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16. Abstract

Rainfall runoff modeling at a watershed scale requires the definition of the storm event and of the conveying characteristics of the watershed. This research project focuses on the geographic definition of the storm event, that is, on the spatial distribution of precipitation over the watershed. As the watershed size increases, the likelihood that a storm will cover the entire watershed decreases, and it becomes necessary to identify which parts of the watershed are affected by the storm and which are not. Traditionally, precipitation estimates have been based on precipitation records obtained at discrete points (i.e., precipitation stations), which led to depth-duration-frequency (DDF) equations or curves. An estimate of the area covered by the storm event, however, has not been included in the analysis, and it has been customary to assume it uniformly distributed over the entire watershed, regardless of its size. Thus far, no model has been developed to map the area of the watershed that is covered by the storm, as well as to determine the spatial distribution of precipitation over this area. Use of NEXRAD precipitation data, however, will allow the development of a model and geographic-information-systems (GIS) based application that relaxes the assumption of uniformly distributed precipitation and estimates the storm precipitation distribution within the watershed.

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GIS STATIC STORM MODEL DEVELOPMENT: LITERATURE REVIEW AND PROGRESS REPORT

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LITERATURE REVIEW

INTRODUCTION

Information about extreme precipitation holds great interest for a variety of purposes including hydraulic structure design, which entails knowledge about the spatial and temporal variability of average rainfall over an area. Design rainfall values are generally expressed in the form of point rainfall intensity values (i.e., the rainfall depth at a location). In order to obtain average rainfall values for an area, hydrologists and engineers require techniques that can transform point rainfall amounts to average rainfall amounts over a specified area. These average values are the mean rainfall depths over an entire catchment. The problem of point-to-area rainfall conversion can be addressed using depth-area curves. Current practices using these depth-area curves are dominated by the use of areal reduction factors (ARFs). Catchment intensity-duration-frequency (IDF) curves are obtained by multiplying the rainfall intensity estimates from the point IDF curves by the ARFs corresponding to that area. Therefore, ARFs are applied to point rainfall depths to convert them to equivalent measurements for the whole catchment area. ARFs are, thus, key parameters in the estimation of hydrologic extremes (Veneziano and Langousis, 2004), and are functions of storm characteristics, such as size, shape, and geographic location (Asquith and Famiglietti, 2000).

ARFs, as defined by the Natural Environmental Research Council (NERC, 1975), "are factors, which when applied to point rainfall values for a specified duration and return period, give areal rainfall for the same duration and return period." The concept of ARFs provides a powerful framework for studying the spatial variability of the different hydrological processes. This problem of reduction of extreme rainfall with respect to area covered by a storm and its duration is a focal issue and has been dealt with in various ways.

TYPES OF AREAL REDUCTION FACTORS

The two types of ARFs commonly used are *geographically fixed* and *storm centered* (U.S. Weather Bureau, 1957, 1958a, 1958b; Miller et al., 1973; Srikanthan, 1995).

Geographically Fixed

Geographically fixed ARFs (also known as *fixed area*) relate rainfall at a given point to rainfall in a given area that comprises the point. They are estimated from the average of frequency-based quantile estimates using annual maxima rainfall series observed at a fixed location (Siriwardena and Weinmann, 1996). The area under observation is fixed in both time and space, and hence these kinds of areal reduction factors are referred to as *fixed-area ARFs*. In this case, the center of the storm needs not coincide with the center of the area, and so the values of the ARFs are based on different parts of different storms instead of the highest point values at the respective storm centers. These ARFs originate from rainfall statistics and not from individual storms, are also referred to as *statistical reduction factors,* and can be represented by:

$$ARF = R_{GF} / P_{GF}$$

where R_{GF} is the mean of annual maximum rainfall values, and P_{GF} is the mean (generally the weighted mean because of uneven spatial distribution of rain gages) of annual maximum point rainfall values at gaged points located within the area under consideration (Bell, 1976).

The values of these ARFs are based on the magnitude of the annual maximum mean precipitation computed for the rain gages in the area and the frequency analysis of their time series. The frequency of the point precipitation is generally taken to be equivalent to the frequency of the areal precipitation. The annual maximum at individual gage stations very rarely occurs at the same time and for the same storm event, which therefore necessitates a very dense network of closely spaced rain gages. These types of ARFs represent aggregate storm behavior and not discrete individual storm behavior, so they are used with information from precipitation frequency studies.

Storm-Centered Areal Reduction Factors

Storm-centered ARFs are associated with the calculation of the effective depth for discrete storms. They represent profiles of individual storms and are supported by data provided by the U.S. Army Corps of Engineers' historical storm rainfall atlases. In reality, the area in which the rain falls is not preset but changes with each storm. In this case, the point of maximum rainfall is the center of the storm and is representative for calculation of the ARF. The ratio of average storm depth over an area and maximum rainfall depth of the storm is defined with the help of these values. Contour lines of depth are divided by the maximum depth of the storm and then integrated to obtain the average storm depth. Storm-centered ARFs are given by:

$$ARF = R_{SC} / P_{SC}$$

where R_{sc} is the areal storm rainfall enclosed by a selected isohyet and within which the rainfall is everywhere equal to or greater than the value for the isohyet and P_{sc} is the maximum point rainfall at the storm center.

This approach to calculate ARFs is difficult to implement on multi-centered storms, and is preferred for individual storms. Likewise, Omolayo (1993) asserts these ARFs are incorrect for estimating areal rainfall of a particular frequency from point rainfalls. Studies relating to probable maximum flood (PMF) generally require this type of ARF, whereas storm-centered ARFs refer to a discrete storm.

Recently, a third approach known as the annual maxima-centered approach (Asquith and Famiglietti, 2000) has also been adopted. This approach considers the spatial distribution of rainfall occurring concurrently with and surrounding an annual maximum at a point within the watershed.

BACKGROUND

PREVIOUS STUDIES ON AREAL REDUCTION FACTORS

As quoted by Michele et al. (2001), theoretical approaches for the derivation of the ARFs were developed based on the correlation structure of the extreme storms (Roche, 1966). The earliest studies based on empirical analysis of single storm events, seldom took into account the return period of the event (U.S. Weather Bureau, 1957, 1958a, 1958b). Bacchi and Ranzi (1996) cited that in some countries, like Italy, these kinds of studies were some of the initial and most influential conducted (Supino, 1964), and even today they are very popular in the definition of a design storm for urban drainage systems. The introduction of variance functions and reduction factors further extended the theoretical approach (Rodriguez-Iturbe and Mejia, 1974b). Other studies presented include a stochastic derivation based on the analysis of the crossing properties of rainfall processes aggregated both in space and time (Waymire et al., 1984; Bacchi and Ranzi, 1996) and prototype studies directed toward estimating ARFs using digitized radar-returned data (Frederick et al., 1977).

Sources of Areal Reduction Factors

The most common sources of ARFs for the United States are the U.S. Weather Bureau (1957) (Technical Paper-29, also referred to as TP-29), Hershfield (1961a) (TP-40), Miller et al. (1973) (NOAA Atlas 2), and Zehr and Myers (1984) (Hydro-35). Miller (1964) (Technical Paper-49) extends the results of the earlier studies to storms with durations up to 10 days. Further, the U.S. Weather Bureau TP-49 (1957) presents ARFs from areas ranging from 0 to 1024 km^2 and for durations from 30 minutes to 24 hours. Data used were from seven dense gauging networks located in the eastern and central United States. The values of ARFs are general values applicable to any region; however, they were particularly developed for the regions east of the Mississippi River and represent an areal reduction factor-area curve based on a 2 year recurrence interval. This curve can be employed for all return periods up to 100 years. The U.S. Weather Bureau (1957) defines ARF as the ratio of mean annual maxima of areal precipitation to the mean annual maxima of point precipitation. This report concludes that average area and storm duration were the parameters that affected depth-area factors. The authors assumed that depth-area relations are not influenced by the recurrence interval of point precipitation. Therefore, frequency of areal precipitation is equal to frequency of point precipitation. Part 2 of the U.S. Weather Bureau report (1957) augments the results of Part 1. The authors used data obtained from additional dense gauging networks in the western United States. Leclerc and Schaake (1972) expressed the results of U.S. Weather Bureau (1957) by:

$$ARF = \frac{Z_E}{Z_T} = 1 - e^{-1.1t^{0.25}} + e^{(-1.1t^{0.25} - 0.01A)}$$

where

Z_E = effective precipitation over the area (inches),

Z_T = point precipitation of the design storm depth for recurrence interval T (inches),

t = duration time (hours), and

A = area (square miles).

Depth-area reduction curves published in Hershfield (1961a) and Miller et al. (1973) were identical to those published earlier in U.S. Weather Bureau (1957) Parts 1 and 2. Miller (1964; TP-49) extended these results to storm duration up to 10 days. Miller included estimates for 2, 5, 10, 25, 50, and 100-year depth ARFs using annual data series, but the results for different return periods were almost the same, and so he concluded that there was no need to publish these results for all frequencies. Other sources for depth duration frequency (DDF) factors are Hershfield (1961a) and its extended document by Frederick et al. (1977) and Hydro 35, which gives the DDF data for eastern United States for durations of 5 to 60 minutes and frequencies up to 100 years (Zehr and Myers, 1984).

METHODOLOGIES FOR THE DERIVATION OF AREAL REDUCTION FACTORS

Development of ARFs mainly has occurred in the United States, United Kingdom, and New Zealand (Omolayo, 1993). However, other parts of the world have not conducted much work to estimate these values because of sparse networks of rainfall stations and short record histories. Scientists use many methodologies to transpose these ARFs to different parts of the world. Some of the major methodologies in practice for the derivation and transposition of ARFs follow.

U.S. Weather Bureau Method (as presented by Omolayo (1993))

This method calculates the areal rainfall of each event of the chosen duration using thiessen weighting factors, and selects the highest of these in each year of the record. The mean of the entire annual series is computed and the highest point measurement at each station in each year is selected. The areal reduction factor results from this mean divided by the total mean over all the stations over all the years of record:

$$ARF_{US} = \frac{\sum_{j} \sum_{i} w_i U'_{ij}}{\sum_{j} \sum_{i} U_{ij}}$$

where

U_{ij} = annual maximum point rainfall at station *i* in year *j*,

Uij′ = point rainfall at station *i* on the day the annual maximum areal rainfall occurs in year *j*, and

w = thiessen weight factor for the station.

UK Method (as presented by Omolayo (1993))

The UK Method notes the point measurements (U_i) of the annual maxima and identifes the maximum point recordings (Ui) at each station in the same year. The ratio of the two values at each station in the year is calculated, and then the grand mean of these ratios over all stations and all years of record is adopted as the areal reduction factor:

$$ARF_{UK} = \frac{(1/IJ) \sum_{j} \sum_{i} U'_{ij}}{U_{ij}}$$

where

U_{ij} = annual maximum point rainfall at station *i* in year *j*,

U_{ij}' = point rainfall at station *i* on the day the annual maximum areal rainfall occurs in year *j*,

w = thiessen weight factor for the station,

I = number of stations, and

J = length of the data records (years).

Rodriquez-Iturbe and Mejia (1974b)

Rodriquez-Iturbe and Mejia (1974b) worked with the concept of effective precipitation to establish a relation for converting the point precipitation to effective precipitation for an area. Their method has application for various geographic areas. This method estimates the effective depths for discrete storms and long-term mean effective precipitation including distribution of precipitation for multiple inputs in a rainfall model. A correlation distance, which is the mean distance between two randomly chosen points, is defined. The correlation factor representing this distance is given by:

$$ARF = \sqrt{E\{\rho(d)\}}$$

where E{ρ(d)} represents the expected value of the correlation coefficients for the derived correlation distances.

Although the approach used by Rodriquez-Iturbe and Mejia (1974b) is simple and provides an extensive framework for transforming point depths to areal depths, it does not focus on the estimation of areal precipitation distribution of design (i.e., frequency based) storms.

Bell (1976)

Bell (1976) developed geographically fixed ARFs based on an empirical approach that is similar to the approach followed by the U.S. Weather Bureau (1957), the difference being that it also accounts for return period. Bell's method calculates areal rainfall using thiessen weights as weighted averages of annual maximum point rainfall values. The values obtained from the annual maximum areal series using thiessen weights and the values of the annual maximum series of point rainfalls for each station are ranked. Using thiessen weights (w_i), point rainfalls of the same rank are weighted and an annual series of weighted maximum point rainfalls is obtained. ARF_r, with the subscript *r* representing rank, is the ratio of the areal precipitation of rank *r* to the thiessen weighted average point rainfall of the same rank. This ratio indicates the variation in ARF with rank, and therefore the return period. Mathematically, Bell's (1976) ARF is represented by:

$$ARF_r = \frac{\sum_{i=1}^{k}\left(w_i \tilde{R}_{ij}\right)_r}{\sum_{i=1}^{k}\left(w_i R_{ij}\right)_r}$$

where

$\widetilde{R}_{ij}$ = point rainfall for station i on the day the annual maximum areal rainfall occurs in year j,

R_{ij} = annual maximum point rainfall for station i in year j,

w = thiessen weight factor for the station, and

k = number of stations in the area.

Myers and Zehr (1980)

Myers and Zehr (1980) developed depth-area curves based on a new statistical simulation approach that accentuates station pair data. They used the approach in the Chicago region, where a dense gauging network covering the entire area is available. The authors point out that *fixed-area* ARFs are the ratio of the expected point precipitation depth to the expected areal average values for a given watershed. Myers and Zehr (1980) underscored the importance of the effect of the return period on the depth-area reduction factors. One of the imperative inferences they came to was that lower depth-area reduction factors are associated with longer return period events than with the shorter return period events. The values of the ARF factors they deduced are generally not intended to describe the spatial and temporal variability of the design storms, nor can the expected values describe the multifaceted structure of the storm. In addition, estimation of ARFs cannot be based on stochastic precipitation simulations. Although the approach followed by Myers and Zehr (1980) is useful, it is computationally complex and is difficult to implement in design practice.

Bacchi and Ranzi (1996)

Bacchi and Ranzi (1996) proposed a stochastic derivation of the geographically fixed ARFs based on the crossing properties of rainfall processes aggregated in space and time. They assumed a Poisson distribution of the number of crossings of high rainfall intensity and adopted a hyperbolic tail of probability of exceedence of rainfall intensity. They conducted their work in parts of northern Italy, and their theory was supported by data collected from analysis of radar maps that were representative of the rainfall events taking place in that part of the country during the passage of frontal systems. This theory is based on a stochastic approach, with substantial modifications. The reduction factor is taken to be the ratio of areal and point precipitation intensity values with the same duration and frequency of occurrence. The analysis focuses on the inference and calibration of the distribution function aggregated process. The factors derived from the formulation of the statistical analysis are analytically complex and represent power law decay with respect to area and duration of the storm. From the research, Bacchi and Ranzi (1996) were able to prove that the ARFs depend upon the return period and the size, in space and time, of the domain where the process was considered stationary and homogeneous. The probability functions and expected values of the directional derivatives of the processes were calibrated by analyzing radar data. The data of the cell value was checked with the corresponding rain gage data collected for that particular place. Map analysis showed that power law functions fitted well in the plots of the expected absolute value of the derivative vs. the spatial and temporal scales of integration. A censored Pareto distribution was chosen for the inference of high-intensity levels of rainfall due to its hyperbolic tail and because it can be expressed using a simple analytical expression. The parameters of the distribution were calibrated using the methods of moments. A further testing of this methodology is required and should be based on analysis of different convective-type meteorological events before these results can be applied further.

Sivapalan and Blöschl (1998)

Sivapalan and Blöschl (1998) presented a methodology to estimate the catchment IDF curves utilizing the spatial correlation structure of rainfall. This methodology has certain advantages over others, as it overcomes the shortcomings of some of Rodriguez-Iturbe and Mejia's (1974a, 1974b) research by distinguishing between the scaling behavior of parent and extreme value distribution of the rainfall process. Additionally, this methodology makes fewer assumptions. It attempts to correlate different empirically based approaches with approaches based on current scientific theories of space-time rainfall fields. This approach differentiates between the variance of point precipitation and that of areal processes and concludes that the variance of point precipitation is higher than the others. As recommended by Sivapalan and Blöschl (1998), the main control of IDF curves is rainfall spatial correlation length, which characterizes the storm type. The methodology adopted is conducted as follows.

1. The foremost step is to specify the parent distribution of the point rainfall process. The exponential probability distribution of point rainfall intensities has been examined in many previous studies and, because of the success of this kind of

distribution, it is stipulated in this approach. Although they adopted an isotropic, exponential correlogram, the proposed methodology can be generalized for any other type of correlation structure and even for anisotropic situations.

2. In the second step, the point rainfall process is averaged over a catchment area.
3. The next step involves the transformation of the parent distribution of the aerally averaged rainfall process to the corresponding extreme value distribution. This is done by using the Gumbel asymptotic extreme value theory. While conducting this study the researchers assumed that the spatial random field of point rainfall intensities was stationary. This areal averaging produces certain effects such as decreases in the variance of the averaged process and variance reduction factor with increasing area. In other words, when the area becomes zero, the reduction factor is equal to one and as the area approaches infinity, the variance reduction factor approaches zero. The value of this reduction factor depends upon the size and shape of the catchment and the correlation structure of the rainfall. The researchers assumed that the catchment was square–shaped, but this methodology can be generalized for different shapes also.
4. Finally, in the last step, the extreme value distribution is matched with the observed extreme value distribution of point rainfall. Using this methodology, the properties of the Gumbel distribution can be used to estimate the mean, standard deviation, and coefficient of variation of extreme rainfall at the catchment scale. ARFs produced by this method have been shown to decrease both with increasing catchment size and increasing return periods. Additionally, ARFs produced for very large return periods became a function of catchment area and the rainfall correlation structure. Therefore, they are independent of particular rainfall regime (i.e., point IDF curves).

Although the methodology proposed by Sivapalan and Blöschl (1998) is an expedient one, it cannot be used successfully at all times because of the crucial assumption of stationarity in space of the rainfall's random field. Therefore, this approach cannot handle finiteness of the storm area and the possible partial coverage of the catchment area. Also, the mean of the areally averaged extreme rainfall decreases with increasing averaging area, which is not in compliance with the methodology proposed by Rodriguez-Iturbe and Mejia (1974b). This may be a result of the estimates of ARFs derived by Sivapalan and Blöschl (1998) being applied to parent rainfall intensities and not their corresponding extreme rainfall intensities.

Asquith and Famiglietti (2000)

Asquith and Famiglietti (2000) proposed that effective depths for a watershed area are computed by multiplying ARFs developed for that particular area by the point rainfall depths. The ARFs calculated are dependent upon watershed characteristics such as the area, shape of the watershed, and the recurrence interval, which represent the storm characteristics. They put forward a new approach termed the annual-maxima-centered approach, which considers the distribution of concurrent precipitation surrounding the annual-precipitation maximum. This approach includes the following steps.

1. For every annual maximum in the rainfall database, the ratio of the annual maxima depth to the concurrent precipitation is calculated and then the separation distance between the rain gages is calculated.
2. From the sample ratios a description of relation between criteria-conditioned sample ratio value and separation distance is given. These relations are defined by specific functions fitted to the empirical ratio relation and produce a best-fit line that gives the expected ratio.
3. From this, the areal reduction functions are computed for a user-defined area and design criteria.

Empirical depth-distance relations provided the basis for this approach to annual-maxima-centered ARFs. This kind of approach was adopted to calculate ARFs for the cities of Austin, Houston, and Dallas in Texas. There is a large database of precipitation data available for Texas, and so this approach can be applied there. It does not require spatial averaging of precipitation.

Michele et al. (2001)

Michele et al. (2001) presented a method for modeling the geographically fixed ARFs for storm rainfall using the concepts of scaling and multiscaling, which provides a dominant framework for studying the temporal and spatial variability of the different hydrological processes. They proposed that ARFs reflect the scaling properties of rainfall in time and space. Using the concepts of dynamic scaling and statistical self affinity, they derived a physical formula for ARF. Michele applied these concepts first to rainfall processes, then to ARFs, and then proposed the relative scaling relation with area and duration. The study, conducted in Milan, Italy, and the United Kingdom, indicates that storm rates in time and space are scalings for extreme events. Rainfall was clumped for areas of 0.25 to 300 km^2 and for time durations of 20 minutes to 6 hours. Annual maximum rainfall values of average rainfall intensities were obtained using the method of kriging. Scaling properties were then applied. The researchers observed that the dynamic scaling exponent for Milan was equal to one, indicating isotropic behavior of rainfall. They obtained a dynamic scaling relation of average rainfall intensity in area and duration, and from this relationship they obtained intensity depth area frequency (IDAF) curves and a particular case of intensity duration frequency curves (IDFs). Combining IDAF and IDF curves, Michele et al. (2001) obtained the ARFs for that region. The results of the study significantly support the conjecture that scaling holds for the storm rates, in time and space, taking into consideration extreme events. Further data analysis is needed to assess the variability of scaling exponents with geography and climate.

Durrans et al. (2002)

Durrans et al. (2002) carried out research believed to be the first to evaluate the potential of NEXRAD radar-rainfall data to develop geographically fixed depth-area relations. The use of radar-rainfall data to develop depth-area relationships was evaluated, and the potential problems that might hinder the use of such data were identified. They explained that radar data, like rain guage data, have certain limitations, but along with representing a rich source of information on the spatial coverage of rainfall, radar data can be expected to become more reliable with time. NWS Hydrologic Research Laboratory provided multisensor (radar + rain guage data) data for the study for a period of 7.5 years. These data were recorded by the Arkansas-Red Basin River Forecast Center.

Omolayo (1993)

Omolayo (1993) estimated the meaning and significance of ARFs for flood frequency studies. He differentiated the reduction factors and categorized them into various types. ARFs calculated for one region can be transposed to different regions assuming that the regions are climatically similar. Omolayo (1993) transposed the 1 day ARFs for the U.S. to Australia, as the two have similar mean annual rainfall, mean annual temperature, etc., which makes them climatically similar. One day rain gage data were obtained for nearly 30 years from the Commonwealth Bureau of Meteorology in Melbourne and Sydney, Australia. Different methodologies like the U.S. Weather Bureau method, UK method, Bell's (1976) method, and Rodriguez-Iturbe and Mejia's (1974b) methods were used to transpose the ARFs. The results obtained were then compared for eight major cities in Australia. This study did not take into account variation of ARFs with return periods and also could not calculate ARFs for areas smaller than 100 km^2 due to the wide scattering of the stations.

Einfalt et al. (1998)

Einfalt et al. (1998) pointed out that the validity of point rainfall data of hydrological simulations has been approached by the use of areal reduction, which depends upon recurrence interval, area of the catchment, and block interval. But in reality, actual events do not obey the block interval classification. The spatial distribution of rainfall is highly dependent upon weather type, and local climatic variations may cause a spatially varying relationship to point rainfall measurement station. Hence, the researchers suggested that there is a need to classify events as a function of rainfall volume, general weather type, subcatchment, and season. The main objective of their study was to establish a relationship between the different parameters like spatial variability of rainfall volumes and weather type, season, geographic location, etc., and the deviation of areal rainfall from the station data of the long-term rain gague used for design studies. The rainfall data employed were continuously used measured data series and not design storms, as used in traditional approaches for determining ARF.

Rakhecha and Clark (2002)

Rakhecha and Clark (2002) provided distribution of areal rainfall for the first time for India. They developed ARFs based on envelope curves of major storms to give ARFs for areas of 10–20,000 km2. The factors calculated varied between 1 and 0.41, but there was no real difference between different durations of rainfall. These values were then multiplied by 1–3 day probable maximum precipitation (PMP), and corresponding maps describing the spatial distribution of areal PMPs were provided.

RAINFALL MODELS IN TIME AND SPACE

The practical need to study the spatial and temporal variability of rainfall over an area has compelled many researchers to develop new space-time rainfall models. Space-time rainfall models lead to more realistic estimations of design storm (and floods) and ARFs for rainfall. These models have gained importance because of the limitations of measuring rainfall both in time and space using other techniques. Different models have been proposed as an appendage to the measurements, and different statistical models can be defined for the rainfall processes. They can be distinguished from one another by their representation of rainfall in time and space. There are three general classes of rainfall models, described in the following sections.

SPATIAL MODELS

Spatial models represent the spatial distribution of a storm's total rainfall over a specified duration. There are two general types of spatial models in use at present: (1) Gaussian random field models and (2) cluster models. Applications for these types of models include designing precipitation sensor sampling strategies and precipitation frequency analysis.

TEMPORAL MODELS

Temporal models represent rainfall accumulation at a fixed point over time. There are two general types of temporal rainfall models: (1) discrete models and (2) continuous models. In a discrete model, fixed-length time intervals (often daily or hourly) divide the time scale. Markov chains and their generalizations describe rainfall occurrences in these types of models. In a continuous model, the time interval is not constrained to discrete intervals. For these kinds of models, Poisson processes and their generalizations define rainfall occurrences.

SPACE-TIME MODELS

Space-time models have come into being from the cluster models framework introduced by LeCam (1961). According to this kind of framework, model rainfall is developed from rain cells organized into larger rain bands having individual life cycles and trajectories. These have been used for assessing sensor design and assessment of the role of spatial variability of rainfall in determining spatial characteristics of infiltration.

VARIOUS RAINFALL MODEL STUDIES

Work on Gaussian models has been done by Bras and Rodriquez-Iturbe (1976). Cluster models are used more frequently these days, and a combination of recent developments in meteorology with LeCam modeling has produced many sophisticated space-time rainfall models (Gupta and Waymire, 1979; Waymire et al., 1984). Different point rainfall models have been proposed based on these properties (LeCam, 1961; Rodriguez-Iturbe et al., 1986, 1987; Coppertwait, 1994). Spatial and temporal rainfall models are somewhat different from one another, and their stochastic modeling has been developed based on three different methods (Austin and Houze, 1972; Zawadzki, 1973; Lovejoy and Mandelbrot, 1985; Lovejoy and Schertzer, 1985; Crane 1990; Gupta and Waymire, 1993). Over and Gupta (1996) follow the approach that exploits self-affinity relationships to produce rain-rate by following an iterative random cascade process. Another approach generates random space-time functions to generate fields with specified spatial-temporal covariance structures (Rodriguez-Iturbe and Mejia, 1974b; Bell, 1987; Bellin and Rubin, 1996). Still another approach is based on stochastic modeling of the physical processes occurring during a rainfall event (Bras and Rodriguez-Iturbe, 1976; Waymire et al., 1984; Rodriguez-Iturbe et al., 1986; Cox and Isham, 1988; Coppertwait, 1995). Other rainfall model studies include those by Marsan et al. (1987); Marshall (1980, 1983); Foufoula-Georgiou (1989); Georgakakos and Bras (1984); Venugopal et al. (1999a, 1999b); and Waymire and Gupta (1981a, 1981b).

Smith and Krajewski (1987) developed a statistical framework for modeling space-time rainfall using radar and rain gage data. The cluster model developed was applied to daily rainfall fields in the tropical Atlantic region covered by the GATE (GARP Atlantic Tropical Experiment) (Hudlow and Patterson, 1979). This form of the model dictated three tasks to be followed:

1. The first step, sampling, determines the relationship between measurement of rainfall fields and the actual values of rainfall.
2. The next step is to determine a rainfall model that fit the data. The temporal evolution of the model is governed by a Markov chain. It assumes a method in which circular raindrops are organized in ellipsoidal rain bands that are randomly distributed in a plane. Geometry of the rainband is specified using radius of the major axis, radius of the minor axis, and the orientation of the major axis from north to south. A method

for estimating parameter values for the probability model was also determined in the study.

3. Finally, the statistical model developed was applied to the Atlantic tropical region. The sampling model in this study was based on the assumption that the advantage of rain gage data is accuracy of time-integrated observations, while the strength of radar is the ability to see the areal extent of rainfall fields.

Due to widespread use of rainfall models, the Australian Bureau of Meteorology operates a suite of Numerical Weather Prediction models (NWP). The latest project developed a model for characterizing the spatial and temporal properties of rainstorms for various climate regions of Australia. The aim of the project was to develop a nowcasting model for forecasting spatial rainfall and developing a statistical method for seasonal rainfall. This model can be used by researchers requiring spatial temporal storm characteristics for design purposes. Another class of space-time models uses causal multifractal models based on discrete random cascades describing the properties of the model and comparing these with Poisson point process-based models. The two important modeling systems evolved from these are a) RAINSIM-a rainfall time series analysis and simulation package suitable for hydrologic studies requiring long generated time series at one or more sites and b) MTB (Modified Turning Bands): a stochastic space-time rainfall field modeling system which can be used for the simulation and forecasting of frontal rainstorms.

There have been many studies that discuss the structure of storms. Some of them are Niemczynowicz (1987, 1991), Shaw (1983), and Sherman (1977).

NEXRAD - USE OF RADAR PRECIPITATION DATA

Successful modeling of hydrologic processes requires precise estimation of the spatial distribution of rainfall. Historically, estimated rainfall distributions assume spatial geometry related to point rain gage observations using techniques like thiessen polygons, inverse distance square weighting, kriging techniques, etc. From a modeling perspective, spatial distributions have very little connection with reality using these gages. Further, in many countries the climatological network of rain gages is not adequate to accurately estimate areal precipitation, especially if the area under consideration is large. This, in turn, makes it difficult to accurately evaluate the various methods for calculating ARFs. Improvements in technology have made radar a viable tool to improve the estimation of rainfall distribution and, hence, calculation of ARFs. Presently, radar-derived rainfall data provide a high-resolution view of rainfall distribution. In the United States, one of the most commonly used radar data sets is that collected by S-Band weather surveillance radar 1988 Doppler (WSR-88D). In the 1980s the National Weather Service deployed WSR-88D radars for reliable data estimations. These radars have been deployed at about 160 sites all over the United States. Computer algorithms are used to convert the radar data into hydrometeorological data.

COMPONENTS OF NEXRAD

NEXRAD stands for NEXt generation RADar, and consists of three main components, described in the following sections.

Radar Data Acquisition (RDA) Unit

The RDA unit transfers and receives signals, collects and converts analog signals to digital data, and produces a stream of raw digital data. No final product is available at this stage

Radar Product Generator (RPG)

In the RPG unit data are passed to algorithms which create three main products: velocity, reflectivity, and spectrum width. Reflectivity is indicative of the amount of moisture present in the air. Large water drops have more density and, hence, give larger reflectivity values. Spectrum width is related to turbulence in the air and represents variation in velocity. The larger the spectrum width, the greater is the turbulence. Radial velocity represents wind velocity (i.e., the speed of the particles toward or away from the radar antenna). A radial velocity value of zero means that there is no movement of air in the direction of the radar. The radar can operate in different modes. In clean air mode, the radar updates every 10 minutes, in precipitation mode it updates every 6 minutes, and in the severe weather mode it updates every 5 minutes. The procedure for rainfall estimation of WSI Corporation, the company selected in 1990 by the National Weather Service to provide the public with access to NEXRAD data, uses a dynamic weather condition-based algorithm to convert reflectivity values to rainfall estimates. A variety of weather parameters track weather conditions and choose the most appropriate conversion from reflectivity to rainfall rate.

Principal User Processor (PUP)

The PUP unit workstation obtains information displayed in alphanumeric or graphic formats and converts the information from one type to another.

RESEARCH STUDIES USING RADAR DATA

Few radar-based areal reduction factor studies exist due to limited samples of radar data. In the United States, Frederick (1977) used the WSR-57 radar to develop depth-area curves. The average power returned by the radar is quantized into 10 discrete levels, with 0 indicating no return and digits 1 to 9 representing returns in increasing order. The radar-returned power is then converted to radar reflectivity using the relationship:

$$Z = 10^{[0.10(-dBm)+11.5]}$$

where Z is the radar reflectivity factor (millimeters × 10^6 per cubic meter) and dBm is the WSR-57 radar power return (decibels). Using the following Z-R relationship, radar reflectivity is converted to rainfall rate by:

$$Z = 55R^{1.6}$$

This yields typical rainfall rates of 1.25 mm/h for level 1 up to 400 mm/h for level 9. Using four *large* storms that occurred during the spring of 1969 near Norman, Oklahoma, prototype ARF curves were developed. The curves were based on watersheds up to 834 km^2 and on 30- and 60-minute accumulation periods. Frequency analysis determined the average areal precipitation with the same frequency of occurrence as point precipitation. Compared to ARF developed by the U.S. Weather Bureau (1957), substantial differences can be noted with the radar-based ARFs. The areal reduction factor calculated for the 30-minute period using radar was considerably larger than the 30-minute gage areal reduction factor for all basin sizes. Also, beyond 371 km^2, the slope of the gage areal reduction factor approaches zero, while the values of the radar-based ARFs continue to decay.

Stewart (1989) utilized the high temporal (and spatial) resolution of the radar data for northwest England to develop amalgamated rain gage-radar areal reduction factor relationships. The study area was approximately 10,000 km^2 and was divided into a number of subcatchments based on the 5-km radar grid points, yielding a total of 544 experimental catchments ranging from 25 to 10,000 km^2. For each day in the radar record in which a heavy rainfall event occurred, researchers calculated the ratio of the maximum areal rainfall for each duration to the corresponding daily areal rainfall total. The values obtained were then averaged to give a single value for each basin size and duration. Using these ratios, areal reduction factor-area curves based on daily rain gage data could then be modified to sub-daily areal reduction factor-area curves.

Curtis (2001) used radar-rainfall estimates to study the shapes, sizes, orientations, and depth-area characteristics of storms in Clark County, Nevada. He used 15-minute; 2 × 2 km radar rainfall estimates over a period of 4 years obtained from WSI Corporation, located in Billerica, Massachusetts. Rain gage data to calibrate the radar for the region were obtained from the National Weather Service. A software package, TITAN, was used to review the 15-minute gage-adjusted radar rainfall estimates to track the contiguous areas of rainfall. In this study, a total of 124,234 individual 15-minute storms were identified and categorized. Curtis showed different categories of storms (large, small, etc.), the frequency distribution of the aspect ratios of the ellipses that fit most of the storms, orientations and spatial characteristics, etc. He was also able to plot the mean storm vectors that summarized the relative speed and direction of the storm movement over the study area. Another important observation was storm activity (the number of times storms were observed at each pixel location). While analyzing the storms using TITAN, each elliptical-shaped storm was identified and the peak rainfall intensity was recorded with the area of each intensity contour in the storm from peak intensity down to approximately 0.08 inches/h. Then a depth-area curve was constructed for each peak intensity. A general observation was that higher peak rainfall intensity produced larger area storms. Other interesting findings of this study include the high number of storms available to evaluate from radar-rainfall database, the small size of the storms, and the small size of high-intensity central intensities of the storms. This brings into question the practice of using spatially uniform rainfall at each time step for design storms. Similar studies were also conducted by Curtis in Florida and Southern California, and they all show the potential for large-scale analysis of radar-rainfall estimates. Other important works carried out in this field are those by Smith and Bradley (1994), Vieux and Bedient (1998), Baeck and Smith (1998), Smith and Krajewski (1987), and Battan (1973).

SOFTWARE USED FOR ANALYSIS OF NEXRAD DATA

Presently, there are several software packages available for the analysis of NEXRAD data. University Corporation of Atmospheric Research (UCAR) (2004) developed the Plan Position Indicator Mesoscale and Microscale Meteorology package, which is a program that displays and analyzes radar measurements taken at spherical coordinates (range, azimuth, and elevation). Priegnitz (2004) developed the IRAS (Interactive Radar Analysis Software) package, which analyzes and displays WSR-88D data. It is an X-Windows-based software tool and has been used exclusively as a research tool to play back base-level data from a number of research radars. WXP (The Weather Processor), developed by Unisys (2004b), is analysis and visualization software developed by Purdue University. SKYVIEW95, developed by Unysis (2004a), is a NEXRAD Level III Product Visualization Software for PC display Level III products, which was developed by National Climate Date Center (NCDC). FasTrac and NexTrac models, developed by Baron Services (2004a, 2004b), ingest the National Weather Service's NEXRAD data and provide crisp, detailed storm imagery atop high-resolution topography and maps. One of the most widely used software worldwide is TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting), developed by Dixon and Weiner (1993). It identifies storms within three-dimensional radar data and checks them as physical entities. The data produced are suitable for scientific analysis for understanding and subsequently forecasting the physics involved in storm development and movement. TITAN undertakes real-time automated identification, tracking, and short-term forecasting of thunderstorms based on volume scan weather radar data.

PROBABLE MAXIMUM PRECIPITATION STUDIES

One of the conceptual paradigms that define the magnitude of extreme precipitation and storms used in the various hydrological practices is probable maximum precipitation (PMP). PMP is used in many countries worldwide including the United States, India, Australia, the United Kingdom, China, etc. (Svensson and Rakhecha, 1998).

PMP is defined as "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given area at a certain time of the year" (Hansen et al., 1982; World Meteorological Organization, 1986). Reliable estimation of PMP values for different durations, which are likely to occur at locations where water resources projects are envisaged, is of great importance. Different methods have been proposed for determining PMP depths. The World Meteorological Organization (1986) has undertaken a comprehensive review of these methods. Also, a variety of procedures for PMP determination have been proposed by Weisner (1970), Schreiner and Riedel (1978), and Collier and Hardaker (1996). PMP estimation methods fall into the following general categories: (1) storm model approach; (2) maximization and transposition of actual storms; (3) use of generalized data; (4) theoretical or empirical methods derived from maximum depth, duration, and area observations; (5) empirical relationships between variables in a particular valley; and (6) statistical methods (Weisner, 1970).

The storm model approach determines the underlying principles of most of the maximization studies. In the storm model approach, physical parameters represent the precipitation process, that is, the precipitation process is expressed in terms of parameters like surface dew point, heights of the cells, inflow, outflow, etc. Collier and Hardaker (1996) used this approach to estimate probable maximum precipitation values. Using equations of continuity, the flow pattern can be expressed in an equation that gives the rainfall as a function of variables that are measurable, have reasonable length of record, and can adequately represent the meteorological conditions both in space and time. This kind of approach is useful in determining PMP values over large areas and in quantities precipitation forecasting, but it is not successful in small areas due to non-precise measurement of the various factors associated with this approach.

Due to deficiencies of the storm model approach, researchers have extensively studied actual storms and extrapolated to their probable maximum values. This method involves collecting and analyzing data from extreme storms that have occurred over the area being studied. It includes developing isohyetal maps, mass curves, and estimating moisture change from the representative dew points of the storms. The storm rainfall depths obtained from isohyetal maps or depth-duration-area curves give PMP estimates for that basin. Maximization of storms consists of increasing observed amounts of precipitation to account for maximum atmospheric moisture convergence. Storm transposition entails translating observed storm characteristics from one or more gaged locations to the location where the PMP estimation is required (typically an engaged location). This approach avoids the shortcomings of storm models, topographical intensifications, etc. But whether this approach is useful depends upon whether sufficient severe storms, adequately described by data, have occurred within the watershed basin.

Suitable methods applied over large regions that encompass numerous watersheds are referred to as generalized estimates (Kennedy et al. 1988; WMO, 1986; Hansen et al., 1988). These methods are developed by maximizing and translating different storms over a large region and involve the classification of storms by calculating the corresponding storm efficiency (NERC, 1975). Factors influencing storm efficiency include vertical velocity of frontal, atmospheric convergence, etc. The principal technique here is to estimate the non-orographic component of PMP and then adjust these values for variations in the regional orography. Many countries have successfully used this method to estimate PMP patterns, including the United States (Miller et al., 1973), Australia (Kennedy et al., 1988), and the United Kingdom (Collier and Hardaker, 1996).

Researchers have developed some general formulae that can represent local or world maximum values of precipitation and can be used to achieve approximate PMP estimates. These methods are sometimes site specific; more specific formulas need to be developed for certain areas.

Rainfall intensity depends upon inflow velocity, moisture content, and storm mechanisms or convergence factors. Well-chosen values of wind velocity and surface dew point can represent meteorological conditions more consistently, including rainfall. Therefore a rainfall formula can be developed that directly relates rainfall intensity to wind velocity and surface dew point. This approach is convenient in areas with complex topology, such as mountains, and in places where there are limited data for elaborate model studies.

Statistical methods involve determining PMP estimates at a particular location or area based on a frequency distribution model fitted to the annual maximum rainfall data. These methods are useful when meteorological data such as dew point temperatures, wind speed, etc., are not easily available but there are large amounts of rainfall data (Chow et al., 1988; Hershfield, 1961b, 1965, 1975; Koutsoyiannis, 1999). They require a series of maximum annual daily rainfall values for a particular location. Hershfield (1965) developed one of the standard reports based on methods suggested by WMO (1986).

SOURCES OF PMP ESTIMATES

NOAA (1978, 1982) – also known as HMR 51 and HMR 52 – contain generalized PMP values estimated for the United States east of the 105th meridian. These reports contain the latest and most relevant PMP studies. Probable maximum precipitation estimates have been made for the following areas:

- Hansen et al. (1977): Colorado River and Great Basin drainages.
- Schreiner and Riedel (1978) and Hansen et al. (1982): United States east of the 105th meridian.
- Ho and Riedel (1980): seasonal variation of 10-mi^2 sections of the United States east of the 105th meridian.
- Schwartz and Miller (1983): PMP and snowmelt criteria for southeast Alaska.
- Hansen et al. (1988): United States between the continental divide and the 103rd meridian.
- Zurndorter et al. (1986): PMP for the Tennessee Valley Authority (TVA) with areal distribution for Tennessee River drainages less than 3000 mi^2 in area.
- Hansen et al. (1994): Pacific Northwest states, Columbia River (including portions of Canada), Snake River, and Pacific coastal drainages.
- Corrigan et al. (1998, 1999): California.

LATEST APPROACH IN THIS FIELD

One of the latest approaches in PMP estimation is a study conducted by Douglas and Barros (2003). In the study, the value and utility of applying multifractal analysis techniques to systematically determine physically meaningful estimates of maximum precipitation from observations in the eastern United States was arbitrated. The multifractal approach provides a formal framework to infer the magnitude of fractal maximum precipitation (FPM, extreme events independent of empirical adjustments), and it offers an advantage over other methods estimating associated risk. Multifractal parameters infer the magnitude of design probable maximum precipitation (DPMP), which can be represented by extreme precipitation consistent with engineering design criteria (e.g., return periods of 10^6 years). These were then compared with PMP estimates using standard approaches (NOAA 1978, 1982) for small dams in Pennsylvania. The FPMs found were lower than the PMPs in most cases. DPMP/PMP ratios were usually greater than one, ranging from 0.96 to 2.0, thus suggesting that DPMP estimates can provide a bound of known risk to standard PMP estimates.

PROGRESS REPORT

HYDROLOGIC DESIGN

Hydrologic design is a series of processes identifying hydrologic events and evaluating their impact on water resource systems and providing important hydrologic variables, which may be deterministic or probabilistic, such as peak flow rates and/or flow hydrographs to satisfy the proper performance of water resource systems.

The objectives of hydrologic analysis and design are to estimate peak flow rates and/or flow hydrographs for the design of minor structures such as small crossroad culverts and drainage ditches and major structures such as a spillway on a large dam. The critical aspect in hydrologic design is to estimate a design flood, associated to expedience probabilities or design return periods, known as flood frequency analysis. Researchers use the estimated value to assign hydrological and hydraulic dimensions to minor and major structures.

Hydrologic design scale is the approximate magnitude range of the design level for different types of structures (Chow et al., 1988). The design scale is selected primarily based on cost and safety. There is a trade-off relationship between cost and safety: a cost-effective design for water resources system planning and management can be obtained at the cost of reducing safety. It is important to determine the practical upper limit of the hydrologic design to achieve the balanced consideration of cost and safety.

The estimated limiting value (ELV), defined as the largest but physically possible magnitude of hydrologic event, is based on all available hydrologic integrity (Chow et al., 1988). The PMP and the PMF are categorized implicitly as ELV. If the hydrologic data are within or near the range of frequent observations, the frequency-based approach is commonly adopted in the lower-down range of design scale. Figure 1 shows the hydrologic design scale.

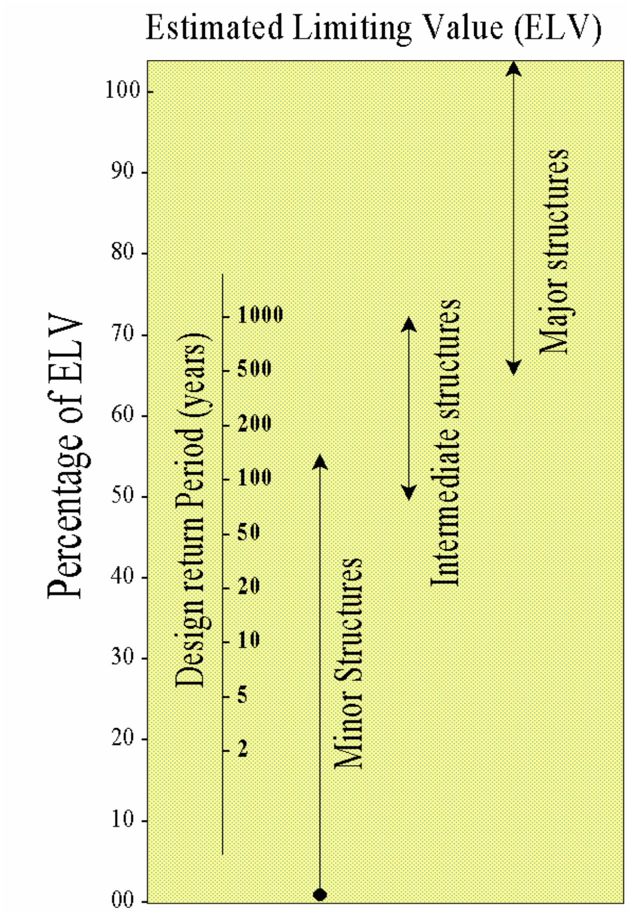

Figure 1. Hydrologic design scales (Chow et al., 1988).

Procedures for estimating design flood flows include the following methods:

- Flow-based methods – examine historical or projected flood flows to arrive at a suitable estimate.
- Precipitation-based methods – evaluate the storms that produce floods, and then convert the storms to flood flow rates.
- Frequency-based methods – based on selecting a design frequency and determining the associated flood.
- Risk-based methods – based on developing designs for a range of flood frequencies and narrowing the final choice on the basis of long-term costs and benefits.
- Critical-event methods – based on designing on the basis of an estimate of the probable maximum storm or maximum flood that could occur at the site.

Standards-based criteria are commonly used for planning and designing new water-control facilities, preparing for and responding to floods, and regulating floodplain activities (USACE, 2000). Standards-based criteria are used as limits, known as the annual exceedance probability (AEP), to set forth an acceptable level of risk to the public. When sufficient hydrologic data such as rainfall and stream flow are available at the site of interest, statistical analysis can specify AEP to estimate design storm or flood. The statistical analysis procedure, however, has many limitations for use in estimating design floods because few streams are gaged or have sufficient records to meet statistical analysis requirements and changing land use due to urban development changes the rainfall-runoff relationship for a watershed. Therefore, a commonly used alternative analysis uses rainfall of specified AEP, known as design or hypothetical storm, coupled with a mathematical model to transform rainfall to runoff. The Hydrologic Modeling System (HMS) developed by the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers provides three alternative standards-based storms (USACE, 2000):

- Frequency-based hypothetical storm (FHS) – based on the point precipitation depths for the selected exceedance probability for durations from 5 minutes through the desired total duration of the hypothetical storm (but no longer than 10 days).
- Standard project storm (SPS) – applicable to basins east of 105° longitude (east of the Rocky Mountains).
- User-defined hypothetical storm (UHS) – allows the user to define the depth and temporal distribution of a hypothetical storm.

The hydrologic design requires various data which are the inputs for hydrologic modeling and affect the results of hydrologic analysis. Two sources provide hydrologic design data:

- Physiographic data – topographic map that contains basin characteristics such as size, shape, orientation, and slope of drainage area, soil, and geology, land use, and so on; and
- Meteorological data – rainfall, temperature, wind, and evaporation in time and space.

DESIGN STORMS

A design storm is a precipitation pattern defined for use in the design of a hydrologic system (Chow et al., 1988). The design storm as a design criterion is the most frequently and widely used in engineering practice. In hydrologic analysis, the design storm provides system inputs for rainfall-runoff simulation models. The critical aspect of engineering practice for hydrologic design is defining the design storm realistically and accurately. Design storms are widely used because they require minimal time and monetary resources and give conservative results. Inaccuracies in defining storms may come from the application of frequency to a design storm, neglect of antecedent watershed conditions and spatial variations of precipitation of real storms, and designs on the basis of the return frequency of rainfall rather than runoff (ASCE, 1992). Researchers define design storms as point rainfall depth with time-distributed hyetographs or spatially distributed rainfall depths with isohyet areas.

Typical precipitation data references used in drainage analysis are Technical Paper 40 (TP-40) and Hydro-35 (Zehr and Myers, 1984). Generalized rainfall criteria for the United States can be obtained from National Oceanic and Atmospheric Administration (NOAA) publications. The criteria consist of maps with isopluvial lines of point precipitation for various frequencies and durations (USACE, 1993). Historical or synthetic rainfall events can be used as design storms. The development of a design storm with synthetic rainfall events involves five main elements:

- **Frequency** – represented by the return period or the exceedance probability, which is the average number of years between events of a given or greater magnitude. The return period is selected based on the particular design criteria and local experience.
- **Duration of the design storm** – defined as the period of time over which precipitation occurs. The duration of a design storm is a significant determinant of the peak discharge and volume of rainfall excess. It is selected based on the particular design criteria or the objective of the hydrologic analysis. Most hydrologic design is based on either the 24 hr storm duration or a duration equal to the time of concentration.
- **Total rainfall depth and IDF relationships** – represented by the annual maximum precipitation, obtained at a single point for a given rainfall duration and frequency by the local climate. The design rainfall depths are converted into rainfall intensities and can then be presented in rainfall IDF curves.
- **Spatial distribution pattern** – the aerial distribution of precipitation depth over the watershed. Local point precipitation estimates are generally extended to represent average rainfall depth over an area of interest
- **Temporal distribution pattern** – represented by hyetograph as system inputs for hydrologic analysis. Temporal distribution of rainfall is a very important determinant that affects the geometry of runoff hydrograph.

RAINFALL DEPTH

Point Precipitation

The extent of precipitation occurring at a single location in space is determined directly using a rain gage. These point measurements are considered to be applicable only for areas up to 10 mi^2. If the point on a hydrologic system does not have a gage station, the precipitation at that point can be estimated by taking a weighted average of nearby points. Once the annual maximum precipitation for a given duration is obtained using frequency analysis, point precipitation data of the annual maxima are used to develop intensity-duration-frequency relationships for a watershed. In the United States, point rainfall depths needed for IDF curves or design storm hyetographs can be found in TP-40, HYDRO-35, and the NOAA Atlas 2. Isohyetal maps of design rainfall depth for the entire United States were published in U.S. Weather Bureau TP-40 for durations from 30 minutes to 24 hours and return periods from 1 to 100 years (Chow et al., 1988). Isohyetal maps for durations from 5 to 60 minutes were presented in the U.S. National Weather Service (NWS) HYDRO-35. The following publications present precipitation frequency maps:

- NOAA Atlas - Precipitation Frequency Atlas of the Western United States,
- TP-40 and HYDRO-35 Maps - Rainfall Frequency Atlas of the Eastern United States,
- TP-49 Maps - Rainfall Frequency Atlas of the United States,
- TP-47 Maps - Rainfall Frequency Atlas of Alaska,
- TP-43 Maps - Rainfall Frequency Atlas of Hawaii, and
- Bulletin 71 - Rainfall Frequency Atlas of the Midwest.

Areal Precipitation

Due to the lack of information on the probability distribution of areal precipitation, point rainfall is used collectively to estimate areal average rainfall. In hydrologic design point of view, storm spatial characteristics become more important as the size of the watershed of interest increases. The main reason to consider areal adjustment for a large area is that the likelihood associated with a high rainfall depth over a large area is not the same as that depth at a single point. In other words, the average rainfall depth over an area is less than the point rainfall depth. Precipitation depth adjustment of a point storm to an average depth over a watershed is critical for establishing rainfall-runoff relationships and for minimizing runoff volume for hydrologic and hydraulic design (Asquith, 1999). The two methods of point-to-area rainfall conversion are usually recognized and known as storm-centered and geographically fixed approach. A third approach is known as the annual-maxima centered approach (Durrans et al., 2002). These three approaches are summarized as follows:

- Storm-centered relationship – represents profiles of discrete storms.
- Geographically fixed depth-area relationship – estimated from averages of frequency-based quantile estimates.
- Annual-maxima centered relationship – considers the distribution of concurrent precipitation surrounding an annual precipitation maxima (Asquith, 1999).

For the location fixed case, an averaging process of precipitations between stations results in geographically fixed depth-area curves.

Areal Average Precipitation

To convert the point rainfall values obtained from various rain gage stations to areal average precipitation over an area of interest three methods have been widely used: arithmetical mean method, Thiessen-polygon method, and isohyet method. Depth-area-duration (DAD) relationships and areal reduction curves can be built using these three methods.

Depth-Area-Duration (DAD) Relationships

The areal distribution of rainfall of given duration at the object site is determined by constructing area-depth-duration relationship. The DAD curves developed from its relationships for a given duration represent the area of the storm over which a given depth is equaled or exceeded. In PMP design storm, DAD curves are used to construct the spatial internal structure of the design storm.

Areal Reduction Curves

The areal reduction factors for an area can be determined by the ratio of point rainfall intensities and average areal rainfall intensities. The areal reduction factor can be estimated Figure 2, developed by the National Weather Service as a guide in reducing point depths to areal depths for areas up to 400 m^2 (Miller 1964).

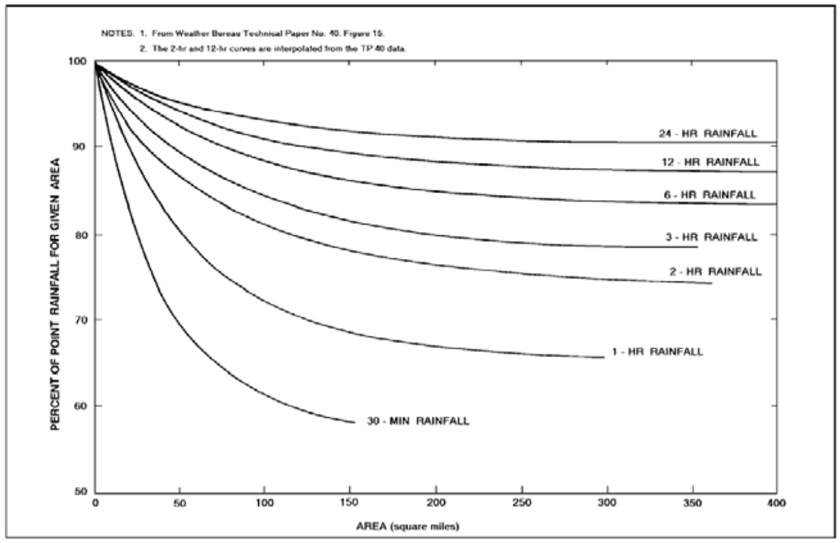

Figure 2. Area-Depth Curves for Use with Duration Frequency Values.

Estimated Limiting Storms

The ELVs commonly employed for water control design are the PMP, the PMS, and the PMF (Chow et al., 1988). The PMP provides a depth of precipitation, and the PMS involves the temporal distribution of precipitation. Estimated limiting values are useful in the design of major hydrologic planning and management projects, such as the spillways of large dams.

Probable Maximum Precipitation

The probable maximum precipitation is "theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size of storm at a particular geographical location at a certain time of year" (NOAA 1978). PMP is usually estimated either by developing a meteorologically possible maximized storm on the drainage basin of interest based on searching, identifying, and analyzing the largest flood-producing storms in and near the region of interest or by using generalized PMP maps based on metrological analysis of the largest storm in a large homogeneous region (Dingman, 2002). The procedure for determining the probable maximum precipitation has five important elements (Mays, 1996; Chow et al., 1988):

- depth-area-duration curves,
- standard isohyetal patterns,
- orientation adjustment factors,

- critical storm areas, and
- isohyetal adjustment factors.

PRECIPITATION VARIABILITY

Precipitation varies spatially, temporarily, and seasonally. Precipitation variability is important for water resources planning and management. Spatial variability can be significant even at small scale and thus requires a denser network of gage stations to capture the rainfall distribution in nature. Precipitation variability includes:

- spatial variation of a storm,
- temporal variation of a storm, and
- seasonal variation of a storm.

Spatial Variation of a Storm

Accurate estimation of the spatial distribution of rainfall as hydrologic system inputs is critical to estimate hydrologic system outputs such as outflow hydrograph. Precipitation data usually have a considerable spatial variation over any region, especially mountainous regions. The spatial rainfall distribution or storm geometry is determined by the climatological conditions such as temperature and wind as well as by geographical elements such as elevation, orography, etc. Researchers have noted at both large and small scales that significant errors in runoff prediction result from the misrepresentation of the rainfall field in time and space (Syed et al., 2003). Effort has been devoted to improvement of precipitation measurement methods, mostly relying on the dense network of rainfall gage stations. Advances in technology have made radar an essential tool to improve the estimation of rainfall between the rainfall gages; radar data are also directly used as inputs for hydrologic modeling. Radar provides a high-resolution view of the variability of rain falling over a region. Geographic information systems GIS can help analyze rainfall estimates statistically using both spatial analysis and geostatistical methods.

GIS AND HYDROLOGIC DESIGN

Geographic information systems (GIS) provide useful and powerful tools to integrate and analyze data from various sources in hydrologic modeling and analysis. GIS promotes the development of distributed hydrologic models to overcome the drawbacks of the lumped hydrologic models. Automated extraction of topographic parameters such as slope and area of a watershed from the topography is enough to replace traditional surveys and manual evaluation of topographic maps.

GIS APPLICATION AND DESIGN STORMS

GIS Development Environment

ArcGIS is an integrated collection of GIS software products developed by the Environmental Systems Research Institute (ESRI). The ArcGIS Desktop is a comprehensive, integrated, scalable GIS system. It consists of a suite of integrated and independent applications: ArcMap, ArcCatalog, and ArcToolBox and can be accessed and handled by software products such as ArcView, ArcEditor, and ArcInfo to provide three levels of functionality. The capabilities of all three levels can be further extended using a series of optional add-on software extensions. ArcGIS Spatial Analyst provides raster analysis, grid algebra, and conversion of either vector to raster or raster to vector. ArcGIS uses Microsoft Visual Basic as the standard interface language. Microsoft Visual Basic with ArcView 8.3 is used to create the ArcGIS Storm Tool for developing design storms. The developed GIS tool can be added in ArcMap as an extension.

GIS Application Tool for Design Storms

The GIS software packages used most widely throughout the world are the ArcInfo™ and ArcView ™ systems developed by ESRI. GIS application tool, working in the ArcView environment, was developed to create design storms and their structures, drainage basins of interest, and related information stored in the form of a geodatabase. Geodatabase is a short term for 'geographic database,' as defined in the dictionary of GIS terminology. This GIS application tool handles Microsoft Access to develop storm data models. A geodatabase provides an important tool for creation of a data model that stores information for various storms and spatial data. A geodatabase represents geographic features and attributes as objects and is hosted inside a relational database management system. In a sense, a geodatabase is like managing coverages, grids, and shape files inside a database management system (DBMS). Enterprise geodatabases require a 'host' DBMS such as SQL Server, Oracle, or IBM DB2, while personal geodatabases are based on the Microsoft JET engine and appear as an .mdb file (Microsoft's JET engine is also used by Microsoft Access). Microsoft Access serves as a warehouse that provides more database capabilities than can be used by the GIS model. The integrated system saves time and money by serving as a comprehensive information source. The model is also valuable because it can be linked and scaled to existing or future databases.

ArcGIS Storm Schematic Overview

Five independent computer programs combine to develop design storms: ArcGIS Storm (under development as part of this project), Microsoft Access, HEC-HMS, HMR52, and TITAN. ArcGIS Storm plays a main role in defining and developing design storms by making it possible to support and utilize processing of various kinds of integrated GIS data for use in the development of hydrologic models. Personal geodatabases based on Microsoft Access provide various tables of necessary information for creating design storms, basin characteristics, and created design storms. The HMR52 computer program, developed by the U.S. Army Corps Engineering Center (USACE), computes basin-average precipitation estimates for PMS accordance with generalized PMP charts in Hydrometeorological Report No. 51 (NOAA 1978), digitized and stored in a geodatabase for this project, and the criteria specified in Hydrometeorological Report No. 52 (NOAA 1982). ArcGIS Storm prepares an input text file for the HMR52 computer program, and triggers the HMR52 program to produce precipitation estimates over space and time. ArcGIS Storm extracts the incremental basin-average precipitation estimates from the text file provided by the HMR52 program and develops a PMP design storm. The precipitation data can be subsequently put into a rainfall-runoff model, such as HEC-1 or HEC-HMS, for computing runoff to obtain a maximum value. The maximized runoff is PMF, and the input storm is PMS. TITAN provides valuable storm characteristics and hydrologic information which is used as design criteria for lumped and distributed hydrologic modeling and hydrologic design. The precipitation estimates computed from TITAN can be converted to GIS raster or vector data format to be applicable in GIS applications (such as ArcGIS Storm).

Geodatabases for Design Storms

The simple geodatabases store all the information of various design storms and other information. Two geodatabases are created for ArcGIS Storm Tool. One is a geodatabase for design storms and the other is a geodatabase for generalized PMP charts. Generalized PMP charts contained in HMR51 are digitized and stored in the PMP Maps geodatabase. All the necessary data such as coefficients for IDF equations and Isohyet areas for storm geometry for creating design storms are prepared as a default when ArcGIS Storm creates directory structures. ArcGIS Storm creates design storms based on the existing storm definitions which have been described. The ArcGIS Storm schematic overview, storm, and generalized PMP geodatabases are illustrated in Figures 3, 4, and 5, respectively.

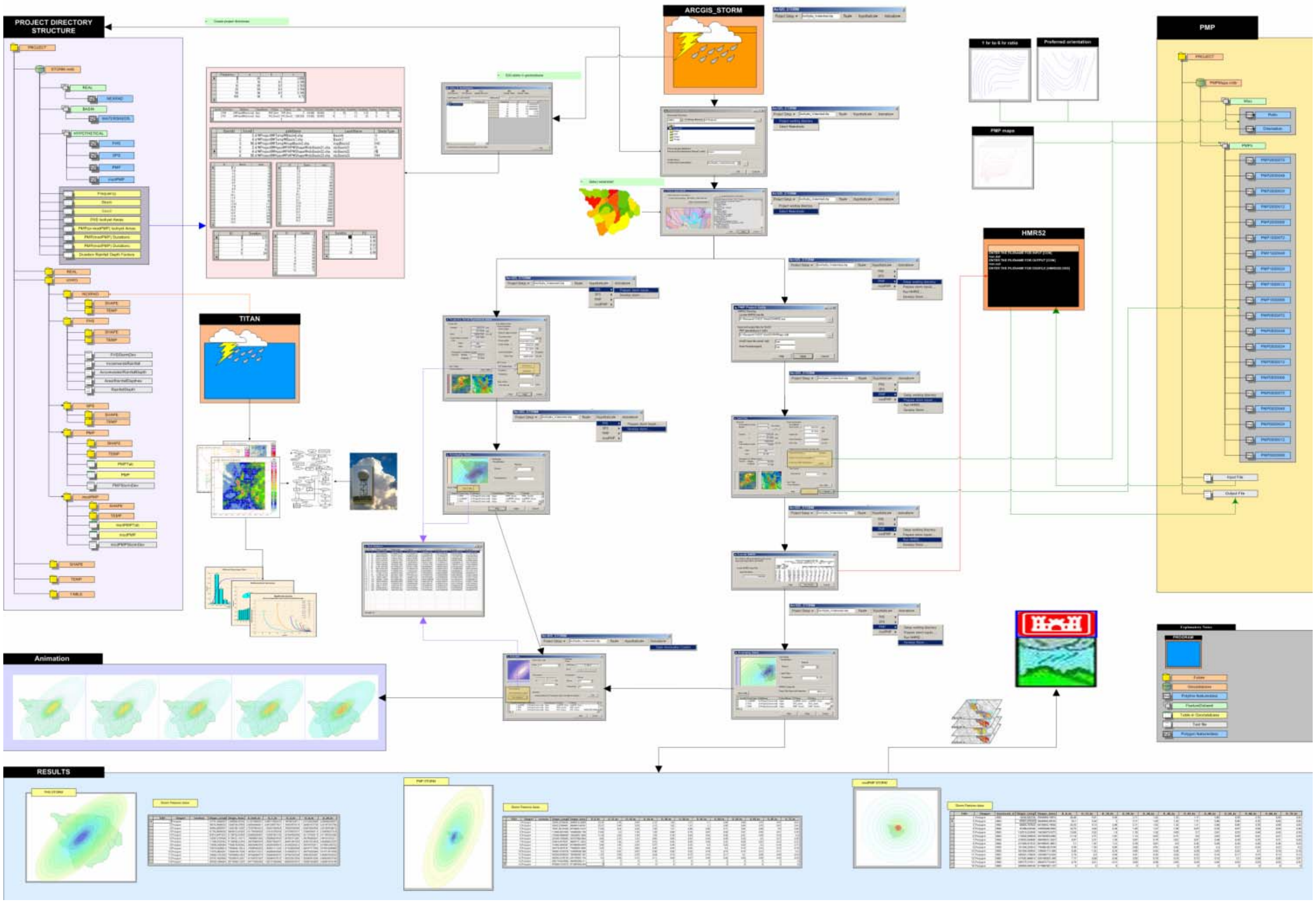

Figure 3. ArcGIS Storm Schematic Overview.

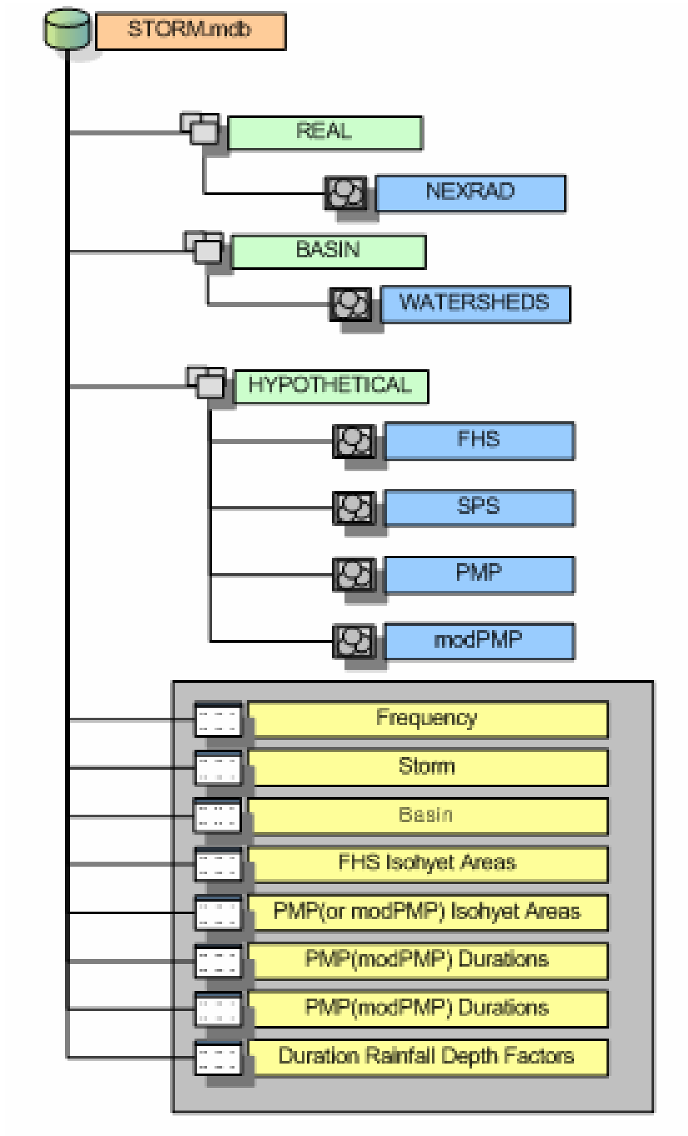

Figure 4. Storm Geodatabase.

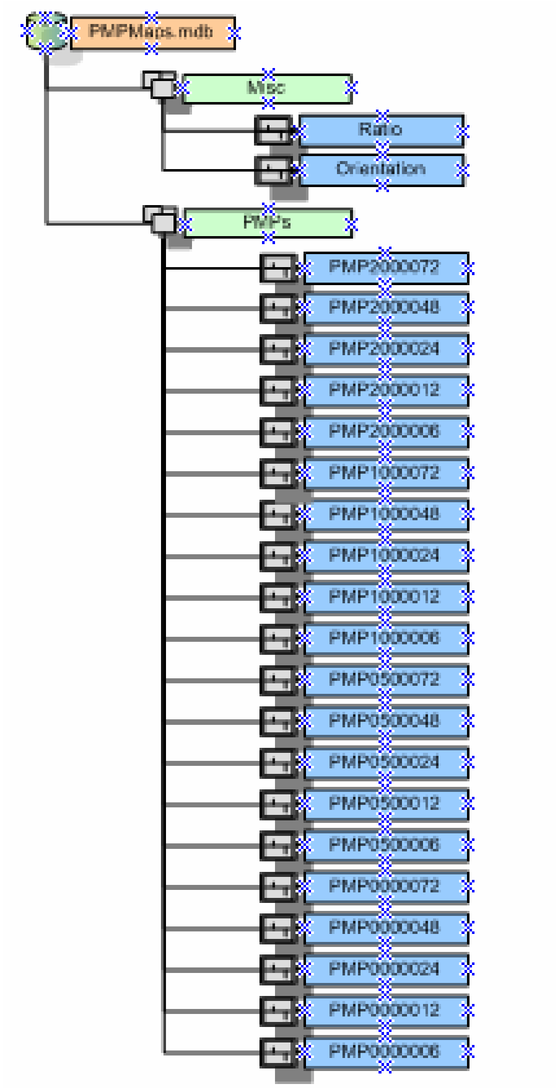

Figure 5. Generalized PMP Geodatabase.

Several tables in storm geodatabase are prepared when ArcGIS Storm creates the geodatabase (Figure 6). The tables contain coefficients of intensity-duration-frequency relationships expressed as equations, isohyet areas, and durations for various storms and empty design storm and basin tables that are populated as result values after storm-generating procedures are carried out.

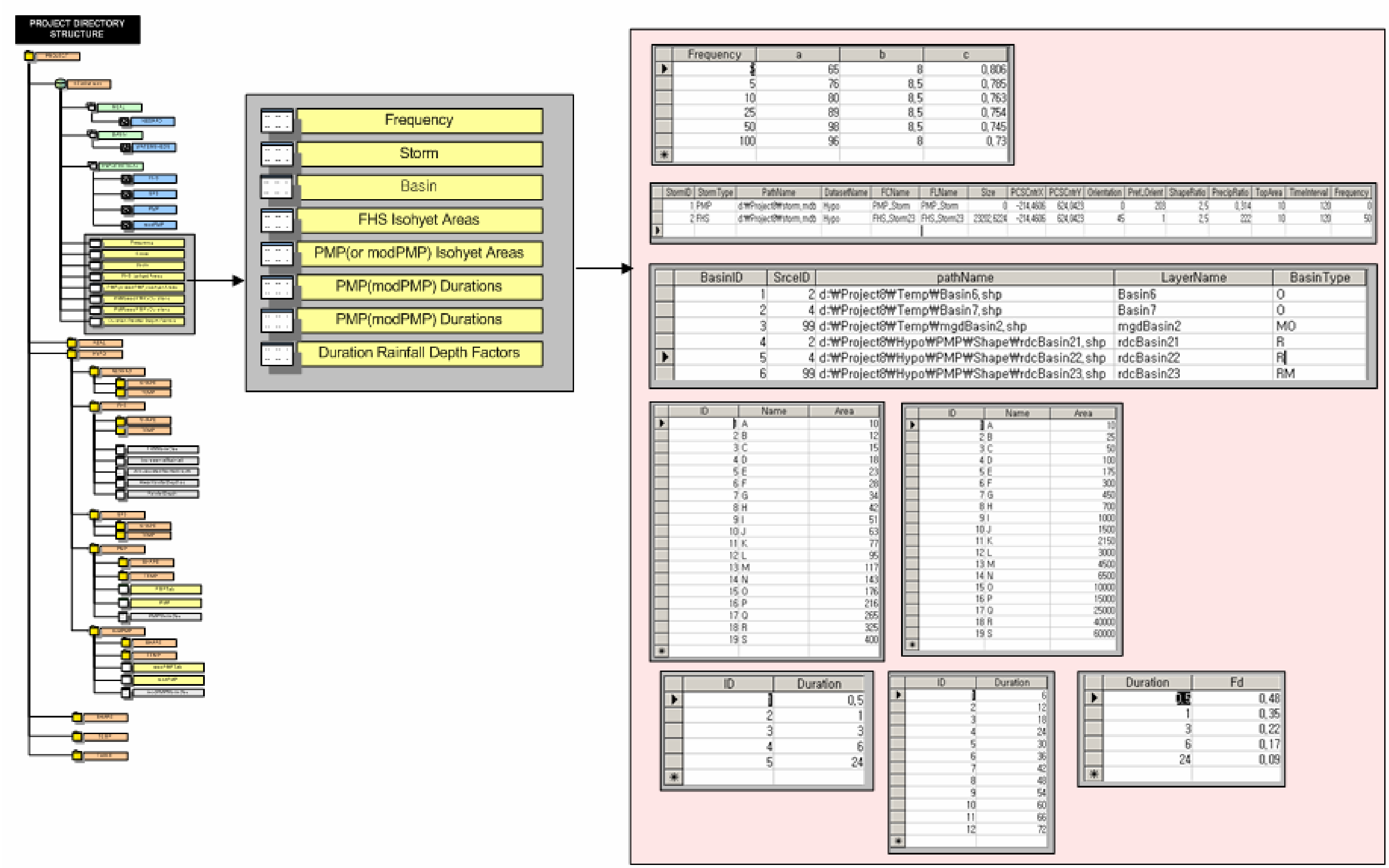

Figure 6. Tables in Storm Geodatabase.

GIS APPLICATION TOOL FOR PMP

Comparison between Conventional Process and GIS-Applied Automatic Process

The HMR52 program requires physiographic and meteorological data for inputs. The geometric properties of subbasins such as size, x and y coordinates of n boundary points, and centroids of watersheds are manually prepared based on traditional topographic maps or field surveys. Manual processes of obtaining such data, however, are time intensive. With computer technology, digitally represented topography data are now available for most of the United States at several levels of resolution and quality. The automated derivation of topographic watershed data is faster, less subjective, more cost-effective, and provides more reproducible measurements than traditional manual techniques applied to topographic maps (ESRI, 2000). The generalized PMP charts, preferred orientation maps, and 1 hr to 6 hr ratio maps are digitally formatted so that information extracted from the digitized maps is more reliable and accurate than that from paper maps. Comparison between the manual and automatic process is shown in Figure 7. The data flow diagram for developing a PMP design storm is also illustrated in the same figure.

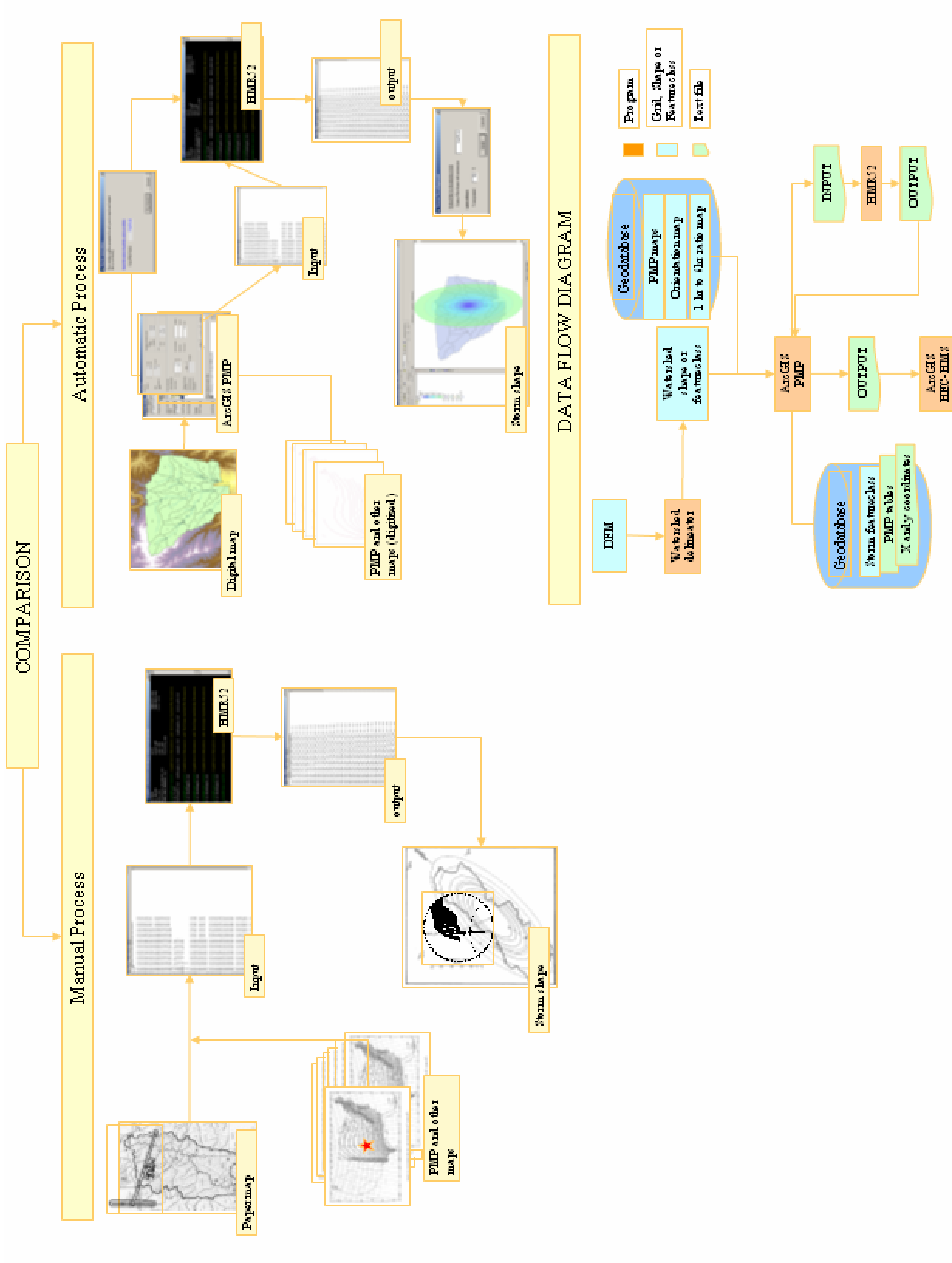

Figure 7. Comparison between Manual Process and Automatic Process in the Application of PMP Design Storm.

HMR52 COMPUTER PROGRAM

The HMR52 program was developed by the U.S. Army Corps Engineering Center (USACE) to produce maximum precipitation in the basin of interest. This program is applicable only to the eastern United States and is intended for areas of 10 to 20,000 mi^2 (USACE, 1984). The program computes the spatially averaged PMP of the subbasins or combinations using an iterating process to maximize basin-average precipitation. The output data file, composed of estimated precipitation, is then input to a rainfall-runoff model to determine runoff, using an appropriate precipitation-runoff program such as HEC-1 (Hydrologic Engineering Center). The precipitation file created by the HMR52 program is subsequently input to a rainfall-runoff model such as HEC-1 to obtain the maximized runoff, which will be the PMF. Once the PMF is determined though the iteration process, the input precipitation can be the PMS. Data required for application of the HMR52 program are (USACE, 1984):

- x, y coordinates of basin and subbasin boundary points,
- PMP from HMR51,
- storm orientation, size, centering, and timing,
- preferred orientation and 1 hr to 6 hr precipitation depth ratio from HMR52, and
- PMP orientation adjustment factors (NOAA, 1982).

Input Preparation for HMR52

The HMR52 program uses a digital definition of the watershed boundaries for computing basin-average precipitation from watershed areas and superposed Isohyetal patterns obtained from HMR51 and HMR52.

Basin Geometry Characteristics

The boundary of a drainage basin is defined by line segments joining a sequence of coordinate points that are defined counter-clockwise around the basin or subbasin (USACE, 1984). Conventionally, the *n* boundary points having coordinates (x, y) of the watershed can be obtained by traditional surveys and manual evaluation of topographic maps. In GIS the basin geometry can be represented as polygon feature class. Feature class is a collection of features, which are data tables that store both spatial coordinates and attributes (points, lines, and polygons) such as watersheds as polygons, streams as polylines, and garage stations as points. The real world can be represented as vector-based or raster-based data as for GIS data format. Vector is a data structure used to store spatial data. Vector data comprise lines or arcs, defined by beginning and end points, which meet at nodes. The locations of these nodes and the topological structure are usually stored explicitly. Features are defined by their boundaries only, and curved lines are represented as a series of connecting arcs. The watershed polygon feature class consists of a set of points, and geometry information of the points can be obtained by ArcObject Interface. The HMR52 program has an internal limit for the number of watershed boundary points so that the number of points cannot be greater than 100. Usually the number of boundary points is much greater than 100. The Spatial Analyst (Figure 8), ArcGIS Extension, minimizes the number of points to less than or equal to 100 through the iterating process of converting feature to raster and back to feature from raster.

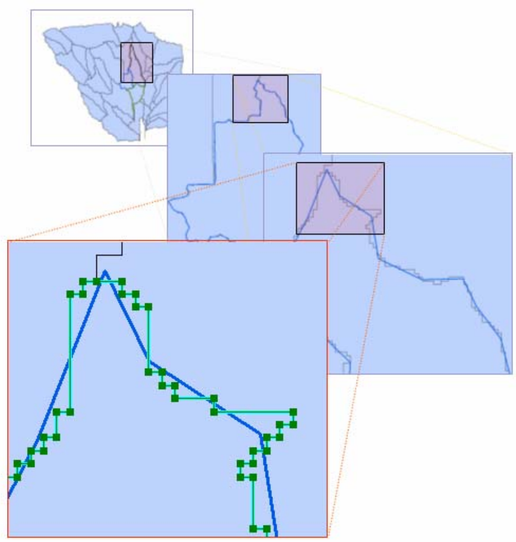

Figure 8. Optimizing the Number of Boundary Points Using Spatial Analyst.

Digitizing the PMP Paper Maps

The PMP tool involves the use of probable maximum precipitation maps developed by Schreiner and Riedel (NOAA, 1982). HMR51 gives estimates of drainage average all-season probable maximum precipitation for United States, east of the 105 meridian, for areas ranging from 10 to 20000 mi^2 (26 to 51,800 km^2) and for time durations of 6 to 72 hours. The HMR52 user manual includes a map for preferred orientation for the PMS and a map that illustrates the ratio of 1-hr to 6-hr precipitation for "A" isohyte of a 20,000 mi^2 storm. In order to initialize the PMP tool, these paper maps had to be digitized. A geodatabase stored these PMP, orientation, and ratio maps. Researchers used ArcView 8.3™ for the digitizing process. Line feature classes were defined for each of the maps and stored in the geodatabase "PMPMaps.mdb." The PMP estimate maps were stored under “PMPs” and the maps containing the orientation and the ratios were stored under “Misc.” The PMP maps were named in the following way:

pmpxxxxxyy- where xxxxx represents the area and yy represents the time.

For an area of 10 mi^2, 00010 is used, 00200 for an area of 200 mi^2, and so on, and yy = 06 represents the map for duration of 6 hours, 12 for 12 hours, and so on. Therefore, pmp2000072 represents a PMP map for an area of 20000 mi^2 and duration of 72 hours. In total, there were 30 PMP maps (HMR51, p. 48-77, figures 18-77), one map for orientation (HMR52, User Manual, p. 4, figure 3) and one map for ratio HMR (HMR52, User Manual, p. 8, figure 8). The following parameters were used while digitizing these maps:

- Projected Coordinates
  Coordinate System:
  Albers
  False_Easting: 0.000000
  False_Northing: 0.000000
  Central_Meridian: -96.000000
  Standard_Parallel_1: 29.500000
  Standard_Parallel_2: 45.500000
  Latitude_Of_Origin: 37.500000
  GCS_North_American_1983
  Datum: D_North_American_1983
  Prime Meridian: 0

The attribute table for the PMP maps gives the shape of the feature class, the value of the isohyet (depth in inches), which is listed in the field called “newid,” and the length of the polyline.

An example of the attribute table for PMP estimates of 5000 mi^2 and 6 hour duration (pmp0500006) appears in Figure 9.

Attributes of pmp0500006

OBJECTID*	Shape*	newid	Shape_Length
1	Polyline	7	2256835.938450
2	Polyline	8	3764558.229528
3	Polyline	9	3091010.491716
4	Polyline	10	2098800.967066
5	Polyline	10.1	1996812.477941
6	Polyline	4	84059.955902
7	Polyline	5	196150.428021
8	Polyline	6	502791.197527
9	Polyline	7	515016.834148

Figure 9. Attribute Table for PMP.

The attribute table for the orientation map gives the shape of the feature class, the preferred orientation (in degrees) listed in the field "newid," and the length of the polyline. For the ratio map the "newid" field gives the value of the ratio of 1-hr to 6-hr precipitation for "A" isohyet of a 20,000 mi2 storm.

The preferred orientation and 1-hr to 6-hr precipitation ratio, supposed to compute precipitation depths with durations less than 6 hr, are also digitized and stored at the different feature data set in the same geodatabase. Inverse distance weighting (IDW), an interpolation method, extracts the PMP estimates, the preferred orientation, and 1 hr to 6 hr precipitation ratio at the specified location of watershed.

Run HMR52 Program

Once the input file for the HMR52 program is created, the HMR52 program is triggered by ArcGIS Storm Tool. The HMR52 program creates an output file which is used as input for HEC-1 program to compute the runoff.

Develop PMP Design Storm

The precipitation depths of 6-hr duration (up to 72 hr) are extracted from the output file created by the HMR52 computer program and displayed in ArcMap™ with a specified symbology and transparency. The design storm is created based on information such as storm orientation, size, shape ratio, and precipitation depths for the corresponding isohyet areas obtained from the output file prepared by the HMR52 program.

GIS TOOL FOR FREQUENCY-BASED HYPOTHETICAL STORM

The synthetic storm of various durations – from five minutes to up to ten days – with a consistent exceedance probability can be developed based on given depth-duration relationship. In the United States, depths for various durations for a specified exceedance probability are available from several sources, including National Oceanic and Atmospheric Administration (NOAA Atlas 2 for the western United States), the National Weather Service (NWS TP-40), and more often from the city, county, or state engineer (locally developed frequency-depth-duration relationship).

Areal Adjustment

Point precipitation, usually applicable for areas up to 10 mi^2, must be converted to areal precipitation for areas greater than 10 mi^2 using point depth reduction factors. The U.S. Weather Bureau (1957, 1958a, 1958b) developed guidelines for adjusting point depths to areal depths for areas up to 400 mi^2. Point precipitation is adjusted to the area of the subbasin using following equation:

$$Cf = 1.0 - BV \times (1.0 - e^{(-0.045 \times Aen)})$$

where

Cf = coefficient to adjust point rainfall,

BV = maximum reduction of point rainfall, and

A_{en} = enclosed area of the subbasin.

Point-to-areal rainfall conversion factors are shown in Table 1.

Table 1. Point-to-Areal Rainfall Conversion Factors (USACE, 1990).

Point-to-Areal Rainfall Conversion Factors	
Duration (hours)	BV
0.5	0.48
1	0.35
3	0.22
6	0.17
24	0.09
48	0.068
96	0.055
168	0.049
240	0.044

Isohyetal Pattern for Design Storm

Storm geometry can be assumed to have elliptical isohyetal pattern for standard isohyet areas with arbitrary shape ratio of major to minor axis. For constructing isohyets, the following relations are provided:

$$a = r_{shape} \times b$$

$$a = \left(\frac{A}{r_{shape} \times \pi} \right)^{1/2}$$

$$r = \left(\frac{a^2 b^2}{a^2 \sin^2 \theta + b^2 \cos^2 \theta} \right)$$

where

a = semi-major axis,

b = semi-minor axis,

r_{shape} = shape ratio of major to minor axis,

A = area of the ellipse, and

r = distance along a radial at an angle θ to the major axis.

Isohyetal Profile for Design Storm

The accumulated rainfall for an enclosed area of ellipse is obtained by applying point-to-areal reduction relationships. The following equations show the incremental rainfall depth for each isohyetal area:

$$V_2 - V_1 = Z_{ave}(A_2 - A_1)$$

$$Z_{ave} = \frac{(V_2 - V_1)}{(A_2 - A_1)}$$

$$V = A \times Z$$

where

A = enclosed area,

Z = accumulated rainfall depth for enclosed area,

Z_{ave} = incremental rainfall depth for isohyetal area, and

V = volume of accumulated rainfall depth for enclosed area.

STORM GEOMETRIC AND DYNAMIC CHARACTERISTICS

Radar provides an important source and tool for capturing precipitation in the air distributed in space and time, at both small and large scale. Radar can give valuable information about storm geometric characteristics such as storm shape and orientation and storm dynamics such as moving direction and velocity. Rainfall estimates from radar in space and time are essential to develop and facilitate distributed hydrologic modeling, which can give us more accurate values of water system inputs and outputs. GIS makes it possible to ingest rainfall estimates from radar and integrate them into distributed hydrologic modeling.

NEXRAD AND WSR-88D

Radar, which stands for Radio Detection and Ranging, was developed for military purposes. Radar imagery, composed of three shades of gray, was accessible in the mid 1960s from 37 radars across the United States. By the late 1970s and early 1980s, color radar imagery could be accessed from National Weather Service radars, known as WSR-57 and WSR-74, and the Federal Aviation Administration (FAA) radars. Advances in technology replaced the old radars across the country, as Doppler radar, known as WSR-88D. The WSR-88D radars, also called NEXRAD radars, are a product of the National Weather Service's Next Generation Weather Radar (NEXRAD) Program. NEXRAD usually indicates the entire system of WSR-88D radars and associated processing equipment, but WSR-88D represents single radar from the national NEXRAD network. The WSR-88D Doppler radar records reflectivity, radial velocity, and spectrum width of reflected signals. The reflectivity can be converted to rainfall estimates using the Z-R relationship between reflectivity and rainfall rate.

WSR-88 Precipitation Products

The National Weather Service (NWS) has developed a set of post-processing algorithms for NEXRAD precipitation estimates, referred to as Stage II, III. NEXRAD precipitation products (Stage I, II, III, and IV) have been used as the principal data source for study of hydrology such as hydrologic forecast operations and hydrologic simulation.

- Stage I: Raw analog radar returns, obtained by the WSR-88D, which propagate through the wave guide to the radar processor at the radar data acquisition (RDA) site.
- Stage II: Converted data from raw analog radar returns by the radar processor, which are reflectivity, radial velocity, and spectral width in polar coordinates.
- Stage III: Various graphical products generated by the radar product generator (RPG) at the National Weather Service Forecast Office (NWSFO).

Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN)

TITAN, developed by the National Center for Atmospheric Research, was intended to provide storm tracking capability and a statistical evaluation tool for analyzing storm track data using data from weather radars operating in volume scan surveillance mode. TITAN retrieves and displays radar data, storm data, and aircraft positions. TITAN runs on the UNIX or LINUX operating system and can operate two modes: archive mode and real-time mode.

Development of Hydrologic Design Criteria Using TITAN

TITAN can identify, track, and quantify rainfall depths from a storm moving with certain speed and direction. TITAN can provide specific and valuable information about a storm such as storm shape, size, duration, decay rate, and dynamics, which have been unknown in the past due to the lack of sufficient data. Once storm characteristic are identified, all the information can be used as design criteria such as development of areal reduction factor and depth-duration-intensity relationships for hydrologic design. The rainfall estimates obtained from TITAN can be integrated into GIS to be used as inputs for distributed hydrologic modeling and as improved hydrologic design criteria.

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* [ ] - These articles have not been directly reviewed by the authors and have been included for reference purposes only.