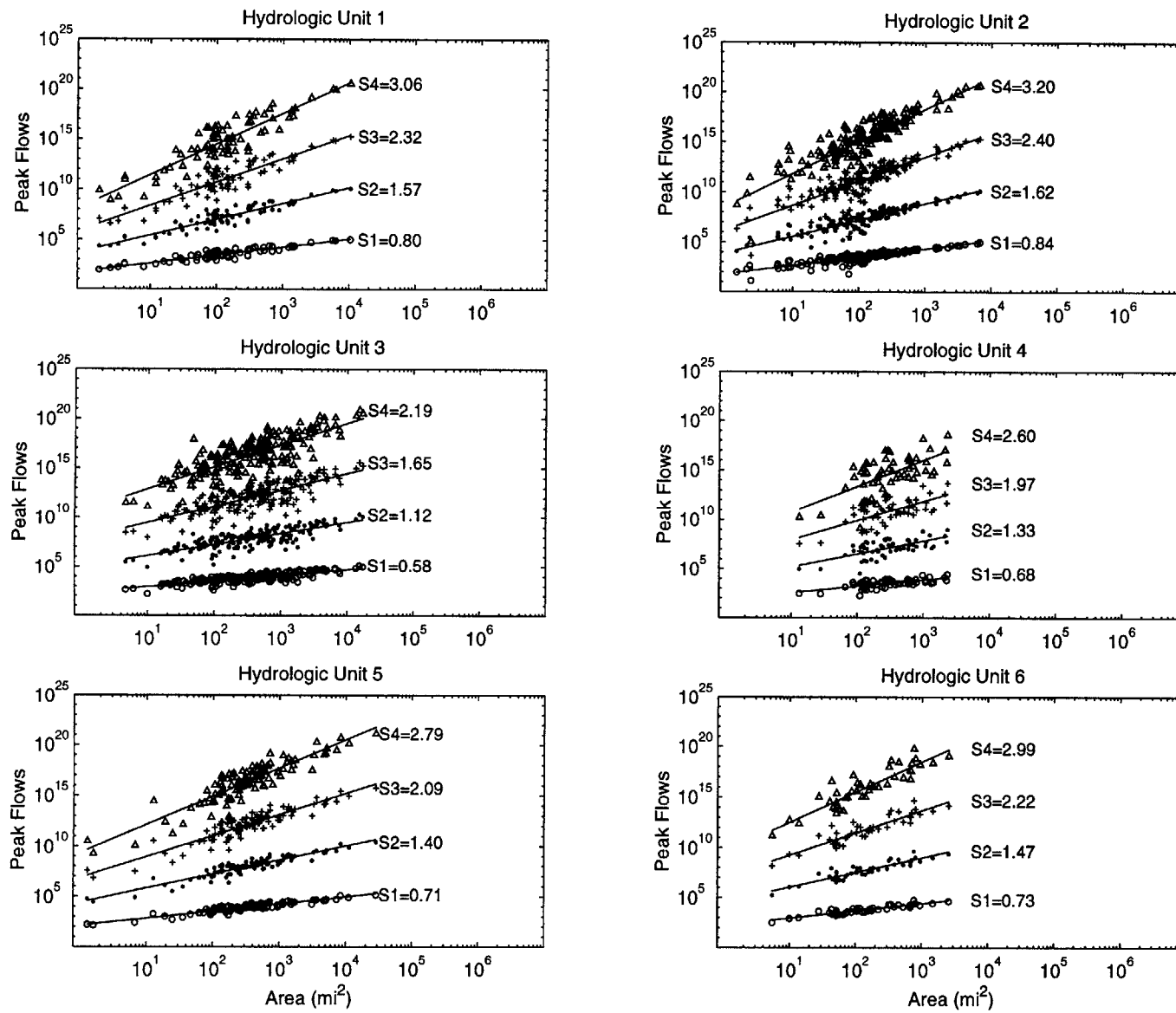


Figure 5.4. Peak flow moments of order 1 (open circles), 2 (filled circles), 3 (+) and 4 (triangles) for hydrologic units 1 to 6. The lines show the fitted regression to the moment orders 1 through 4; slope of each regression is indicated for each region.

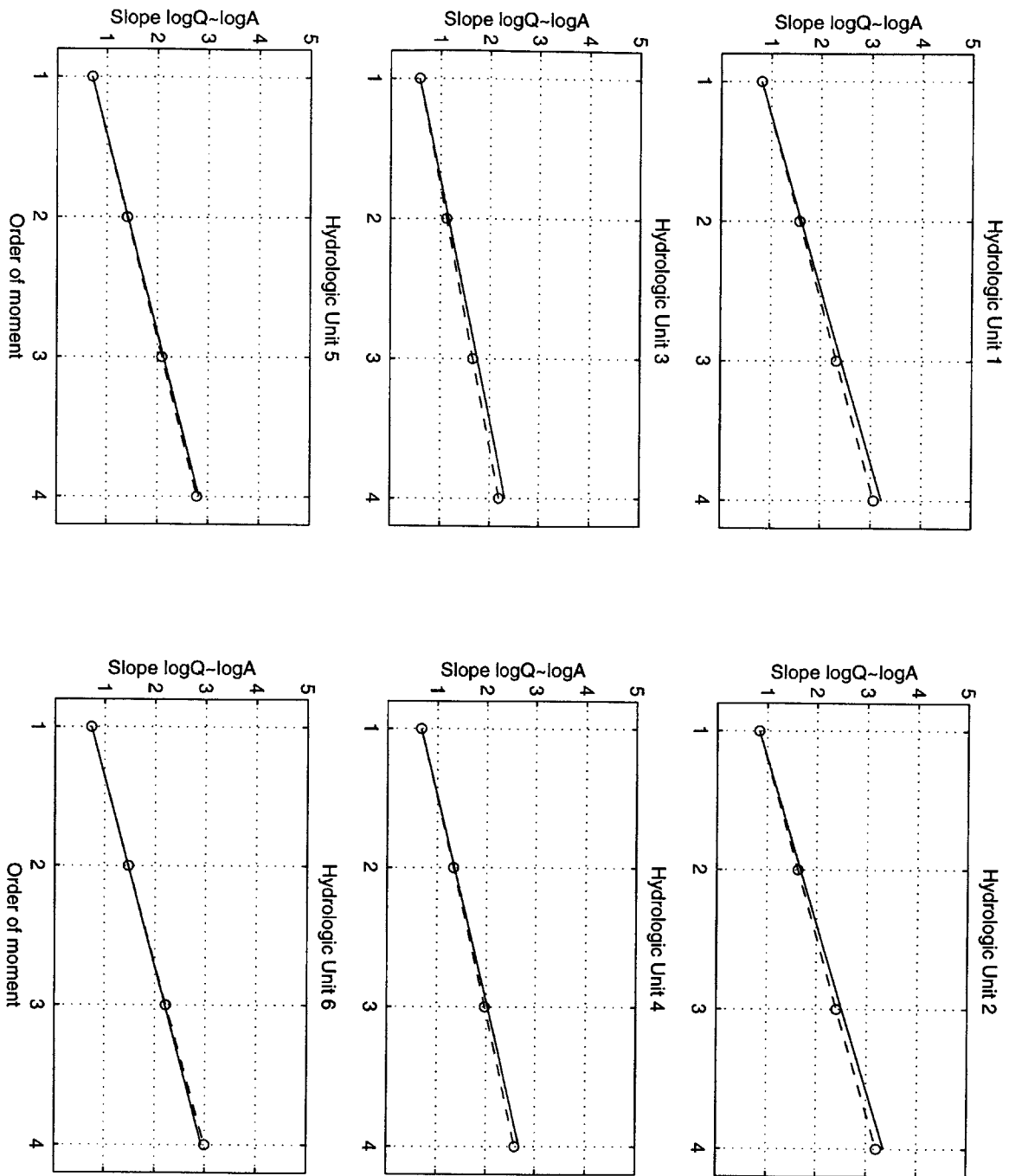


Figure 5.5. Growth of scaling exponent of peak flows for hydrologic units 1 to 6. The solid lines show the linear growth of scaling exponents.

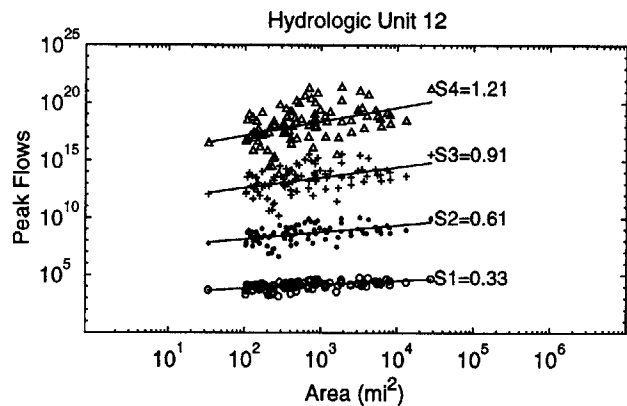
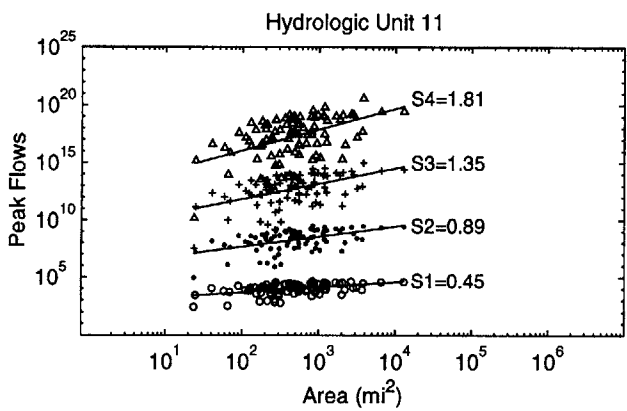
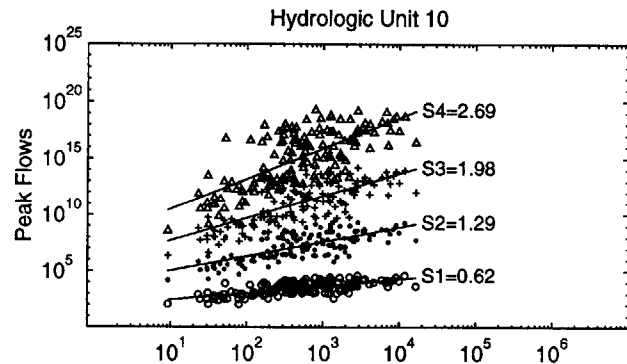
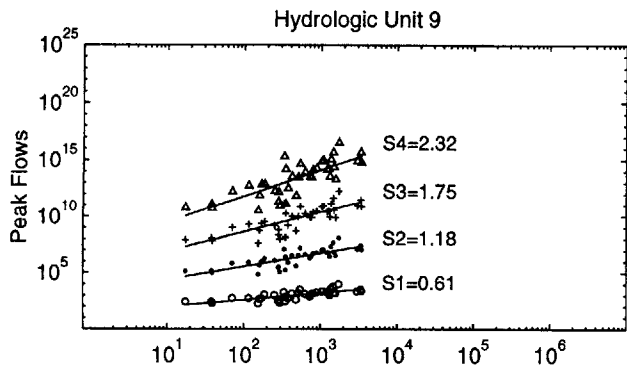
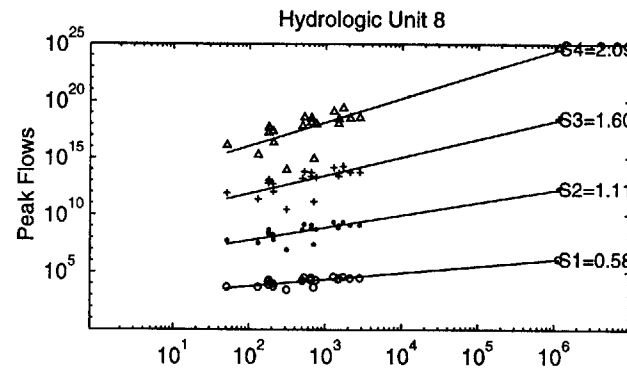
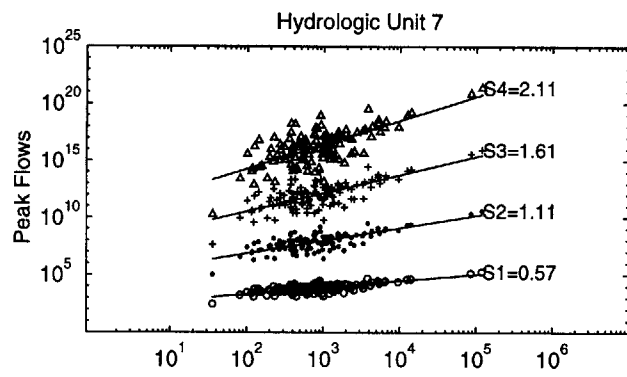


Figure 5.6. Peak flow moments of order 1 (open circles), 2 (filled circles), 3 (+) and 4 (triangles) for hydrologic units 7 to 12.

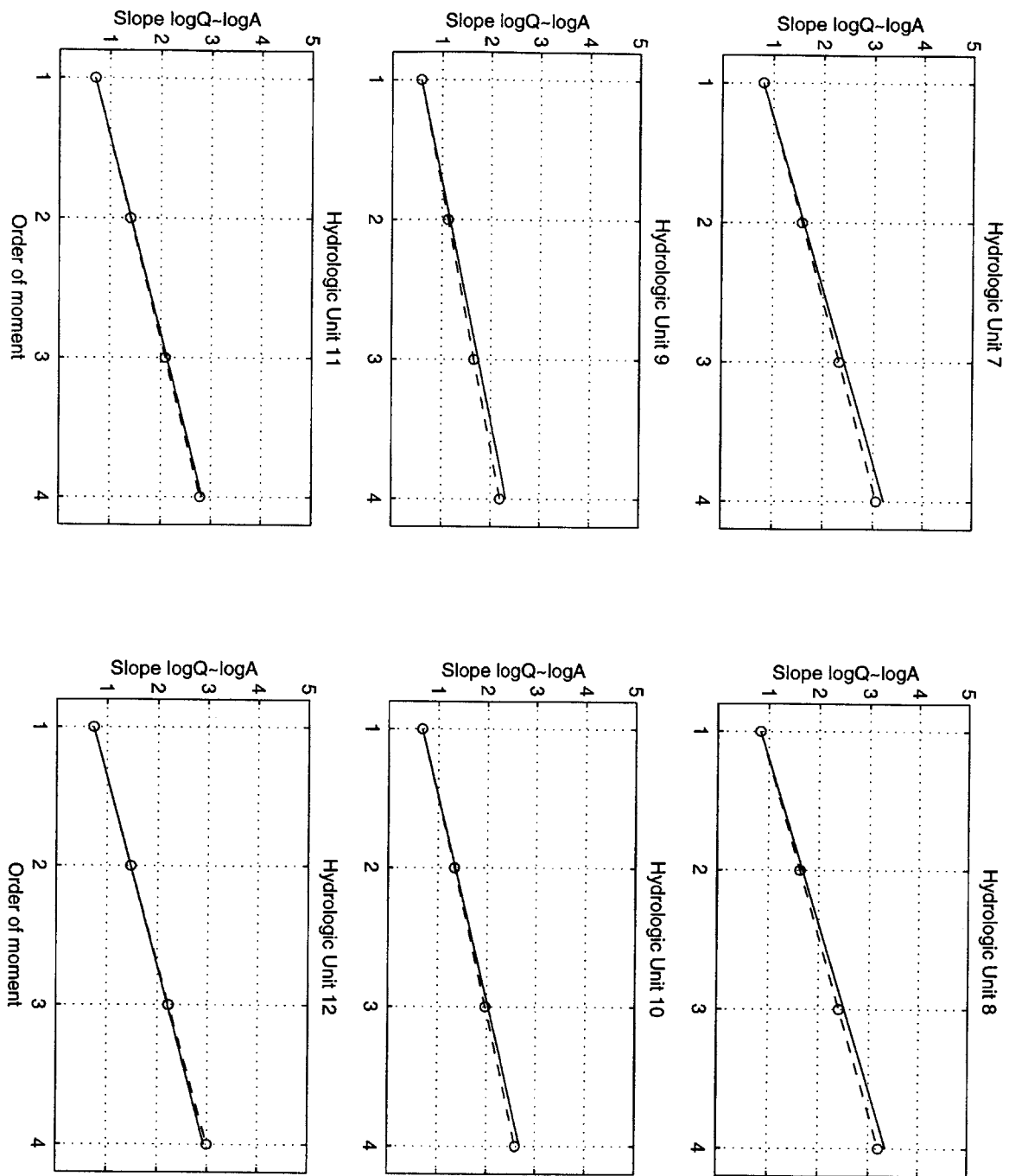


Figure 5.7. Growth of scaling exponent of peak flows for hydrologic units 7 to 12. The solid lines show the linear growth of scaling exponents.

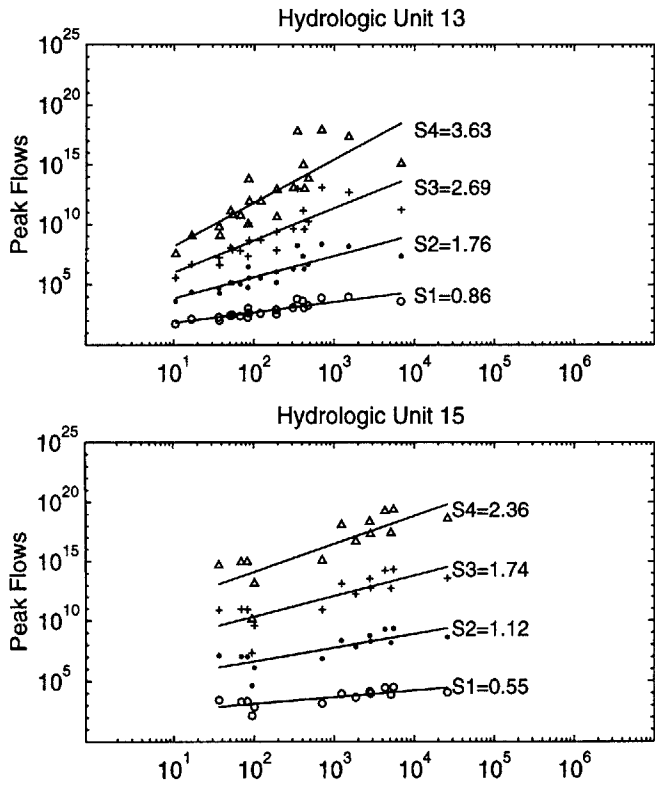


Figure 5.8. Peak flow moments of order 1 (open circles), 2 (filled circles), 3 (+) and 4 (triangles) for hydrologic units 13 to 15.

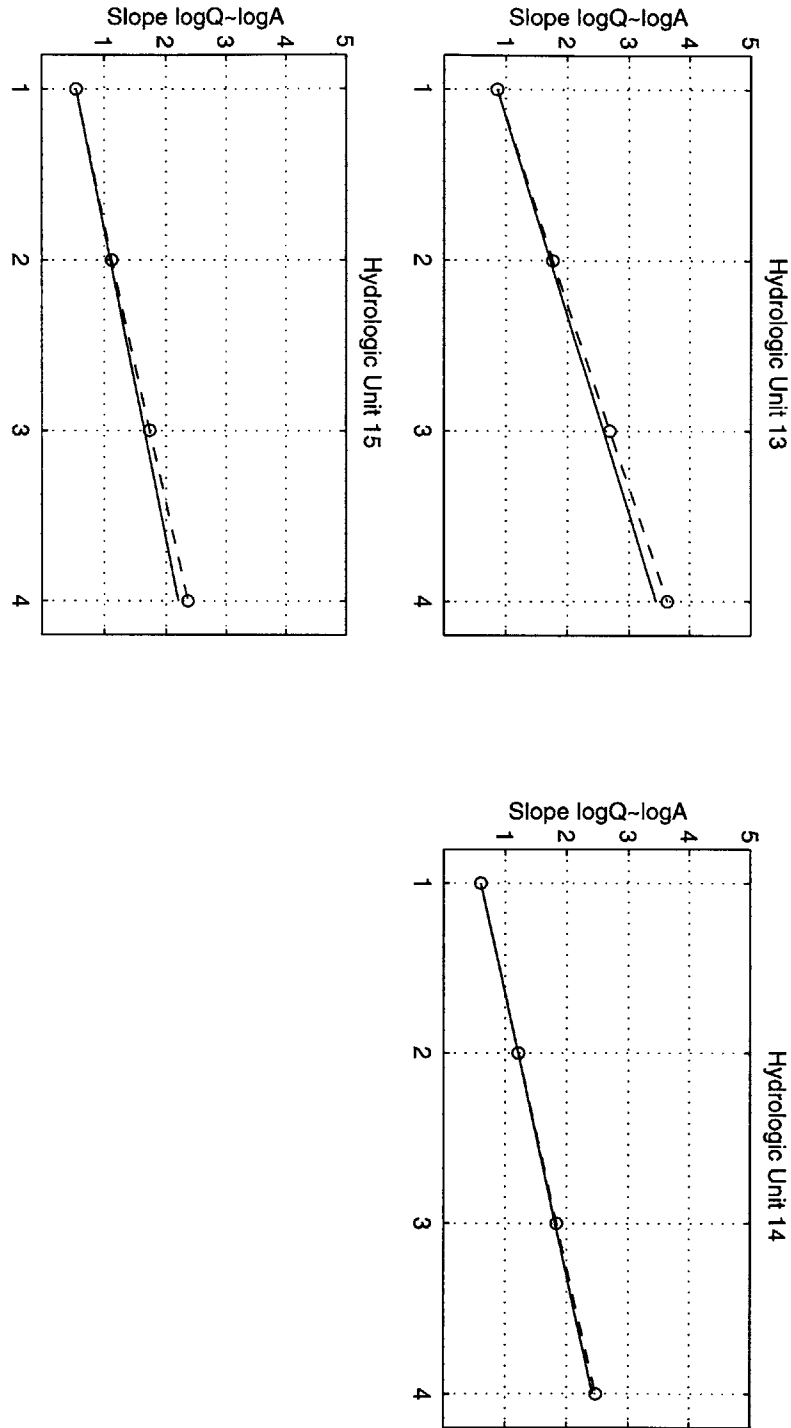


Figure 5.9. Growth of scaling exponent of peak flows for hydrologic units 13 to 15. The solid lines show the linear growth of scaling exponents.

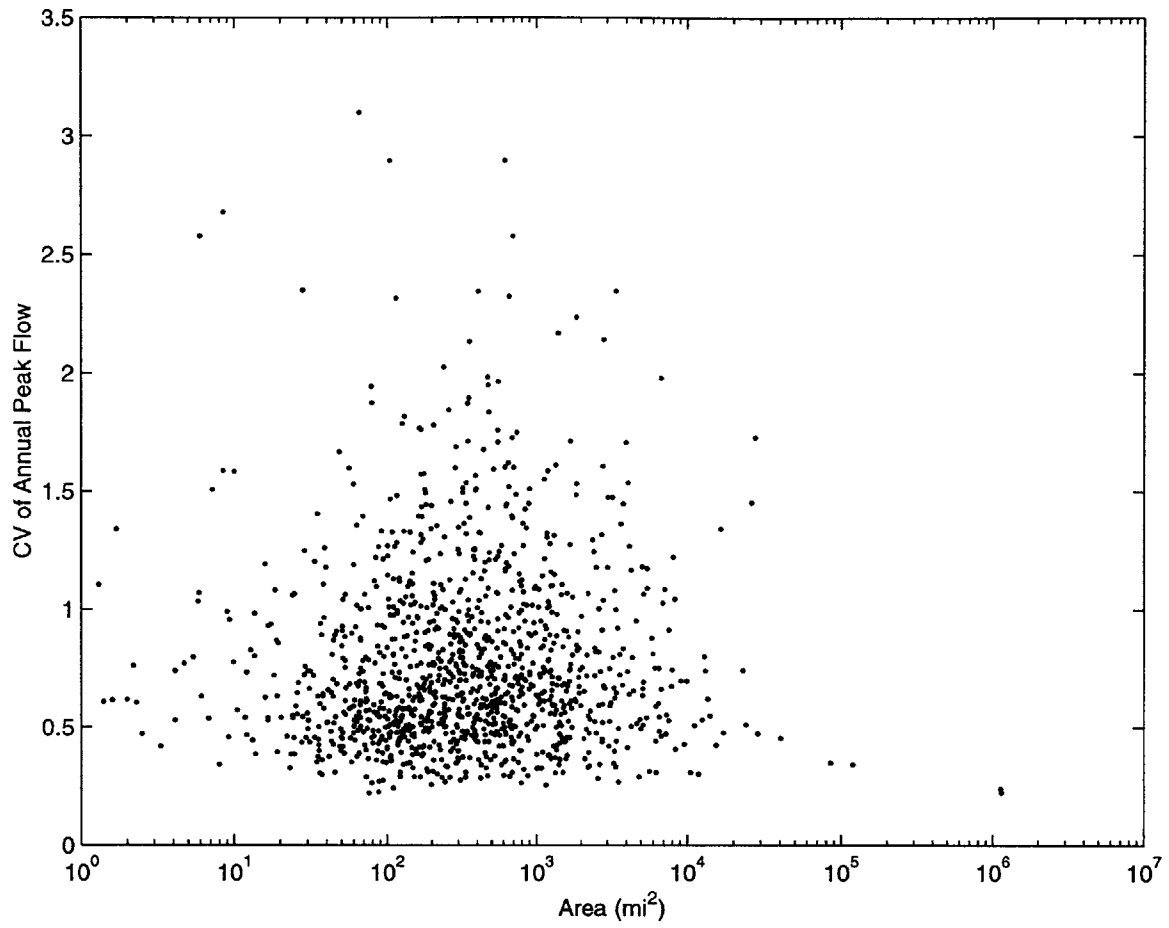


Figure 5.10. CV vs. Area for all hydrologic units.

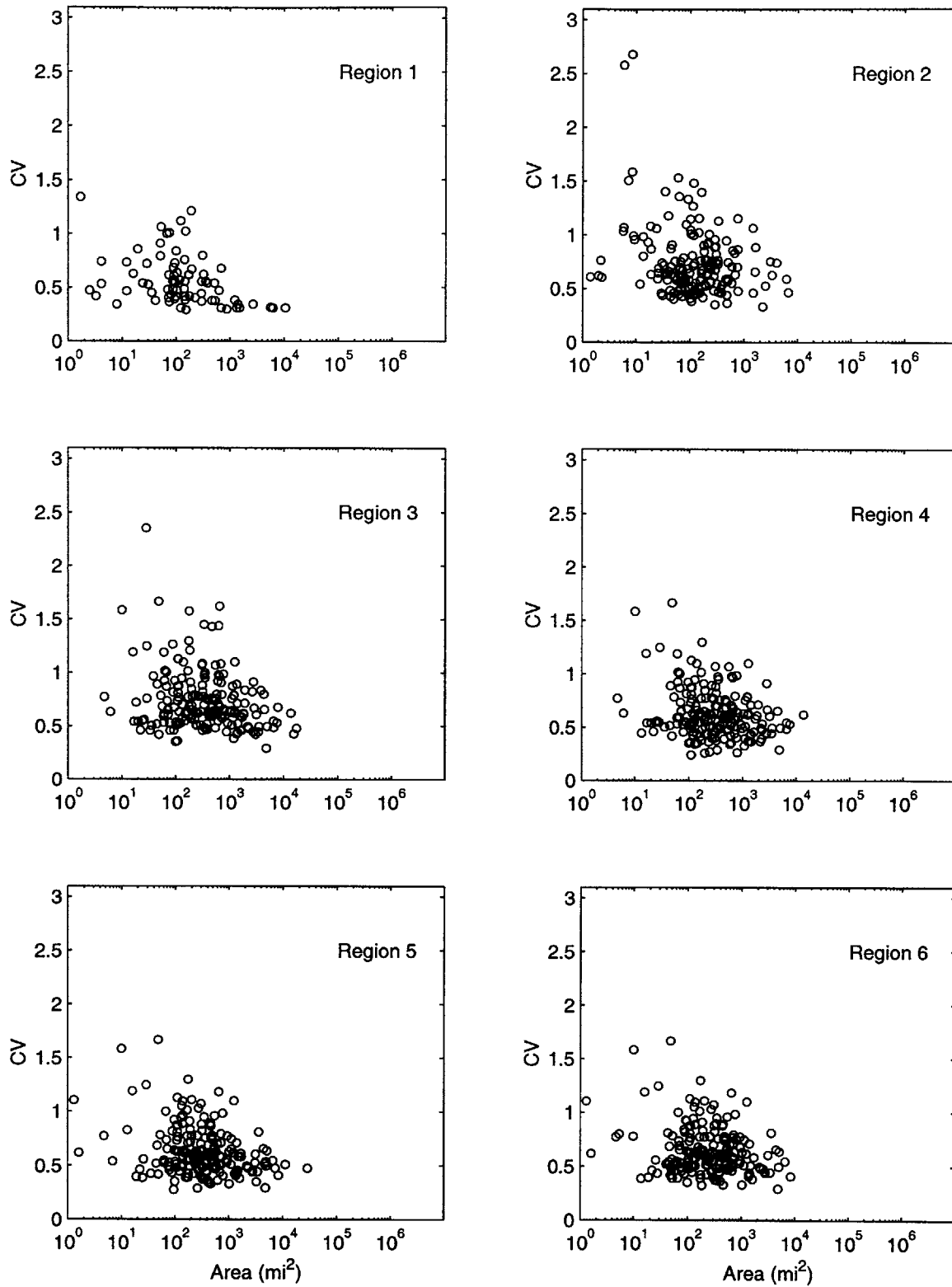


Figure 5.11(a). CV vs. A for hydrologic units 1-6.

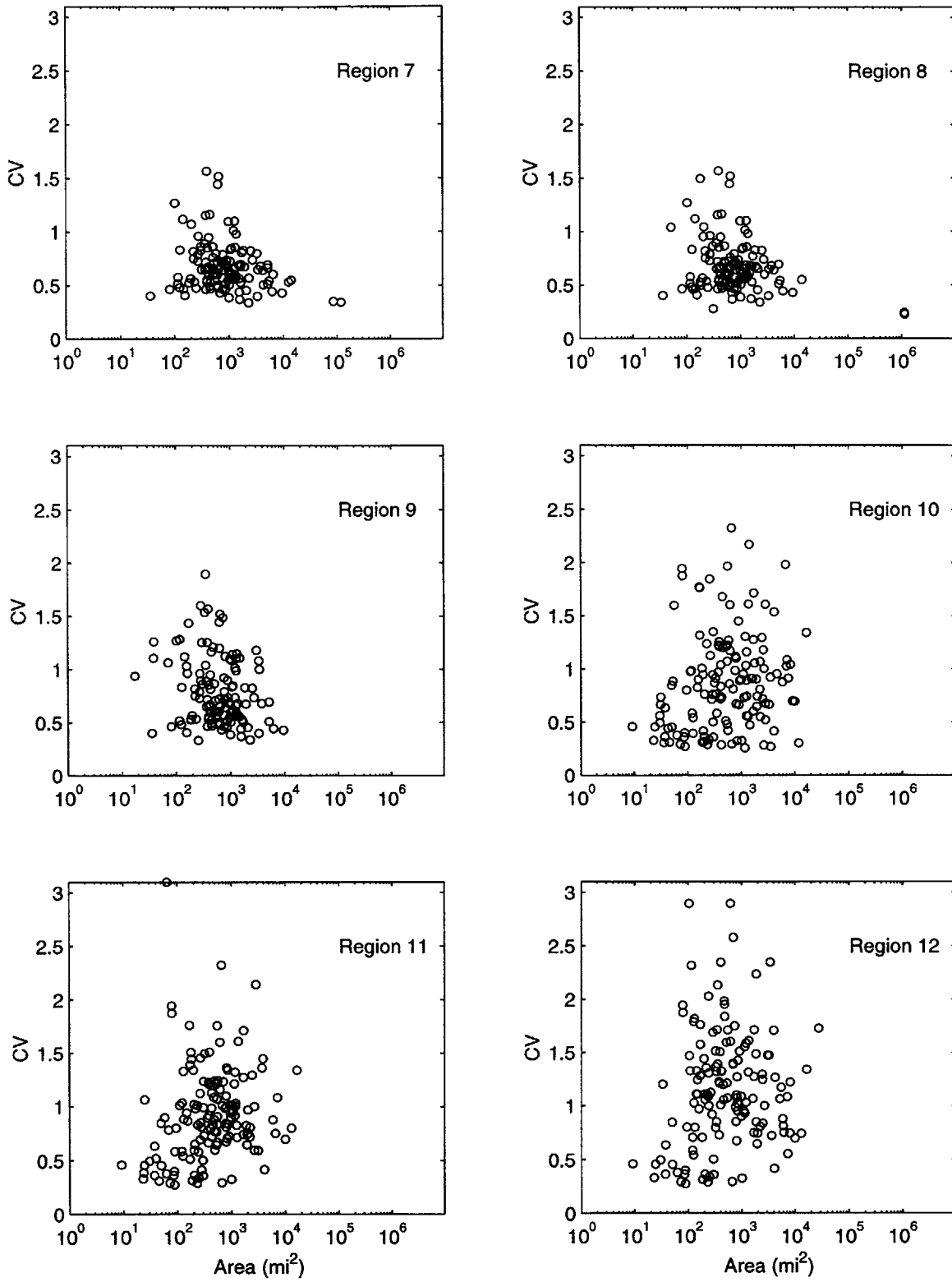


Figure 5.11(b). CV vs. A for hydrologic units 7-12.

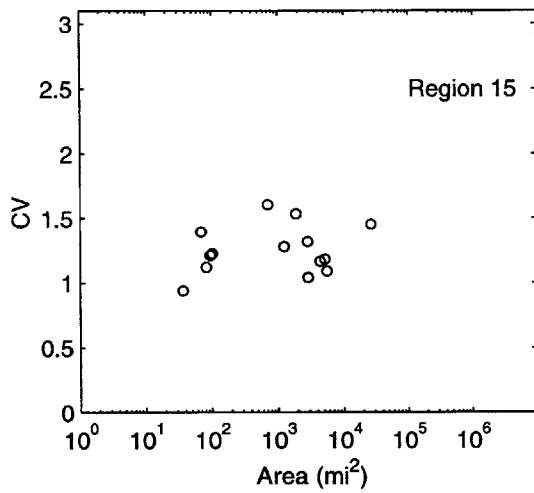
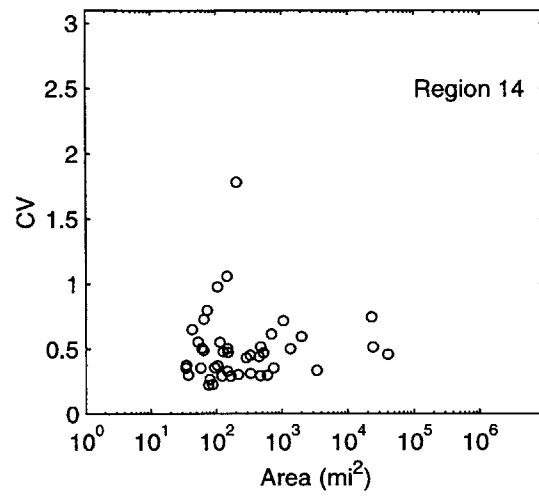
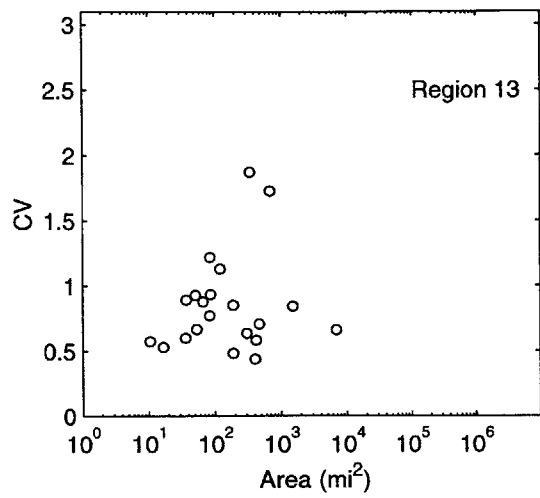


Figure 5.11(c). CV vs. A for hydrologic units 13-15.

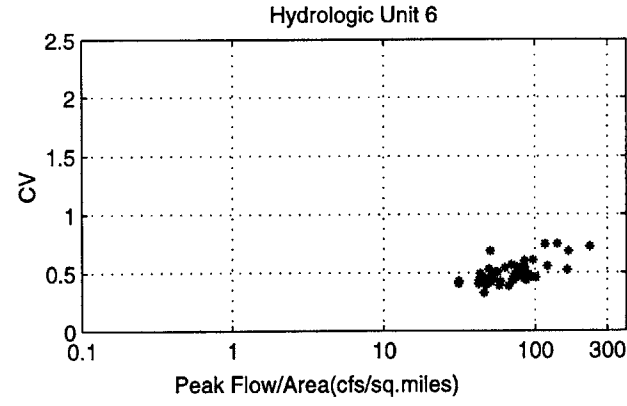
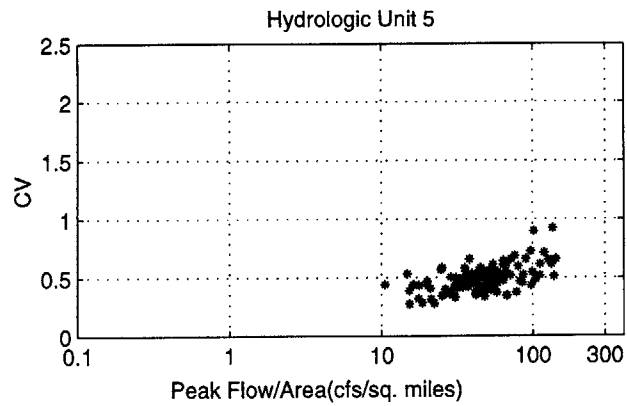
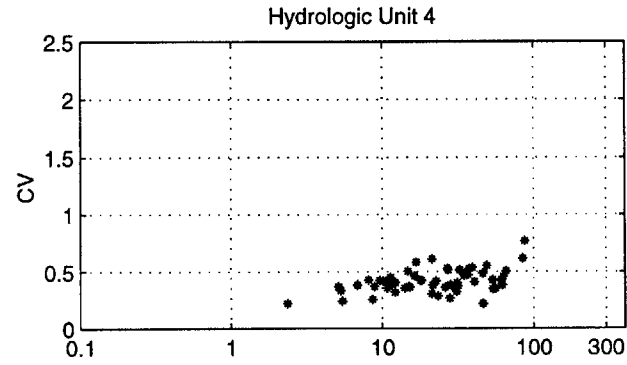
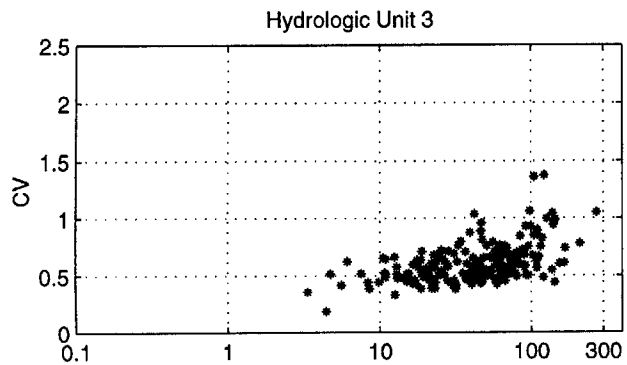
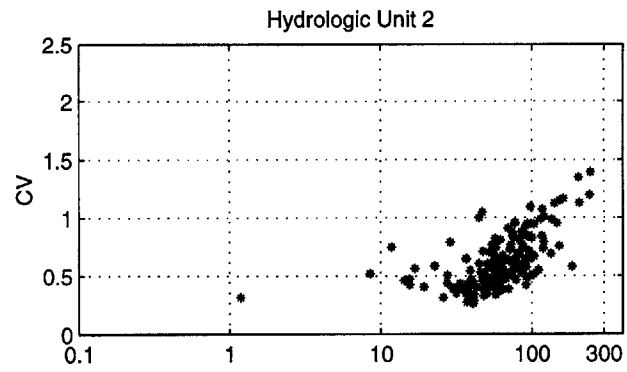
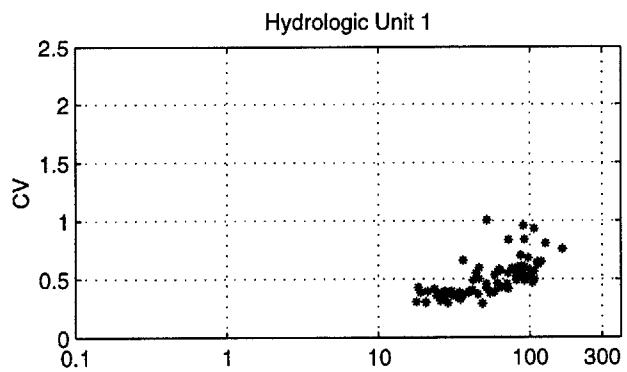


Figure 5.12. CV vs. Peak flow / Area: hydrologic units 1-6.

CHAPTER 6

Conclusion

This thesis has investigated the scaling of peak flows and its relation with the scaling of rainfall and the IDFs. We have used a two step approach. In the first step, we have related the scaling behavior of rainfall to the scaling of the IDFs and in the second step, we have developed a model to explain the scaling of peak flows from the scaling of IDFs. We have validated both scaling models by extensive data analysis. Our main findings are as follows.

Scaling of Temporal Rainfall

Data analysis of a 40-year hourly time series from Hartford, Connecticut, showed that rainfall exhibits multifractal scaling behavior between 2 hours and 4 days. Box counting analysis of rainfall time series showed how the series deviates from the multifractal behavior after 4 days. Similar conflicting evidence has been reported by others (Olsson 1995, Schmitt 1998). In particular we have confirmed the observation of Schmitt et al. (1998) that the dry duration distribution is not consistent with a multifractal model over all durations. We have found that a reasonable model for dry duration is a mixed exponential model. We found the fit of this model to be good for both the annual and the seasonal rainfall. Based on this model, a stochastic approach to estimate critical dry duration is recommended.

The moment scaling analysis of temporal rainfall supports the multifractality of rainfall from 8 hours to 128 hours. This is consistent with the limits of scaling indicated by the spectral analysis.

Scaling of the IDF Curves

We have used the Hartford rainfall time series to confirm the observation (Burlando, 1996; Menabde, 1999) that the IDFs at a point follow simple scaling in the range of durations for which rainfall itself is multifractal. We have used the theory of Veneziano and Furcolo (1999) to obtain the scaling exponents of the IDFs from the multifractal parameters of rainfall and compared these exponents with the actual behavior of the empirical IDF curves. The theory was verified to hold for both large and small durations and for all seasons.

The confirmation of scaling in return period T could not be made conclusively, because the scaling exponent requires accurate estimation of high-order rainfall moments.

We have made a limited extension of the above analysis of temporal rainfall and IDF to space-time by averaging rainfall from rain gage locations near Hartford. Ideally, a radar rainfall data set with fine spatial and temporal resolution should be used for space-time analysis of rainfall. We find that the scaling holds for the space-time rainfall and spatial IDFs.

Veneziano and Furcolo (2000) have argued that if rainfall in space-time is a locally stationary and homogeneous process with isotropic multifractality, then it could be

hypothesized that the scaling of IDFs in space is the same as the scaling of IDFs at a point; therefore, one could obtain the scaling parameters of spatial IDFs from the temporal time series. This is an issue which deserves further research .

We pooled the rainfall data from the 5 available gages into one long series and derived ARFs corresponding to different durations and return periods. As discussed in section 4.5, these results are only valid for the duration corresponding to the response time of the basin under consideration.

Scaling of Peak Flows

We have performed moment scaling analysis of peak flows for more than 1000 stations distributed across the U.S. and grouped by the hydrologic units, as defined by the USGS. We found that peak flows exhibit both simple and multiscaling with basin area. Most of the deviations from the simple scaling were mild and the non-linearity was mostly concave which indicated a decrease in variability with scale. For simple scaling, the exponent of peak flow varies from 0.33 to 0.86, most likely due to climatic differences (Pitlick, 1994; Gupta et al., 1995).

In order to connect the scaling of peak flows with the scaling of IDFs, we developed a simple model which expresses the scaling exponent of the peak flow in terms of: (1) the scaling exponent of the spatial IDFs, and (2) an exponent which describes the basin response and is composed of how the channel length and basin area are related and the celerity in the channel. This allows us to systematically study the relative effect of the spatial rainfall and basin response.

Other factors, such as physiographic characteristics of the basin and climatic features such as the role and contribution of snowmelt and baseflow, which are not represented in our simple model, should also be considered. Further work needs to be done in this direction. The USGS uses a quantile regression method with a number of descriptors (such as basin area, precipitation, basin topography) to estimate the flood for a given return period. Scaling studies can provide a sound basis for such analysis. Sivapalan et al. (1987, 1997) have used numerical-physical models to explain the underlying physical mechanisms controlling flood frequency curves. One can use the understanding of the physical phenomenon with the scaling observation to improve the extrapolation of frequency of extreme events. This would also be an important direction because of the practical significance of such results for regional flood frequency analysis. Gupta et al. (1994, 1996) have tried to address the issue and concluded that: (1) rainfall generated floods show multiscaling and (2) peak flow scaling in small basins is controlled by the basin characteristics. Further in-depth analysis, using a dense network of gages and stream flow from nested basins, combined with information about the basin physiographic characteristics (such as those reported by the USGS) is needed to confirm if and how the flood generating mechanism control the simple or multiscaling behavior of flood peaks.

CHAPTER 7

Review of Flood Damage Mitigation Policies

7.1 Flood Damage Mitigation through Effective Public Policies –

Introduction and Issues

The objective of this chapter is to review the formulation of effective policies for mitigating flood damage in the United States. Mitigation has been defined as any action taken to permanently eliminate or reduce the long-term risk to human life and property that can be caused by natural and technological hazards (Interagency Flood Management Review Committee, 1994). Flood mitigation measures can be classified from the standpoints of adjustment to natural hazards, flood damage prevention, flood damage reduction and flood policy making (Yevjevich, 1994). The main branches of flood control measures include structural flood defense and regulatory measures. Structural flood control is achieved by building levees, flood walls and dams. Regulatory approaches include floodplain management, flood insurance, better warning systems and educating the public about the risk. The limitations of hazard reduction through structural protection were well recognized by 1950. Experience with the levees only policy in the U.S. has shown that such policies prove to be unsuccessful due to a number of reasons. Structural measures are not only expensive but they also alter the floodplain and may have a negative impact on the environment. By preventing small and medium-sized floods, dams and levees convey a false sense of security to the public.

This, in turn, leads to increased urbanization of the floodplain resulting in increased exposure of the region to flood risk.

Non-structural or regulatory measures, such as floodplain management and flood insurance, were introduced by the Government in the 1960s after their successful use at a number of locations. Regulatory measures include both cooperative and mandated programs. Programs can be cooperative, based on agreements and sharing of responsibilities; mandated where a community is coerced or required to implement a given program; or a combination of the mandated and cooperative. Financial policies include both positive and negative incentives through subsidies, loans and differential tax systems and can be formulated to encourage appropriate levels of development in some areas and discourage investment in hazardous areas. Some policies may encourage or require insurance against flood. National Flood Insurance Program (NFIP) began as a cooperative program where the federal government subsidized flood insurance for homeowners in communities that adopted floodplain management regulations. However, due to minimal participation, the National Flood Insurance program was changed from a cooperative to a mandated approach in 1973. Other non-structural flood mitigation programs include public loss recovery program, relocation and direct public acquisition.

Over the years, a number of studies and task forces have presented the results of their findings and recommended actions (see for example, Federal Interagency Floodplain Management Task Force, 1992; Interagency Floodplain Management Review Committee, 1994). The regulatory measures have received considerable attention from such studies.

However, to the extent that the non-structural policies have been adopted and implemented by the government, these policies have not been able to meet their expected goals. In this chapter, we look at the issues associated with flood mitigation policy, evolution of the policy with time, analyze the rationale behind different mitigation measures and identify the barriers to effective implementation of flood mitigation policies. We attempt to answer questions such as:

- How have the flood damage mitigation policies evolved in the U.S. ?
- What is the role of politics in flood mitigation policies?
- How do the regulating agencies assess risk?
- How does the public perceive the risk?
- How is disaster assistance carried out?
- Who pays for the damages incurred – individuals, state government, federal government or the taxpayers?

7.2 Literature Review of Policies for Flood Mitigation

This section summarizes the evolution of policies dealing with floods in the United States. The changing socioeconomic and demographic conditions in the U. S. have resulted in an increase in both the damages from floods and the accompanying protection costs. The U. S. has witnessed an event-driven flood policy where large and damaging flood events resulted in “windows of opportunity”, the politically active period immediately after an event with the heightened awareness among public and

pressure on Congress to act. Listed below are some of the main timelines in the history of U. S. flood policy making:

- 1861 Levees only policy – funds provided for the Army Corps of Engineers.
- 1879 Mississippi River Commission.
- 1927 Great Flood of 1927.
- 1933 Tennessee Valley Authority created.
- 1938 Flood Control Act; National Crop Insurance Program.
- 1950 Disaster Relief Act of 1950 marked the start of federal involvement in disasters. President could declare disaster and provide assistance to the communities in disaster zones.
- 1959 Report submitted to the government: A Program for Reducing the National Flood Damage Potential.
- 1965 Establishment of the Bureau of the Budget Task Force on Federal Flood Control Policy.
- 1966 Report of the Task Force: House Document 465 cites numerous problems with the past approach of levees and advocates a broader perspective on flood control within the context of floodplain development and use.
- 1967 National Flood Insurance Program (NFIP) set up by Congress; NFIP provided relief from the impacts of flood damages in the form of federally subsidized flood insurance to participating communities, contingent on flood loss reduction measures embodied in local floodplain regulations.
- 1970 Disaster Assistance Act.
- 1974 Disaster Relief Amendment.

- 1979 Federal Emergency Management Agency (FEMA) was set up.
- 1988 Stafford Act – constituted principal federal authority for providing disaster relief.
- 1992 Federal Interagency Floodplain Management Task Force Report and Recommendations.
- 1993 The Great Flood of 1993.
- 1994 National Flood Insurance Reform Act – tightened flood insurance purchase requirements and expanded mitigation incentives.

In response to the recurrent flooding in the Mississippi Valley, Congress created the Mississippi River Commission in 1879. The Commission was to survey the Mississippi and its tributaries, formulate plans for flood control, and report on the practicality and costs of various alternative courses of action. The commission agreed on the levees only approach to control flooding on the Lower Mississippi.

The Great Flood of 1927 showed the vulnerability of the levees-only policy. Changnon (1996) reports that “much of the levee system along the Mississippi failed, and the flood torrent fanned out over the flat delta.” In the 1940s, a number of experts voiced concern about the prevailing levees-only policy. White (1942) advocated “adjusting human occupancy to the flood plain environment so as to utilize most effectively the natural resources of the flood plain, and simultaneously applying practicable measures to minimize the detrimental impacts of floods”. White (1942) characterized the prevailing national policy as “essentially one of protecting the occupants of floodplains against floods, of aiding them when they suffer flood losses, and of encouraging more intensive

use of floodplains". Interestingly, even after 60 years, the national policy still faces the same problems.

By the mid 1950s national flood damage potential was increasing at a faster rate than it could be controlled under existing flood protection construction programs (Changnon, 1996). In 1933 Congress created Tennessee Valley Authority (TVA), a federal regional agency to provide a sound technical basis for flood damage prevention planning.

In 1965 the Bureau of the Budget Task Force on Federal Flood Control Policy was established under the leadership of Gilbert White. A broader perspective on flood control within the context of floodplain development and use provided the groundwork for redirecting the federal involvement from structural control to a more comprehensive approach for a flood plain management, which included establishment of the National Flood Insurance Program (NFIP) and passage of the National Environmental Policy Act (NEPA) (Changnon, 1996). Congress created the NFIP in 1968 in response to increasing flood losses and escalating costs to the general taxpayer for disaster relief. NFIP represents a policy of distributing losses among potential flood victims rather than among all taxpayers, with additional goal of reducing vulnerability through land use management. The standards published by the NFIP are designed to supplement the federal government's program of structural flood works. The NFIP includes three main components: risk identification, hazard mitigation and insurance. Effective integration of these three components requires cooperation between the federal government, state and local governments, and the private property insurance industry. Risk identification is discussed in the next section (FEMA web site).

Since flood hazards are considered uninsurable by private insurers, FEMA provides direct insurance against flood losses through the National Flood Insurance Program (NFIP). The NFIP requires flood insurance and imposes hazard mitigation requirements on all properties with federally insured mortgages in flood-prone areas. Flood insurance is covered in detail in the next chapter. The NFIP is funded through the National Flood Insurance Fund, which was established in the U.S. Treasury by the National Flood Insurance Act (FIA) of 1968. The collected premiums are deposited into the fund and the fund pays for the expenses. The NFIP also has the authority to borrow up to \$1 billion from the Treasury. In 1981, the administrator of the FIA established a goal of making the program self-supporting for the average historical loss year by 1988. The National Flood Insurance Program has been operating at a loss since 1993. A major issue for the NFIP is to deal with those existing structures that are subject to repeated damages. Issues with NFIP are discussed again in the next chapter in the context of insurance as a tool for flood disaster mitigation policy (Kunreuther et al., 1998).

FEMA makes the Flood Mitigation Assistance program (FMA) available to a State on an annual basis. The FMA program provides grants to communities for projects that reduce the risk of flood damage to structures that have flood insurance coverage. This funding is available for mitigation planning and implementation of mitigation measures only. The State is the administrator of the FMA program and is responsible for selecting projects for funding from the applicants submitted by all communities within the State. The State then forwards selected applications to FEMA for an eligibility determination.

Although individuals cannot apply directly for FMA funds, their local government may submit an application on their behalf.

Since 1968, government agencies have been working on developing strategies and tools to guide federal, state, and local decision makers in implementing a unified national program for floodplain management. A Federal Interagency Floodplain Management Task Force (FIFM) prepared reports in 1976 with updates in 1979 and 1986. The 1986 report had two main ideas for floodplain management: to reduce loss of life and property, and to reduce the loss of beneficial sources from unwise land use. An excerpt from the report lists the four primary strategies to achieve the two floodplain management goals:

Strategy 1: Modify Susceptibility to Flood Damage and Disruption

1. Floodplain regulations
2. Development and redevelopment policies
3. Disaster preparedness
4. Disaster assistance
5. Floodproofing
6. Flood forecasting and warning systems and emergency plans

Strategy 2: Modify Flooding

1. Dams and reservoirs
2. Dikes, levees, and floodwalls
3. Channel alterations
4. High flow diversions
5. Land treatment measures

6. On-site detention measures

Strategy 3: Modify the Impact of Flooding on Individuals and the Community

1. Information and education
2. Flood insurance
3. Tax adjustments
4. Flood emergency measures
5. Post-flood recovery

Strategy 4: Restore and Preserve the Natural and Cultural Resources of Floodplains

1. Flood, wetland, coastal barrier resources regulations
2. Development and redevelopment policies
3. Information and education
4. Tax adjustments

Another report related to floodplains damage mitigation was published by the Federal Interagency Floodplain Management Task Force in 1992. This report had a number of important findings which included: increasing individual risk awareness, need for enhanced technology, need for interdisciplinary approaches, role of disaster assistance and a need for setting up national goals. According to the recommendation of the FIFM report, national assessment of the floodplains was initiated and a group of specialists evaluated the effectiveness of floodplain management. Changnon (1996, p259-260) has listed the key findings as:

- Individual Risk Awareness Although substantial progress has been made in increasing institutional awareness of flood risk, individual awareness falls far

short of what is needed, resulting in unwise use and development of flood hazard areas.

- Migration to Water People are attracted to riverine and coastal environments but not usually due to economic necessity. In recent decades, the annual growth rate in these areas has greatly exceeded that of the nation as a whole.
- Flood plain Losses Despite attempts to cope with the problem, the large-scale development and modification of riverine and coastal floodplains has resulted in increasing damages and loss of floodplain resources.
- Short-term Economic Returns In many instances, private interests develop land to maximize economic return without regard to long-term economic and natural resource losses. This increases public expenditures for relief, recovery, and corrective actions .
- Enhanced Knowledge and Technology Institutions and individuals that deal with floodplain problems require a broad range of information, a variety of technologies to deal with emerging problems, and standards to which they can refer for guidance. Research enhances our knowledge about these areas.
- National Flood Protection Standard Protection from the effects of greater, less frequent flooding is still needed in areas where such flooding will cause unacceptable or catastrophic damages.
- Limited Governmental Capabilities Many states and communities lack the full resources necessary to bring about comprehensive local action to mitigate flood

problems without federal support. Local governments are necessary partners to any successful solution.

- Need for Interdisciplinary Approaches Plans to solve flood problems have to encompass the entire hydrologic unit and be part of a broader water resources management program. Training in a variety of disciplines is required to devise and carry out mitigation strategies.
- Application of Measures The measures implemented locally typically involve only floodplain regulations (to meet the requirement of NFIP and state programs) and eligibility for the individuals to purchase insurance. Communities typically have not implemented other floodplain management measures .
- Effectiveness of Mitigation Measures Structural flood control measures have been effective in reducing economic losses. The application of additional structural measures is limited because of economic and environmental considerations. Land use regulations required by some federal programs and implemented by state and local governments have reduced the rate of floodplain development. Compliance with regulatory controls is a significant problem. New technologies and techniques associated with risk management, forecasting, warning, and construction practices have substantially improved these activities. The potential of NFIP has not been realized: less than 20 percent of floodplain residents have insurance.

- Role of Disaster Assistance Liberal federal assistance in post-flood relief and recovery has reinforced expectations of government aid when flood disasters occur. This view has resulted in limited mitigation planning and actions by communities and individuals.
- National Goals and Resources Despite significant progress, the United States still lacks a truly unified program for floodplain management. Ambiguity in national goals has hindered the effective employment of limited financial and human resources.

The role of disaster assistance merits further comments and discussion as we believe that this is one of the most important issue in managing flood mitigation. As the report pointed out above, if the state and local governments believe that the federal government will meet their needs in every disaster, there is very little incentive to spend scarce state and local resources on disaster preparedness, mitigation, response and recovery. This has the effect of raising the cost of disaster to federal taxpayers. People are encouraged to take risks which they otherwise would not take. Due to the attention which the disasters get from media and politicians, the decisions for disaster assistance in the past have been political as well. This undermines the very idea of effective disaster mitigation strategies recommended by the experts. Congress provides additional benefits to disaster victims through the federal tax code. Businesses in particular may write off many kinds of uninsured expenses involved in restoring property to predisaster condition (Kunreuther et al., 1998).

The Great Flood of 1993 flooded 20.1 million acres of land and caused 12.7 billion dollars damage. Due to the heavy damages, 532 counties were declared to be disaster areas by the President. The President also issued a statement that described the "Cost-Share Adjustment for Midwest Flood Recovery." It led the president to change the reimbursement of eligible public assistance disaster costs from the 75 percent federal/25 percent nonfederal to 90 percent federal/10 percent nonfederal. With the passage of the Hazard Mitigation and Relocation Assistance Act of 1993, the funding for hazard mitigation was increased. Under the new legislation, the federal government could fund up to 75 percent of the eligible costs of a project, a change from 50-50 cost-share formula. The funds which were made available were mostly used for buying out flood damaged property from willing sellers. The act also made clear the condition for such buyouts: complete removal of flood-prone structures and the dedication of the purchased land "in perpetuity for a use that is compatible with open space, recreational, or wetlands management practices." More than 20,000 people agreed to sell their homes to the government and move to higher ground.

The Disaster Relief Fund of the Federal Emergency Management Agency (FEMA) is the major source of federal disaster recovery assistance to state and local governments. To replenish the fund, FEMA requests annual appropriations from Congress that are based on an average of annual fund expenditures over the previous 10 years. When incurred costs rise above the average, FEMA relies on supplementary financial allocations. Flood aid is distributed by FEMA under the Stafford Disaster Relief and Emergency Assistance Act of 1974, amended in 1988. The most typical form of federal disaster assistance is a

loan that must be paid back with interest and the average "Individual and Family Grant" payment is limited to US\$2500.

The National Flood Insurance Reform Act of 1994 introduced major changes to the flood policy of the United States. One of the provisions of the Act was the establishment of the Technical Mapping Advisory Council to advise FEMA on the accuracy and quality of the Flood Insurance Rate Maps (FRIM). Part of the 1968 National Flood Insurance Act was repealed and replaced by a new National Flood Mitigation Fund into which \$20 million will be transferred annually from the National Flood Insurance Fund. The mitigation fund is intended to provide grants to states and local jurisdictions, on a 75/25 percent share basis, for urban planning and for the implementation of longer-term projects such as relocation, property buy-outs, floor elevation etc. The 1994 Act also required lending institutions to complete a "Standard Flood Hazard Determination Form" for every loan secured by improved real estate. The purpose was to ensure that legally required flood insurance is actually bought. For existing loans, and where borrowers are not carrying flood insurance, lenders are directed to notify such borrowers that insurance is mandatory. If the borrowers do not then purchase insurance, the Act directs the lenders to purchase it on the borrower's behalf and charge appropriate premium and fees. To prevent opportunistic buying of policies, the Federal Insurance Agency (FIA) introduced a 30-day waiting period for flood insurance cover to take effect under the Standard Flood Insurance Policy (Platt, 1999).

In January 1994, the Executive Office of the President assigned to a federal Interagency Floodplain Management Review Committee the mission of delineating major causes and

consequences of the 1993 Midwest flooding and evaluating the performance of existing floodplain management. The Interagency Floodplain Management Review Committee Report was based on research and interaction with the stakeholders such as federal, state and local officials, businesses and interest groups. The report emphasized that the support for those in floodplain should be conditioned on their participation in self-help mitigation programs such as flood insurance. The report also pointed out that the state and local governments must have a fiscal stake in floodplain management. The federal government, on the other hand, has ignored these recommendations and has continued helping disaster victims unconditionally. President Clinton has nearly doubled the number of official disaster declarations in recent years, making federal aid available for even modest weather events, such as eastern Massachusetts flooding in 1998 that drew \$12.5 million in aid (Boston Globe, September 20 1999).

During the last decade, FEMA introduced "Project Impact" which is a pre-emptive strike to remove homes from flood plains and reduce the risk of future flood loss. Project Impact encourages communities, businesses and individuals to take personal responsibility for preventing disaster losses before they occur (Platt, 1999; FEMA web site). Project impact has contributed to the buy out payments for flood prone properties. Between 1978 and January 2000, the federally subsidized national flood insurance program paid out \$3.5 billion for 87,500 buildings that had been flooded more than once. The National Flood Insurance Program has been operating at a loss since 1993. About 30 percent of the 4.1 million insured properties have subsidized premiums, costing just one-third of the actuarial premium, which is the premium based on the calculated risk.

In 1999 Congress, supported by the Federal Emergency Management Agency, attempted to tackle the problem of repetitive flood loss buildings insured under the National Flood Insurance Program through legislation (FEMA web site; The Times-Picayune, August 9, 1999). House Resolution 2728 was introduced in Congress which would authorize an additional \$400 million during the next four years for FEMA's current mitigation grant program. This program would offer money to relocate, elevate or flood-proof properties that are at the greatest risk from flooding. The increased funding proposed in HR 2728 would be an added investment to help FEMA get more people who have been flooded time and time again finally out of harm's way or at least get them high and dry above the reach of the next base flood. FEMA estimates that this investment would save almost \$80 million each year in flood insurance claims and pay for itself upon completion of the effort in five or six years.

7.3 Flood Hazard Assessment

Flood hazard assessment is carried out by hazard mapping. Hazard maps are used to show areas of relative safety and degrees of risk. An important part of the risk assessment of an area includes details on the frequency and expected intensity of flood events. Hazard maps form the basis of sound land use planning and insurance rates.

In the U.S. the Federal Emergency Management Agency (FEMA), as the administrator of the National Flood Insurance Program (NFIP), is responsible for mapping flood hazards. With the help of the U. S. Army Corps of Engineers and engineering firms, FEMA has developed floodplain hazard maps throughout the United States that designate the 100-year floodplain. These maps show where the flood risks are based on local hydrology,

topology, precipitation, flood protection measures such as levees, and other scientific data. Due to land development, variable weather patterns, and other factors, these maps continually change. A Flood Insurance Rate Map (FIRM) is the official map of a community on which Federal Emergency Management Agency has delineated both the special flood hazard areas and the flood risk premium zones applicable to the community. Communities are mapped by the Army Corps of Engineers. Special Flood Hazard Areas, SFHA's, a darkly shaded area on a FIRM or Flood Hazard Boundary Map, FHBM, identify an area with a one percent chance of being flooded in any given year; hence the property is in the 100-year floodplain. Any land area susceptible to being inundated by flood waters from any source, is identified as a floodplain (FEMA web site).

FEMA determines the flood hazard areas by using statistical analyses of records of river flow, storm tides, and rainfall; information obtained through consultation with the community; floodplain topographic surveys; and hydrologic and hydraulic analyses. The Flood Insurance Study (FIS) covers those areas subject to flooding from rivers and streams, along coastal areas and lake shores, or shallow flooding areas. In 1997, FEMA introduced its Map Modernization Plan, with the goal of modernizing the flood hazard mapping effort. The basic components of this plan include the improvement of map accuracy and completeness, map utility, map production, and public awareness and customer service.

The hazard maps are prepared on the basis of hydrologic modeling and flood frequency analysis. The lumped hydrologic models (e.g. HEC-1 and HEC-2) developed by the

U. S. Army Corps of Engineers are the most commonly used models. Analysis begins with the rainfall record for the local area and then simulates the likely discharge that will result from storms of various probabilities. The simulated discharge is routed through the channels and floodplains to estimate flood depth at various locations (Deyle et al., 1998).

The determination of hazardous areas also suffers from the other inherent shortcomings associated with lumped hydrologic modeling and flood frequency analysis. Earlier chapters have discussed the limitations of flood frequency analysis in detail and emphasized the need for better models and understanding for extreme hydrologic events. Scaling approach was presented as an alternative to conventional flood frequency. The statistical analysis currently used by FEMA to assess limits of flood hazard areas is sensitive to the data size and representativeness. It is rare to have sufficiently lengthy records to determine accurately the return period for extreme events. As more data becomes available it becomes part of the record and as subsequently the results of the analysis will also change – this is particularly true for large flood events. However, this is considered to be the best index of flood damage risk and continued to be used. Another important factor in risk estimation is the level of government making the determination of the risk. The risk of flooding for a state is much greater than that for individual regions in the state. Similarly, the risk and the uncertainty becomes even higher at the federal level.

A major problem with traditional flood hazard mapping is the fact that it is based on existing upstream conditions in the watershed. The flood discharge depends on the

upstream land use conditions. In case of an upstream development, the amount of runoff in the watershed can increase beyond the prior estimation. Such regions require frequent updating of flood hazard maps. Some governments have tackled this problem by assuming complete development of each watershed for its models.

It is important to evaluate the significance of the 100-year flood event, the procedure for estimating the 100-year flood and the accuracy of those procedures. This is important because the limits of a 100-year map affect the development and infrastructure in the floodplain. It is also critical to evaluate how the public perceives the risk associated with a 100-year event and the limits prescribed by the hazard map. There are a number of misconceptions associated with the flood frequency and the 100-year flood. Hazard maps have a psychological effect on the risk perception of individuals. It is important to inform the public about the real meaning of the '100-year' flood and the limitations of the procedure by which it is estimated. For example, in Sacramento, CA, updated FEMA hazard maps showed a tremendous expansion of the 100-year floodplain, which created political chaos in the floodplain region. Tobin (1993) states three concepts which the public should be aware: (1) the probability that a 100-year flood will strike a river is the same every year, regardless of how long it has been since the last 100-year flood; (2) it is not a certainty that the 100-year event will occur sometimes in the next 100 years; (3) it is a virtual certainty that the defined 100-year floodplain is not the actual 100-year floodplain.

Friends of the river, a non-profit organization dedicated to preserving, protecting, and restoring California's rivers, streams, and their watersheds, criticizes the current mapping practices (<http://friendsoftheriver.org>):

"In many circumstances, simply because homes are no longer in the regulatory floodplain does not mean they are no longer in danger of being flooded. The much coveted status of being mapped outside of the regulatory floodplain provides the legal fiction that a community or home has complete flood protection. It lulls communities into sense of security because they could be in an area by its geographic location, not its uncertain structural protection that remains at risk from a foreseeable flood event."

7.4 Conclusions

This chapter has briefly presented how federal policies, programs and pronouncements concerning flood hazard mitigation have evolved over the years. Literature review shows that the event-driven policy for mitigating flood damage in the US has come a long way. The focus has shifted from the levees-only policy toward non-structural measures. Adopting non-structural measures has resulted in some improvements but the penetration and effectiveness of these measures is still below their expected level. The recent highly damaging, low probability flood disaster events have had a profound effect on the policies of both the federal government and the insurance industry.

The literature review shows that various task forces, special reports and individual researchers have pointed out a number of problems associated with current flood mitigation policy. Similarly, solutions to those problems have also been suggested by

multiple sources involving individual researchers and government committees etc. The recommendations of the Interagency Floodplain Management Review Committee Report are important for policy making. It is critical to note that the report reiterates earlier recommendations which were neglected by the government. It is obvious that the real problem lies with *implementing* the recommended policies. Without doubt, the implementation issues are complex and governments at different levels have exhibited reluctance to carry the burden of fiscal and political consequences of such policy implementation. Lack of intergovernmental cooperation and coordination is a key factor impeding progress in flood mitigation policies.

One of the most important issues is of appropriate division of fiscal and political responsibility between the federal government and the American society. The state and local elected officials are encouraged by the system to ask for maximum federal disaster assistance. This brings up the question whether the national policy is a program of grants through the federal government or whether it is primarily the responsibility of local communities and private owners to protect themselves, with financial assistance from the federal government when absolutely needed (Platt and Rubin, 1999)

The risk perceived by the people in a community has a large influence on the success of any flood mitigation policies and strategies there. A variety of factors can contribute to the formation of risk perception, including the availability of information about the risk, ability to estimate risk to personal property and life, perceived cause of flood hazard associated with extreme hydrologic events and personal experience with flood hazards. It is believed that people use heuristics to simplify risk assessment. Individuals have

difficulty imagining low probability, high consequence events happening to themselves. This may be one reason why a certain percentage of the populations has a high risk tolerance level. Earlier sections discussed the misunderstandings associated with the 100-year flood events and the unintended effects of the 100-year flood concept. Critics argue that by choosing the 100-year flood, FEMA increases the exposure to low probability, high consequence floods.

Information dissemination can be used to increase awareness. FEMA has been using various channels of information (including advertising and Internet) to provide detailed information for both public and technical professionals. Mitigation through information, however, is not enough because the cost of hazard mitigation and exposure is spread out to society as a whole. Mandatory programs such as required flood insurance in high risk areas are used to counter such attitudes.

In the next chapter, we evaluate policy options for flood hazard mitigation, discuss land use planning and insurance policies in detail, identify the barriers to effective flood damage policy formulation and present recommendations.

CHAPTER 8

Recommendations for Flood Damage

Mitigation Policy Options

8.1 Policy Goals

Public policy goals for mitigating flood disaster damages involve a complex blend of social, political, economic and psychological factors. Policy, which can be made and set at any level of government (see figure 8.1), sets the framework within which actions are taken. The policy process is dynamic and iterative, starting with analysis and continuing with formulation of policy and implementation. It involves a number of steps: problem definition, analysis of the cast of characters, bring together multiple interest stakeholders, definition of strategy, developing alternative solutions or strategies, determining a means of implementation, enforcement and regulation and finally revision of the policy. Chapter 7 presented a history of the issues and discussed the role of stakeholders and the political nature of flood policies. This chapter would focus on policy formulation and policy implementation.

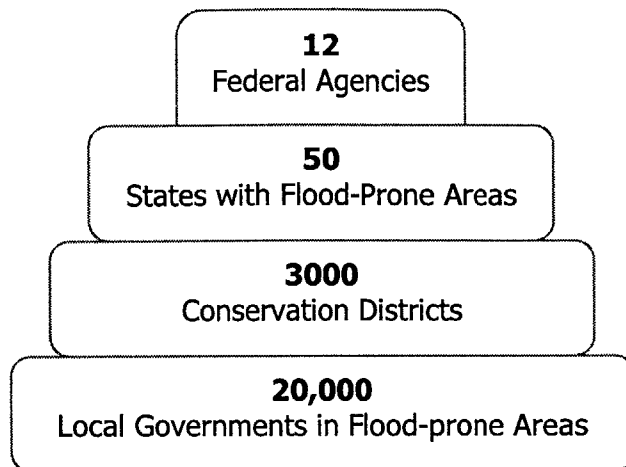


Figure 8.1. Agencies and levels of government sharing responsibility for flood hazards.
Source: Burby (1998); Federal Emergency Management Agency.

In order to formulate effective policies for flood damage mitigation, the goals of the desired policy should be clear. The goals of the policy serve to specify the appropriate levels of responsibility and the appropriate relationships among public authorities (Tobin, 1993). In general the goal of any hazard-related policy is to reduce exposure and vulnerability in a cost-effective manner while placing the burden of recovery on those who suffer losses from natural disasters. Any goals of reducing vulnerability to floods has a number of options embedded in it, each of which must be considered in relation to the nature, values and operations of the political system as well as the needs and constraints associated with flood hazards. We would discuss the policy options for flood damage mitigation in the next section. Then, we will focus on: (1) land use planning and management and (2) Insurance, as the tools for mitigating flood damage. For each of these options, we will consider the history, issues, effectiveness of the approach and the obstacles to formulating effective policies. Finally recommendations and strategies for implementing the land-use and insurance policies are described.

8.2 Alternative Flood Damage Mitigation Policy Options

Evaluation of alternative flood damage mitigation policies can be carried out through a variety of methods and approaches. A detailed evaluation of policy options is necessary in order to understand their effectiveness and limitation. It should be emphasized that comprehensive flood mitigation policy is a combination of careful planning and implementation of a number of different policy options, not just any one option in isolation.

Godschalk et al. (1998) have enumerated a comprehensive list of principles and criteria for preparing and evaluating mitigation plans. The principles include clarity of purpose, citizen participation, issue identification, policy specification, fact base, policy integration, linkage with community development, multiple hazard scope, organization and presentation, internal consistency, performance monitoring and implementation.

Economic criteria are often used to decide about the planning for disaster planning and mitigation. Planning for hazard mitigation has clear benefits in terms of reduced losses, but must be balanced against the costs of implementing and maintaining a policy. The opportunity cost of a piece of land not being utilized must be taken into account. As mentioned earlier, this presents a situation where an economic value has to be placed on many intangible factors including loss of human life and social disruption. Clearly, this is a difficult question and answer to this problem remains elusive. A common economic based method is the benefit-cost analysis, in which all costs and benefits are evaluated in terms of dollars and a net benefit-cost ratio is computed to determine

whether a project should be undertaken. Usually a hydrologic-hydraulic-economic model is used to estimate expected flood damage.

Evaluating costs and benefits of flood mitigation policies is a complex task. Not all of the damages and costs are financial and therefore are difficult to quantify. Also, flood events produce ripple-effects throughout the community thus increasing the variables to be considered. To the extent possible, efforts are made to base decisions on objective criteria and to get an objective understanding of the net benefit or loss associated with these actions.

Another approach to evaluate the flood damage mitigation policies is the cost-effectiveness method. Cost-effectiveness analysis evaluates how best to spend a given amount of money to achieve a specific goal; this type of analysis does not necessarily measure costs and benefits in terms of dollars, or any other common unit of measurement.

In a study entitled "Report on Costs and Benefits of Natural Hazard Mitigation" , the Federal Emergency Management Agency (FEMA) used both benefit/cost analysis and cost-effectiveness analysis because of the inherent difficulties in empirically measuring all the disaster impacts and the corresponding value of mitigation measures (FEMA web site). Wherever possible however, associated costs and benefits of mitigation measures were measured in terms of dollars by FEMA. The report notes that land use planning is generally most effective in areas that have not been developed, or where there has been minimal investment in capital improvements. Since location is a key factor in

determining the risks associated with natural hazards, land use plans are a valuable tool in that they can designate low-risk uses for areas that are most vulnerable to natural hazards impacts.

The conclusions presented at the end of chapter 7 also point out that land use planning has the potential to be a very effective tool for mitigating flood damages in the future. It was also discussed that flood insurance has a potential to be effective measures for flood damage mitigation but it has not been fully utilized in the past. In the next sections we discuss in detail the possible advantages of using land use planning and insurance and the associated issues and concerns of the various stakeholders.

8.3 Land Use Planning

Land use planning in the floodplain encourages controlled development in flood hazard areas through open space reservation, building restrictions and flood insurance requirements. The basic idea is to keep the people out of the flood's way (instead of the other way round) by discouraging development of hazardous areas or, where development is warranted on economic grounds and little environment harm results, by imposing special building standards that reduce vulnerability. Land use regulations transfer much of the burden of avoiding disaster costs to the owner of the affected property. Compared to other measures for flood mitigation, land use planning provides a less expensive and highly effective means of controlling damages from floods.

Even though the logic of land use planning and management as a main instrument for mitigating flood disaster is clear, there are a number of reasons why only a few regions

have proactively implemented land use planning. Space occasionally inundated by floods is often ideal for residential and commercial use during nonfood periods. Floodplains provide relatively flat lands where buildings, roads and utilities can be easily constructed.

The stakeholders in the flood disaster mitigation policy have conflicting objectives with regard to land use planning. Accordingly, there is a conflict in public policy goals of promoting the economically beneficial uses of land and the accompanying desire to allow individuals free use of their property with the goal of promoting public safety and protection against flood damages. Further complicating factors include the inaccuracy in estimation of the risk and preparation of hazard maps, public misconception of the risk and lack of incentive in the public for bearing higher share of the responsibility and financial cost of the damage.

The two main types of land use measures are location and design (Burby, 1998). The goal of the locational approach is to reduce losses in future disasters by limiting development in hazardous areas. This approach tends to be effective in reducing losses, preserving environmental values and providing opportunities for outdoor recreation. Tokyo city is an example where floodplain space is utilized for parks. These gains come at the cost of giving up some of the economic benefits offered by hazard prone land. The goal of the design approach is safe construction in hazardous areas. This type of land use allows economic gains to be realized, but at the cost of susceptibility to greater damage when flood event is of a greater magnitude than the design standards employed can resist. It is important to develop a right mix of these two land use approaches.

Location planning includes land use regulation such as zoning and a number of nonregulatory techniques such as buying hazardous areas and using them for temporary activities such as recreation and locating development-inducing public facilities and services only in areas that are relatively free of hazards.

Design and development of structures is also subject to regulatory and nonregulatory measures. Regulatory measures includes building codes and ordinances controlling design. Nonregulatory measures include disseminating public information and training programs about flood-proofing design techniques and low-cost loans and other types of subsidies for making the improved designs attractive and affordable.

It should be emphasized that land use approach is not suitable for all locations and there are complex socioeconomic and political barriers to this approach. Later sections will discuss these issues in detail.

Land Use Planning and Management in the United States

Land use planning and management for flood disaster management in the U.S. started in 1930s. The Tennessee Valley Authority developed pioneering programs in floodplain management along with other related programs in 1933. The National Flood Insurance Program was another major step towards land use planning for flood mitigation in combination with insurance. The Flood Disaster Protection Act of 1973 made land use management and participation in the NFIP prerequisites for federal financial assistance including disaster assistance. The Act required (in contrast to 'encourage' as it was stated in the 1968 law) states or local communities as a condition of future federal

financial assistance, to participate in the flood insurance program and to adopt adequate flood plain ordinances with effective enforcement provisions consistent with federal standards to reduce or avoid future losses. Until 1960s, zoning considerations did not include hazards.

Dunham (1959) argued that floodplain zoning should be held valid to protect (1) unwary individuals from investing or dwelling in hazardous locations, (2) riparian landowners from higher flood levels due to ill-considered encroachment on floodplains by their neighbors, and (3) the community from the costs of rescue and disaster assistance (Platt, 1999). In 1972, the Massachusetts Supreme Judicial Courts in *Turnpike Realty Co. v. Town of Dedham* provided a strong decision upholding a local floodplain zoning ordinance. The court relied on the Dunham (1959) rationale mentioned above and declared that the general necessity of flood plain zoning to reduce the damage to life and property caused by flooding is unquestionable. During the 1970s and the 1980s, state and local floodplain regulations were widely adopted in response to the National Flood Insurance Program and increasing public recognition of floods. When dealing with challenges to these laws, the courts mostly followed the *Turnpike Realty* rationale.

The report of the Interagency Floodplain Management Review Committee in 1994 had a cautious view of land use control. The report stated that land use control is the sole responsibility of state and local entities. The federal responsibility rests with providing leadership, technical information, data and advice to assist the states.

In the 1990s, the property rights movement and some other political movements presented strong opposition toward governmental regulations over the use of private land. The property rights movement has challenged public land use regulations of many types through political action, litigation, public outreach, and, in extreme cases, intimidation. Restrictions on building along hazardous coastal shorelines have been particularly controversial. Property right advocates have also sought to enlarge the scope of compensation for “regulatory takings” in many recent Supreme Court decisions. They base their argument on the fifth amendment to the U.S. Constitution, which states in part: “nor shall private property be taken for public use without just compensation.” Jansujwicz (1999) provides a detailed account of the backlash against regulation by the property rights movement.

8.4 Flood Insurance

Insurance is a method for redistributing flood losses. The people at risk join forces, in advance, with a large financial organization to spread the cash burden from one major flood disaster over a number of years through the payment of an annual premium (Smith, 1998). If the premiums are set at an appropriate rate, those premiums can be used to compensate the minority who suffer loss in any given year. Due to the high direct cost of floods, insurance is regarded as an important loss-sharing strategy.

Insurers can address the problem of the increasing economic cost of disasters through joint efforts with other stakeholders, and through the use of strategies that combine insurance with well-enforced building codes and land use regulations. In this section we look at the supply and demand of insurance policies for flood damages, the effectiveness

of the National Flood Insurance Program (NFIP) in the past, the problems and issues surrounding NFIP, regulation of insurance and the possible future role of private insurance companies.

Flood insurance poses some special problems for the insurance companies. The ratio of claims to premium is unfavorable for the insurers. The setting of appropriate premium is difficult. These problems are exacerbated by adverse selection which occurs when a large potential loss is spread over a relatively narrow policyholder base (Smith ,1988). Since the flood-prone area residents are more likely to buy insurance, the insurers face a higher risk of paying large claims. Therefore, policy underwriters try to ensure that the property they insure is spread over diverse geographical areas so that only a fraction of the total value at risk could be destroyed by a single event.

Moral hazard, another problem faced by both the insurance and the reinsurance industries, refers to an increase in the probability of loss caused by the behavior of the policy holder. A usual way to deal with moral hazard is to provide deductibles and coinsurance as part of the insurance contract. A sufficiently large deductible can act as an incentive for the insureds to continue to behave carefully after purchasing coverage because they will be forced to cover a significant portion of their loss themselves.

Insurance may even encourage invasion into flood-prone zones. The very availability of flood insurance guarantees reimbursement and removes the risk of catastrophic financial failure (Lind, 1967). The premiums should be such that the flood insurance

costs at least as much as the average annual damage. Subsidizing the premium can make the land use in a flood-prone area more attractive.

Reinsurance provides protection to the insurance companies against extraordinary losses. It is important for offering insurance against natural hazards where there is a potential for catastrophic damage. In a reinsurance contract, the reinsurer charges a premium to indemnify another insurance company against part of the loss it may sustain under its policies of insurance. A common type of reinsurance contract is a treaty, a broad agreement covering some portion of a particular class of business.

Different sharing arrangements are possible between the reinsurer and the insurer: quota share treaty, pro rata treaty or excess of loss treaty are examples of the common treaties.

Reinsurance is a global business because of the need to spread risk and access domestic and foreign capital markets to help cover losses. About two-thirds of all property reinsurance placed on risks occurring in the United States is held by foreign reinsurance companies. In the 1990s, the cost of natural disasters rose to alarming heights due to a number of low probabilities, highly damaging events. These events exposed the vulnerability of the financial performance of the insurance agencies. For the first time, the risk of market failure was real. Since then the insurance and reinsurance industry have taken steps to ensure a better response from their industry to catastrophic events. In 1993, reinsurers renegotiated contract terms according to the reevaluation of catastrophic exposure. Also there has been a trend of consolidation among reinsurers which reflects a demand by ceding companies for greater reinsurance security.

National Flood Insurance Program

The market conditions for flood insurance made it unprofitable for the private companies to provide insurance against floods. The National Flood Insurance Program (NFIP) was set up by Congress in 1968 to ensure the nationwide availability of insurance for floods. The NFIP was based on cooperation between the federal government and the private insurance industry. The insurance structure of NFIP includes two classes of properties: those insured at full actuarial rates and those that, because of their date of construction, are statutorily eligible to be insured at lower rates which do not reflect the full risk to which the property is exposed. Flood Insurance Rate Map (FIRM) is used to determine the rates. Properties built prior to the date of availability of FIRM (called pre-FIRM structures) are insured at subsidized rates to provide incentive to local communities to participate in the NFIP. These subsidized rates as a percentage of the actuarial rate, have been increasing over the years. At the same time, the number of properties requiring a subsidy has also declined from 75 percent in 1978 to 35 percent in 1997. The premium paid by this group of insureds are estimated to be about 38 percent of the full-risk premium needed to fund the long-term expectation for losses.

In 1983, NFIP involved the private insurance companies through the Write-Your-Own-Program (WYO), an arrangement by which the private insurers sell and service federally underwritten flood insurance policies under their own names, retaining a percentage of premium for administrative purposes. The responsibilities of both the insurers and the federal government are specified in an annual contract. The companies are represented

on the WYO Standards Committee. At present, about 92 percent of NFIP policies are written by WYO companies (FEMA web site).

The National Flood Insurance Program's (NFIP) Community Rating System (CRS) was implemented in 1990 as a program for recognizing and encouraging community floodplain management activities that exceed the minimum NFIP standards. The National Flood Insurance Reform Act of 1994 codified the Community Rating System in the NFIP. Under the CRS, flood insurance premium rates are adjusted to reflect the reduced flood risk resulting from community activities that meet the three goals of the CRS: (1) reduce flood losses; (2) facilitate accurate insurance rating; and (3) promote the awareness of flood insurance. The communities are recognized based on their floodplain management activities. A community receives a CRS classification based on the scores of its activities, evaluated by field verification of the activities included in the application. There are ten CRS classes: class 1 requires the most credit points and gives the largest premium reduction; class 10 receives no premium reduction. A community that does not apply for the CRS or does not obtain a minimum number of credit points is a class 10 community. About 32 percent of the CRS communities are a class 8 or better.

Now we review the financial status of NFIP. As discussed previously, the NFIP is funded throughout the National Flood Insurance Fund. Before 1981, no action was taken regarding the level of subsidy for existing properties in high-risk areas because the program wanted to promote community participation. Consequently, program expenses exceeded income. The continuing statutory requirement to subsidize certain existing properties in high-hazard areas still makes actuarial soundness an unrealistic goal

(Kunreuther et al., 1998). About 30 percent of the 4.1 million insured properties have subsidized premiums, costing just one-third of the actuarial premium, which is the premium based on the calculated risk. Until 1986, federal salaries and expenses, as well as the costs associated with flood mapping and floodplain management, were paid by an annual appropriation by the Congress. From 1987 to 1990, however, Congress asked the program to pay these expenses out of premium dollars. FEMA suffered a loss of about \$350 million because it could not adjust the premium rates till 1990. Currently, a federal policy fee of \$30 is levied on most policies in order to generate the funds for salaries, expenses and mitigation costs (Kunreuther et al., 1998).

NFIP, nevertheless, operated with a positive cash balance from 1986 to 1995. However in the four fiscal years from 1993 through 1996, the program experienced over \$3.4 billion in losses. Since 1995, the program has started borrowing from the Treasury and the outstanding amount in August 1999 was \$541 million.

Out of the 4.1 million NFIP policies in force (PIF) currently, non-residential structures account for only 4.3 percent of all PIF. The Interagency Floodplain Management Review Committee Report in 1994 criticized the extent of the NFIP market penetration: "The NFIP has not achieved the public participation needed to reach its objectives. This situation is evidenced by the assistance provided to individuals and businesses during the Midwest Floods ... Estimates of those covered by flood insurance nationwide range from 20 to 30 percent of the insurable buildings in identified flood hazard areas".

Kunreuther et al.(1998) identifies the following reasons for this low market penetration as:

- Many floodplain residents fail to estimate the real risk of floods.
- Moral hazard plays a key role – people expect federal disaster assistance in case of a disaster.
- Lack of information and awareness about NFIP. The insurance policies of NFIP are not marketed aggressively.
- Lenders have not been especially zealous in requiring the purchase of flood insurance as the law requires. The insurance NFIP policies are difficult to write.
- NFIP policies are single-peril policies and are considered more costly than other lines of coverage.

In 1995, NFIP launched an advertising campaign to raise national awareness about flood insurance. In the first two years of this campaign, the policy base increased five fold more than the annual average growth.

The 1994 Reform Act was intended to address some of the factors responsible for low market penetration of the NFIP. Some of the changes brought by the National Flood Insurance Reform Act were presented in chapter 7. Some of the ways in which the 1994 act expands the mandatory purchase provisions include:

- The 1973 act required purchase of insurance only at loan inception. The 1994 act calls for lenders to buy flood insurance whenever it becomes known that the property is located in the flood hazard zone.

- It allowed the homeowners to pay for a portion of the premium each month as part of a mortgage payment eliminates the annual temptation to drop the coverage.
- The 1994 Reform Act provides for financial penalties for noncompliance. The absence of real consequences for lenders not requiring flood insurance had created a situation where the importance of flood coverage as mortgage protection was recognized only at the time of an actual flood.

The 1994 Act also provided for additional mitigation tools and buyout options. A “National Flood Mitigation” fund was established to provide grants to states and municipalities for a variety of measures to address local circumstances related to serious flood hazard. Coverage of NFIP was extended to include the additional cost needed to meet NFIP building standards after a flood. Also statutory recognition of the Community Rating System was made.

Issues and Problems with National Flood Insurance Program

NFIP has a complex relationship to federal disaster assistance policies. The role of insurance industry is closely linked to the subsidy provided by the general taxpayers for the disaster struck areas. If the subsidy is low, the burden of paying for the damage is on those living in the hazard prone areas. The availability of federal disaster assistance is considered to be a major disincentive for people to buy flood insurance. In chapter 7, the recommendations of the Interagency Floodplain Management Review Committee provide support for this view. The public perception that federal disaster assistance is equivalent to the financial protection provided by insurance is wrong and serves as a

deterrent to the purchase of flood insurance. Objections have been raised on the buyout programs authorized by the Stafford Disaster Relief and Emergency Assistance Act. The buyouts are available to all affected residents of targeted area whether they are insured or not. If the owners assume the availability of buyouts in the event of a flood, the incentive to purchase flood insurance is reduced considerably.

A main defect of FEMA's floodplain policy is the continuing reliance on the 100-year flood because an increasing percentage of the annual flood damage results from very large floods of low probability, such as the Mississippi flood of 1993. At the least, FEMA should ensure that such exposure to risk is well known to the residents.

In theory, insurance is one of the most effective policy tools for achieving the objectives of cost-effective risk reduction measures while placing the burden of recovery on those who suffer losses from natural disasters. In practice, insurance has not been able to play this role. Insurers do not charge a premium that encourage loss prevention measures because they believe that few people would voluntarily adopt these measures based on the small annual premium reductions in relation to the large up-front cost of investing in these measures. Insurance is a highly regulated industry; rate changes and new policies generally require the approval of state insurance commissioners. Premium schedules with rate reductions for adopting certain mitigation measures require administrative time and energy both to develop and to promote to the state insurance commissioners. If potential policy holders do not view mitigation measures as attractive investments, insurers who developed those premium reduction programs would be at a competitive

disadvantage relative to those firms who did not develop such program (Kunreuther et al., 1998).

8.5 Identification of Constraints and Barriers to Policy Making for Flood Damage Mitigation

In this section, first we discuss the type of constraints on public policy making for flood damage mitigation. Then, based on our discussion of land use planning and insurance as measures of flood disaster measures, we present a list of the most important barriers to implement the policies most likely to bring the highest benefit of flood damage mitigation. The next section will discuss ways of dealing with these barriers.

Type of Constraints

The constraints on public policy can be categorized as:

- physical and technical;
- financial;
- legal, administrative and ownership.

Physical and technical constraints apply most directly to issues of engineering feasibility. Site-specific studies are important and plans should be contingent upon detailed analysis of the local environment. The problem of estimating low probability events is one of the major technical constraint.

Financial resources are perhaps the largest constraint on policy makers. Financial feasibility is dependent on finding enough funds for the project – economic viability is a separate issue which was discussed in a prior section. Usually the projects where results are more readily visible and salient are preferred by politicians.

Questions of legality and administration also constrain the public policy. Individual property rights can directly interfere with the effectiveness of land use planning. There has been a hostile reaction to regulation of private property in the U.S., as witnessed in a number of court cases. Lack of sufficient administrative workforce is an important constraint for enforcement of regulations.

Barriers to Flood Damage Mitigation Policies

We divide the discussion on barriers to flood damage policies in three parts. Before discussing the particular barriers applicable to land use planning and insurance policies, we describe the broad barriers which we find are the most important.

- A need for integrated and coordinated policies at various levels of government. The nation needs a shift from the incremental decision making of the past and pay attention to the score of recommendations by the task forces and investigation groups. For example, inconsistent policies have resulted in a patchwork of land use governance. Federal efforts are limited in focus and undermine the objective of reducing exposure to risk (e.g. by inappropriate disaster assistance).
- Governmental assumption of risk and misguided funding priorities. Current policies place a large financial burden on taxpayers when a disaster occurs. This creates the

classical problem of moral hazard and provides a disincentive for buying insurance and encourages building and development hazardous areas.

- Improper use of fiscal incentives by the federal government in the past. The presidential disaster announcement of even small disasters encourages state and local governments to avoid responsibility of local disasters. The process of disaster declaration is largely political. The nonfederal share of disaster assistance is only 25 percent and even this share has been waived to varying degrees in at least 15 major disasters since 1985. Furthermore, the nonfederal share itself may be obtained from federal sources.
- Lack of a political entity to enforce regulations. Governments at all levels have been reluctant to act on regulations which are politically unpopular.
- Improvement of risk estimation As discussed in chapter 7, the current risk estimation techniques suffer from a number of shortcomings. Improved risk estimation is a critical factor in effective policy making. The recent technical advances should be helpful in making progress in this direction.
- Lack of a clear role of private sector in mitigating flood. Both the local community and private sector need to be engaged more actively in flood damage policies.
- A need to improve public perception of risk by education and information dissemination. Awareness levels are still low. Advertising through the new media can be effective.
- Failure to act regionally. Many of the improvements are only possible at the local regional level. Unless the local communities and governments get actively involved in flood hazard mitigation, the public policies do not have a good chance of success.

- Inconsistent policies. One form of inconsistency has taken place with policies that promote development and policies that seek to limit exposure to risk. The second level of inconsistency is between state and federal provisions. When federal programs rely on incentives and inducements, there is the potential for divergent state policies to undermine federal initiatives (May and Deyle, 1998).
- Complicated stakeholder arrangement. Different stakeholders have a difficult time understanding each others' point of view. For instance, insurance industry and building industry differ on important issues. The large number of government agencies involved in flood hazard mitigation have conflicts. Property right owners are another politically powerful group.

Barriers to Effective Land Use Planning

We have discussed the history of land use policy making in the U.S., the current status of land use and the issues surrounding land use planning. Summarizing, the major barriers to effective land use planning are listed below.

- Avoidance or hesitation at all levels of government to enforce effective land use controls in areas of known hazards. The federal government depends on local government to put hazard mitigation measures in place. However the local governments, facing the problem of balancing desires for development against needs for mitigation, shirks the fiscal and political burden of regulating land use in areas subject to floods (or for that matter, other natural hazards).
- Legal constraints to land use planning. The property right groups have strong lobbying and political power.

- Intergovernmental relationship has been difficult. Local governments complain about the overly prescriptive and coercive attitude of federal government. This results in a lack of trust and divergence in policy goals.
- Uncertainty in the flood hazard maps This underscores the importance of accurate risk mapping and the associated psychological impact on the public perception of risk.
- Insufficient management at local levels to implement policy and ensure compliance
- Fragmentation and inconsistency of policies at various levels of government.
- Conflicts of interest between sectoral (housing, business, agriculture) and public hazard management policies.

Barriers to Effective Insurance Policy Planning

In section 8.4, a detailed discussion was presented on the NFIP and how the private insurance industry can play a role in the flood insurance market. Here we present the obstacles to implementing cost-effective flood insurance policies. These obstacles can be summarized as follows:

- Uncertainty of the risk or in other words, improving the estimate of risk. This is a critical element for the insurance industry.
- Reliance of FEMA on the 100-year flood. This exposes large developed areas to low probability, high consequence floods. This also has the effect of promoting development in areas outside the 100-year floodplain as the public wrongly perceives them to be practically risk-free.
- Property subject to repetitive damages. Such properties account for a high percentage of claims paid by NFIP.

- Public perception of the risk. Unless the public realizes the risk and is able to weigh it against the benefits provided by insurance, insurance penetration will remain low.
- Misunderstanding of the capabilities of insurance industry. Other stakeholders do not fully grasp the limitations and problems faced by the insurance industry.
- Regulation. Insurance premiums are subject to regulation by the government.
- Federal disaster assistance serves as a disincentive to purchasing insurance.
- Subsidized premium rates cost heavily and make it difficult for NFIP to sustain itself. Subsidies partially account for the massive increase in development in hazard-prone regions.

8.6 Policy Recommendation for Implementation

Now that we have presented the history and current conditions, defined the needed changes, identified the impediments and suggest strategies, we present recommendations on how to implement those strategies.

This section answers questions such as:

- What should be done to ensure that the recommended policies are implemented successfully?
- What are the requirements for such implementation?
- Is it realistic to hope that these recommendations would be implemented?

The recommendations are divided in three parts. The first two sets of recommendations deal with land use planning and insurance. Finally some emerging trends and ideas are

presented. Throughout the previous and current chapter, it has been pointed out that federal government has assumed a large portion of the natural disaster cost in the US. It is high time for the federal government to shift the responsibility of mitigating flood damages to the local governments and communities through land use planning, insurance and other measures. The federal government should support the appropriate legislative measures. According to a 1994 report of the National Academy of Sciences, only a fraction of the mitigation measures known to be effective have been implemented. Before we discuss specific recommendations for land use planning and insurance, we present some broad flood disaster policy recommendations.

- Provide consistent and long-term policies at different levels of government
- Improve intergovernmental working relationship
- Reduce need for declaration by depoliticizing individual assistance
- Reduce the share of federal disaster assistance
- Support the non-federal flood mitigation
- Share decision making from the whole array of stake holders

Recommendations and Suggestions for Land Use planning

The Interagency Floodplain Management Review Committee Report (1994) recommended improvements to the floodplain management program. To ensure a long term, nationwide approach to floodplain management, the committee proposed legislation to develop and fund a national floodplain management program with principal responsibility and accountability at the state level.

State and local governments must develop commitment to manage hazardous areas. This will involve citizen participation. The Community Rating System of FEMA is a step in this direction and has been fairly successful. However, for communities with floodplains that have not been developed extensively, the Community Rating System does not provide enough incentive for communities to begin planning before these areas are committed irreversibly to urban development (Burby et al., 1998).

A few states have experimented with state growth management programs that feature the formulation of integrated and internally consistent state goals and policies along with state mandates that local governments engage in systematic processes to plan and manage land use (Burby et al., 1998).

Burby et al. (1998) recommend the following steps for the federal government to ensure that state and local planning and land use management include natural hazard management considerations:

- Local preparation of floodplain management plans
- Requiring area wide hazard adjustment plans that give full consideration to land use, not just plans for individual projects
- Increase the payoffs for planning by increasing the insurance credit given through the Community Rating System
- In addition to flood hazard maps, provide expanded risk analysis

Recommendation on Effective Insurance Policies

The recent developments in technology and data analysis and the recent availability of capital market funding for supplementing traditional reinsurance, allow us to develop a strategy in which private insurance can play a major role in encouraging cost-effective risk reduction measures.

Obviously, improving the estimates of risk would be very valuable for the insurance industry. The federal government can play an important role by using the existing knowledge base and transferring that knowledge to the private-sector decisions related to flood hazards.

An individual's perception of risk plays an important role for the individual's decision to purchase an insurance. The public should be educated about the risk and the options to mitigate the risk. Experience has shown that aware and informed property owners are more likely to engage in risk reduction activities. Technologies such as Geographic Information Systems (GIS) have greatly improved the accuracy and speed of producing maps. Similarly, Internet has proved invaluable for spreading useful and timely information to the public.

Providing financial incentive to buy the insurance is another way to encourage purchase of flood insurance. The most common financial incentives include premium reductions, lowering the deductible, changes in coinsurance schedules etc. Deductibles and coinsurance encourage the policy holder to proactively guard oneself against minor losses; the insurance company is spared the expense of dealing with small claims. The

open question is: What would be the most effective ways of providing subsidies to low-income families to encourage them to adopt cost-effective risk reduction measures?

Property owners will most likely be encouraged to implement mitigation measures if obtaining insurance depends on verification that the property to be insured has been built to an acceptable standard, or retrofitted to reduce the risk of property damage (Kunreuther et al., 1998). The Federal Insurance Administration has demonstrated the power of conditional availability as an incentive by making flood insurance under the NFIP dependent on the participating community's adoption and enforcement of floodplain management regulations.

Other Alternatives for Protection Against Catastrophic Losses

In order to broaden the protection against catastrophic losses, new sources of capital from the private and public sectors could be utilized by the insurers. In the recent years, investment banks and brokerage firms have shown considerable interest in developing new financial instruments for protecting against natural disaster losses. Their objective is to find ways to make investors comfortable trading new securitized instruments covering catastrophe exposures. One example is the Act of God bonds floated by the insurance company USAA in 1997, which provided them with protection should a major hurricane hit Florida. Use of insurance pools has also been considered. However, there are a number of legal and political challenges faced by such pools (Kunreuther et al., 1998).

Lewis and Murdock (1996) proposed that the federal government offer catastrophe reinsurance contracts, which would be auctioned annually. The Treasury would auction a limited number of excess-of-loss (XOL) contracts covering industry losses between \$25 billion and \$50 billion from a single natural disaster. XOL contracts would be sold to the highest bidder above a base reserve risk-priced price. Insurers, reinsurers, and state and national reinsurance pools would be eligible purchasers. Half of the proceeds above the reserve price would go into a mitigation fund and the other half to be used for payouts.

Another proposed option is for the federal government to provide reinsurance protection to the private insurers by charging a fee for excess-loss-coverage. This allows the government to use its resources to protect the insurers and the insurers do not have to pay the higher-risk premium that the reinsurance market demands.

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