Report for 2002LA4B: Flood Risk Mapping of the New Orleans Area

- Articles in Refereed Scientific Journals:
  - Lan, Z. and Singh, V. P., Bivariate flood frequency analysis using the copula method. ASCE Journal of Hydrologic Engineering, under review, 2003.
  - Singh, V.P., Wang, S.X. and Lan, Z., Frequency analysis of non-identically distributed flood data. Journal of Hydrology, under review, 2003.

Report Follows:

Flood Risk Mapping of the New Orleans Area

Abstract: The conventional methods of incorporating risk in floodplain delineation, and design of drainage systems and surface impoundments are the safety factor and return period. These methods are, however, inadequate and do not directly consider the damage distribution. This project argues for incorporation of a more comprehensive definition of risk based on three aspects: (1) scenario or cause identification, (2) probability of that scenario, and (3) the consequence of that scenario. Using this risk definition, a risk methodology is proposed for determining flood risk and then constructing a flood risk map. This methodology is illustrated by applying to the New Orleans area, one of the most flood prone areas in the United States, and can be easily extended to other areas of the country. The risk map can be employed as a tool for making real-life decisions.

1. Introduction

The Gulf Coast region (GCR) is perhaps one of the most flood prone areas in the United States. This is even more true in Louisiana where flooding is a regular annual occurrence in one part or the other. For example, the 1995 related floods of southeast Louisiana and Mississippi claimed seven lives and resulted in property damage estimated at over 3 billion dollars. Landfalling hurricanes occur frequently during the hurricane season and cause extensive flooding and property damage. In 1992 hurricane Andrew made a landfall in Florida and Louisiana resulting in 58 deaths and caused over 30 billion dollars of property damage. These damages were attributed in part to the heavy rainfall which caused extensive flooding. The flooding patterns are greatly influenced by climatic factors. Climatic anomalies such as El Nino also affect the spatial distribution of the amount and intensity of rainfall and its intensity.

Louisiana has as much if not more risk from hurricanes and other types of flooding than any other state. Over the past century, south central Louisiana has experienced what appears to be the highest number (6) of landfalls of major hurricanes (Category 3-5 storms). Louisiana and Texas typically rank number one and two in annual flood insurance claims. New Orleans is the most vulnerable major city on the Gulf Coast and perhaps in the entire United States. Had Hurricane Georges not taken a last minute turn to the east in 1998, major portions of New Orleans would have flooded. It would likely have been one of the worst disasters of the century in terms of loss of life and damage. Additionally, Louisiana has extensive infrastructure of oil and gas facilities, chemical plants, and hazardous, industrial and residential landfills. Most of these facilities are in flood prone areas and within the confines of levee systems protecting housing and other structures from flooding. Even in areas where mitigation strategies have been engineered (i.e., levee, drainage, and pumping systems), such designs are unable to capture and control all storm water runoff from occasional extreme rain events.

Louisiana's outer buffer or defense to hurricane winds and storm surges are its coastal wetlands and barrier islands. Since 1930 approximately 1 million acres of buffer have been lost. Even with the present coastal restoration activities (i.e., Coastal Wetlands Planning, Protection and Restoration Act), future wetland loss will range from 28,000-32,000 acres a year. The corridor from Morgan City through Houma to New Orleans loses about 20,000 acres of buffer annually. Thus, potential impacts are far more severe now than in the past and the picture worsens every day. A major flood in Louisiana would have greater impacts compared to a similar sized flood in North Carolina, posing more severe health risks.

The New Orleans area possesses an unusual topography in that some of the area is below the mean sea level and some barely above it. It is close to the Gulf of Mexico and is subject to intense hurricane activity almost on an annual basis. It has the distinction of having the Lake Ponchartrain and the Mississippi River flows through the city of New Orleans. It has an annual rainfall of more than 1700 mm. Flooding in the New Orleans area is caused either by high rainfall, hurricanes, storm surge, high tides or a combination thereof.

Flooding of the New Orleans metropolitan area is of highest priority for the state of Louisiana. Recent studies and evaluations indicate that the city is at risk during an extreme flood event. What is that risk? What will be the consequences if an extreme flood event occurred? What can be done to minimize the risk? These questions require serious thought. A careful consideration would show that to answer these and other related questions would involve a risk analysis and assessment. This is especially true of the design of urban drainage facilities as well as other civil works. Therefore, it is reasoned that drainage works, flood control projects, and other civil works must be designed, based on risk analysis. This issue is addressed in the proposed study.

2. Current Practice of Incorporating Risk

Flood plain mapping, land use zoning, design of drainage facilities, design of surface impoundments, and water diversion systems are based on an appropriate (or acceptable) level of risk. There are two conventional criteria to account for the acceptable risk. The first is the safety factor criterion. However, this risk criterion is unacceptable for two main reasons. First, the cost of increasing the safety factor is too high in most cases. Second, even with increased safety factor, there will usually be some risk, for risk cannot be eliminated entirely.

The second criterion which is more popular in water resources planning, design and management is the selection of an appropriate return period. This concept is simple but has serious drawbacks. First, in practice neither the form of the most appropriate stochastic model of flood frequencies nor the values of the parameters of the model are known and therefore assumptions and estimates must be made. As a result, because of statistical and epistemological uncertainties, the best estimate of the flood of a given probability (p) and return period (T) will probably be exceeded in the future more frequently than once in T years. In other words, if risk is defined as the probability that the design flood will be exceeded in any one year, then the expected risk of having a flood event greater than its estimated magnitude in future is greater than the exceedance probability p. Thus, what is needed is not the best estimate of the magnitude of the flood of probability p but instead the flood with the expected risk of occurrence (Stedinger, 1991). It is, therefore, necessary to estimate the flood with an expected risk (Beard, 1960; Hardison and Jennings, 1972). This flood magnitude will be higher than the conventional best unbiased estimate of the p-probability flood, and the difference will depend on the uncertainties in parameter estimation. The difference between the two magnitudes can be seen as an adjustment factor.

The other difficulty with the return period criterion, which is more serious, is that it provides no information on damage resulting from the T-year flood. Damage is one of the most important considerations in the risk evaluation and analysis (Borgman, 1963). This difficulty is because of the very narrow interpretation of the concept of risk implied in the return period criterion.

3. Related Research

There is vast literature on flood frequency analysis (Rao and Ahmad, 2000). By comparison, flood risk has received limited attention. Kaplan and Garrick (1981) provided perhaps the best quantitative definition of risk. However, this definition has been employed only in a few hydrologic studies and to our knowledge it has never been applied to flood risk in the New Orleans area. Borgman (1963) was one of the first to consider risk criteria for wave heights in coastal areas. His analysis, however, did not consider flood risk in a comprehensive manner. Murota and Etoh (1984) applied the equi-risk line theory to the design of a detention reservoir. Arnell (1988) obtained unbiased estimation of flood risk with the generalized extreme value distribution. His methodology was based on the return period criterion and did not consider the damage issue. Young and Walker (1990) developed a risk-cost design of pavement drainage systems. Like other studies, they did not consider risk as a set of triplets. Haimes et al. (1992) developed a partitioned multiobjective risk method for analyzing extreme events. Their study is probably the most comprehensive of above-cited risk studies. But it may not be entirely appropriate for the New Orleans area, because it arbitrarily divides the extreme events into three categories which may not be appropriate. Thus, there is a gap in our knowledge of flood risk, especially in the New Orleans area. The objective of this project was to fill this gap.

4. Objectives

This research project employed a more versatile definition of risk and the resulting methodology which remedies the aforementioned drawbacks and omissions. Thus, the overall goal of this proposal was to develop a flood risk methodology and a flood risk map of the New Orleans area. To that end, the specific objectives were: (1) to develop a flood damage model, (2) to develop a flood frequency model, (3) to develop a flood risk model, and (4) to develop the flood risk map.

5. Risk Methodology

Before presenting the risk methodology, it is deemed important to clarify the definitions and develop the context. The term risk is used in many different senses and defined differently. Intuitively, the notion of risk involves both uncertainty and some kind of loss or damage. Risk is the possibility of loss or injury and the degree of probability of such loss. The loss or injury stems from a source of danger; this source is called hazard. Thus, risk includes the likelihood of conversion of that source into actual delivery of loss, injury or some form of damage. This points to the concept of reducing risk by employing safeguards. In other words, risk also involves hazards and safeguards. It may be noted that risk can be reduced but as a matter of principle it cannot be completely eliminated.

Thus, risk has three elements: (1) cause, scenario, or source (s), probability of that scenario or source (p), and (3) consequence of that scenario or source. Now, following Kaplan and Garrick (1981) risk (R), as used in the proposed research, is defined as a set of triplets:

$$R=\{(s_i, p_i, x_i)\}, \qquad i=1,2,3,............,N \tag{1}$$

where s_i is the i-th source or scenario, p_i is the probability of s_i, and x_i is the i-th consequence. In our case, for example, s_1 may be flooding due to extreme rainfall, s_2 may be flooding due to storm surge, and so on. Likewise, the consequences of flooding may be denoted as: x_1 is the damage to dwellings, x_2 is the damage to roads, x_3 is the damage to water supply, and so on.

Keeping the above considerations in mind, the proposed risk methodology entails the following elements as illustrated in Fig. 1.

(1) Flood Model: There is a large number of flood models available in the hydrologic literature (Cunnane, 1973; Singh, 1998). We tested the log-Pearson type III and the generalized extreme value and select the best, depending on the nature of the hydrologic series. Both univariate and bivariate models were developed. The bivariate models were developed using the copula method.

A brief discussion of the flood models is in order.

Univariate flood frequency analysis: Empirical methods of flood frequency analysis (FFA) were used for analysis of a single flood variable, such as flood peak, flood volume or flood duration, as a function of return period, T. If there are n-year daily flow data available, then an n-year annual flood series can be constructed by extracting the maximum daily value for each year. Assuming that annual floods are independent and identically distributed, the probability distribution function can be derived by conventional frequency analysis. Here, F(Q) is the cumulative frequency (probability) distribution (CDF), $P(Q \leq q)$ is the probability of Q being less than or equal to a given value q. In frequency analysis, T-year event, q_T, is interested, where T is the average time interval (or return period) between two exceedances of q_T ($Q \geq q_T$) and is given by T=1/(1-F). Univariate flood frequency analysis is the first step in the whole study in order to perform the multivariate analysis according to stationary and nonstationary assumptions.

Multivariate flood frequency analysis using copulas: Several multivariate (bivariate) flood frequency analysis methods have been developed by many researchers. However, these models have the following drawbacks:

(1) Each bivariate model must have the same marginal distributions. This requirement is too restrictive, since in practice, the two hydrologic variables may not have the same distribution type.

(2) The measure of association or correlation is sensitive to the marginal distributions for the correlation structure of these bivariate distributions is constructed directly or indirectly from Pearson's product moment correlation coefficient.

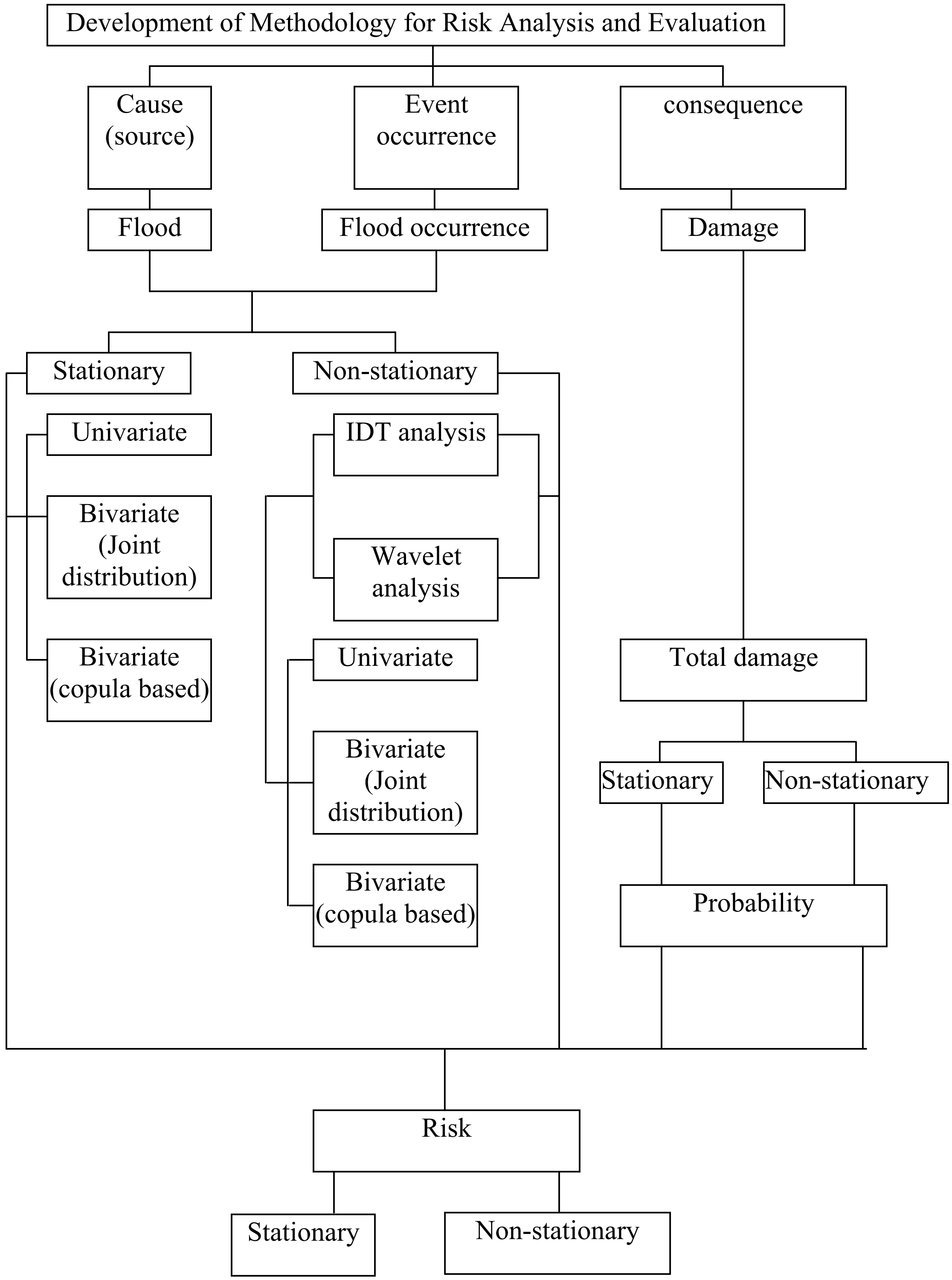

Figure 1. Outline of Risk Methodology.

(3) Except for the bivariate normal distribution, other bivariate distributions can hardly be extended to more than two dimensions as their correlation structure among variables is not known.

In order to overcome those drawbacks, the copula method was introduced and applied for the multivariate (bivariate) flood frequency analysis. The theory of copulas has not yet been applied to represent joint statistical properties of hydrologic events. Although a number of copulas have been proposed in the statistical literature, it is not clear which may be directly applicable for modeling multivariate hydrologic events.

Determination of copulas: The following was pursued in this study:

(1) Investigation of the existing copulas for modeling bivariate events with the same marginal distributions, such as bivariate normal, lognormal, exponential and Pearson (gamma) and Log-Pearson III distributions. Since these bivariate distributions have been applied to model two correlated hydrologic variables, it was instructive to compare the copula models with conventional models. Such a comparison sheds light on the advantages and shortcomings of the copula models in comparison with conventional models.

(2) Investigation of the existing copulas for modeling bivariate events with a mixture of marginal distributions. More frequently, two correlated hydrologic variables may have different distribution types. It is important to model a joint event with a mixture of marginals than to model it with the same marginals. Therefore, the suitability of the existing copulas for modeling bivariate events with a mixture of marginals was examined.

(3) Investigation of the existing multi-dimensional copulas for modeling multivariate (more than two dimensions) events with a mixture of marginal distributions. In hydrologic practice, more than two correlated hydrologic variables may be correlated and have different distribution types. In such cases, it is necessary to model a joint multivariate event with a mixture of marginals using a multivariate distribution model. The suitability of the existing multidimensional copulas for modeling multivariate events with a mixture of marginals was examined.

(4) Development of new copulas. The copulas reported in the literature may not be suitable for modeling correlated hydrologic variables. When necessary, new copulas were developed.

Identification of parameters based on multi-dimensional copulas: In practice, when a number of random variables are of interest, given their observed sample data, such as flood peak, flood volume, and flood duration, the following questions must be answered. (1) What distribution do they follow? What is an appropriate copula for constructing the dependence structure between these variables? The two-step way of constructing multivariate models via multi-dimensional copulas permits to identify univariate marginals and a copula function separately. That is, parameters of marginal distributions and the parameters of copula function can be estimated independently.

Identification of marginal distributions: Appropriate marginal distributions were determined first, based on univariate data. Both the conventional stationary and nonstationary statistical approaches were used for deriving the distribution of a single variable.

Identification of an appropriate copula: The basic idea for identifying a copula should be identical to the selection of a goodness-fit of the distribution type for univariate frequency analysis, i.e., determine a theoretical model that fits the observed data best. The procedure is based on nonparametric estimates of $K(u) = P(U_i \le u_i)$, the distribution function of pseudo-observations U=H(x_1,x_2,…,x_N). By comparing the parametric estimates from copulas K(z), the best-fit copula to the observations can be selected. The general equation for the two-dimensional copula is generated by:

$$1+(1-\theta)\frac{1-H(x,y)}{H(x,y)} = \left[1+(1-\theta)\frac{1-F(x)}{F(x)}\right]\left[1+(1-\theta)\frac{1-G(y)}{G(y)}\right] \tag{2}$$

$$\mathrm{C(u,v)} = \frac{[1-(\theta-1)(\mathrm{u}+\mathrm{v})] \pm \sqrt{[1+(\theta-1)(\mathrm{u}+\mathrm{v})]^2 - 4\mathrm{uv}\theta(\theta-1)}}{2(\theta-1)} \tag{3}$$

or

$$C(u,v) = \varphi^{-1}(\varphi(u)+\varphi(v)) \tag{4}$$

The parametric $K_\phi(z)$ with an Archimedean copula is:

$$K_\phi(u) = \Pr[C(U_1,U_2,...,U_N)] = u + \sum_{n=1}^{N}(-1)^n \frac{\varphi^n(u)}{n!} M_{n-1}(u) \tag{5}$$

with

$$M_n(u) = \frac{\partial_u M_{n-1}(u)}{\partial_u \varphi(u)}, M_0(u) = \frac{1}{\partial_u \varphi(u)} \tag{6}$$

In the bivariate case, this formula simplifies to

$$K_\phi(u) = u - \frac{\varphi(u)}{\varphi'(u)} \tag{7}$$

Multivariate stationary flood frequency analysis: There is a large number of flood models in hydrologic literature, (Singh,1998; Rao and Hamed, 2000) for stationary flood frequency analysis. The best fitted statistical model were selected and the proper parameter estimation method were used to determine model parameters. The following joint statistics obtained from the copulas important for a multivariate (bivariate) flood model, can be derived:

(1) The joint distribution of an event with X≤x, and Y≤y;

H(x,y)=Pr(X≤x, Y≤y) and with the probability density function h(x,y), the joint return period of an event with X>x, Y>y or both X>x and Y>y

T(x,y)=1/[1-H(x,y)],
and the joint return period of an event with both X>x and Y>y:
T'(x,y)=1/[1-F(x)-G(y)+H(x,y)].

(2) Conditional distribution of X given Y=y, $F(x \mid Y = y) = \int_{-\infty}^{\infty} \frac{h(x,y)}{f(y)} dy$ and return period T(x|Y=y)=1/[1-F(x|Y=y)].

(3) Conditional distribution of X given Y≤y, F(x|Y≤y)=H(x,y)/F(Y≤y), and the corresponding return period T(x|Y≤y)=1/[1-F(x|Y≤y)].

From joint return periods, one can obtain, for given a return period, various combinations of flood peak and volume and vice versa. Or for a given flood peak and volume, the joint return period can be derived. The scenarios corresponding to different combinations of peaks and volumes are useful for planning, management and design. For example, for a spillway and flood control reservoir, a design flood hydrograph (DFH) is needed. The various pairs of flood peak and volume values associated with a given return period provide a more complete picture of a flood event, and more possible choices on which DFH should be selected. This information permits a better selection of the most crucial scenario according to a specific water resources planning, management, or design problem, which cannot be achieved by single-variable frequency analysis.

(2) Parameter Estimation Model: The most popular parameter estimation methods are the method of moments, maximum likelihood estimation, linear moments, probability weighted moments, and entropy (Singh, 1998). No one method is the best method for every flood model. Thus, depending on the choice of the flood model, the best parameter estimation method selected were the methods of moments and maximum likelihood estimation

(3) Flood Damage Model: This is the trickiest part in the risk methodology and the least investigated in hydrologic literature. From a theoretical point of view, the stochastic flood damage model consists of two parts: (1) the no-damage part and (2) the distribution of damage due to floods exceeding the threshold no-damage flood. Two submodels are needed. The first submodel is for the distribution of damage due to a flood event exceeding a threshold value. The second submodel is for the distribution of the total damage which embeds the first submodel. These two distributions have been derived from the empirical data collected for the New Orleans area. At this stage it seems that the two-parameter gamma distribution is a good candidate for a damage model. The literature, however, provides little guidance in this regard. The model is under testing.

(4) Risk Model: Based on the calculations done using the above models, the value of risk, R, as defined above is computed. Then, for each damage level, the cumulative probability is computed. To that end, the scenarios are first arranged in order of increasing order of severity of flood damage. Then, the cumulative probability, adding from bottom, is obtained for each damage. Then, the risk curve against each damage and flood exceedance is plotted. This part is still under investigation.

Kaplan & Garrick (1980) developed the triplet concept to analyze risk. They stated that risk involves both uncertainty and some kind of loss or damage, which can be written as: Risk=uncertainty+damage. Risk is the possibility of loss or injury and the degree of probability of such loss, which includes the likelihood of conversion of that source into actual delivery of loss, injury, or some form of damage. It is obvious that risk can be reduced but cannot be completely eliminated.

Fundamentally, in the triplet concept, there are 3 elements: (1) s_i: scenario (source) identification (2) p_i: the probability of that scenario; (3) x_i: is the consequence or evaluation measure of that scenario (source). Then, risk can be denoted as a set of triplets: $R=\{s_i, p_i, x_i\}$. The risk can be obtained from the outline of the following table:

Table 1. Scenario list with cumulative probability.

scenario	likelihood	consequence	cumulative probability
S_1	p_1	x_1	$P_1=P_2+p_1$
S_2	p_2	x_2	$P_2=P_3+p_2$
.	.	.	.
.	.	.	.
.	.	.	.
s_i	p_i	x_i	$P_i=P_{i+1}+p_i$
.	.	.	.
.	.	.	.
.	.	.	.
s_{N-1}	p_{N-1}	x_{N-1}	$P_{N-1}=P_N+p_{N-1}$
s_N	p_N	x_N	$P_N=p_N$

In Table 1, scenarios have been arranged in increasing order. By adding a fourth column in which we write the cumulative probability, and adding from the bottom, the risk curve can be obtained from the triplets.

(5) Risk Map: For each streamflow gaging station and each raingage station in the New Orleans area, the risk curve is under construction. Then, iso-risk lines will be plotted on the area map. This will be the risk map of the area.

6. Results: This research has led to the development of a systematic methodology for estimating flood risk, which can be used for flood plain delineation, design of drainage facilities, evaluation of the existing drainage facilities, land use zoning, design of detention ponds, and the like. Second, it will provide a flood risk map, with an application to the New Orleans area. The methodology can, with little effort, be extended to other areas. Thus, the results obtained in the research will be of great practical value to planners, designers, and decision makers.

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