

SEASONAL RISK ANALYSIS FOR FLOODPLAINS IN THE DELAWARE RIVER BASIN

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ABSTRACT: Overland pollutant transport via surface runoff and flooding is a primary concern in the management of agricultural land resources in the Delaware River Basin. The Catskills is home to multiple water reservoirs that supply the drinking water for New York City. Contamination of this water by pollutants emanating from agricultural sources located in floodplain areas necessitates risk quantification for these locations. This study was performed to assess the risk of rivers topping their banks, or flooding, during various time periods of the year. Streamflow data for seven stations were analyzed to produce monthly partial duration and maximum series. A log-Pearson Type II analysis was performed on the maximum and partial duration series to produce monthly probabilities of flooding. Based on the maximum series, on average, March had the highest probability of flood occurrence at 28%, and April and December had the next highest, at 18 and 12%, respectively. Larger flood probabilities were calculated using the partial duration series, and this result was attributed to the tendency of some months to have multiple floods. Calculated yearly flood probabilities from monthly results agreed well with theoretical values. This study has important ramifications for decision making based on hydrologic risk of pollutant transport in floodplain soils (e.g., this information is needed to determine surface water pollution risks from manure-spread agricultural fields and develop schedules to reduce this risk).

INTRODUCTION

There is acute concern about agricultural non-point-source pollution of the New York City reservoirs residing in the Catskill Mountains portion of the Delaware River Basin. Overland pollutant transport in the Delaware and Catskills watersheds occurs primarily through two mechanisms of surface runoff: saturation-excess overland flow and floodwater recession. The Cornell Soil Moisture Routing Model was developed to predict saturated area runoff from hillslope areas (Frankenburger et al. 1999) and has been used to evaluate associated surface water pollution risks (Water et al. 2000). The model has been shown to be effective in determining runoff from land areas with shallow soils and significant slopes, but it is less appropriate for predicting runoff from low-lying areas adjoining rivers and streams (Zollweg et al. 1996; Frankenburger et al. 1999). These areas are most susceptible to flooding where water may overtop stream or riverbanks and carry pollutants from floodplain soils directly into waterways. Though they comprise a relatively small portion of the land area in the Delaware River Basin, the beneficial nature and topography of floodplain soils lead to relatively high concentrations of farms in these areas, thus intensifying the need to properly characterize the hydrological sensitivity of floodplain areas. During flooding, large amounts of organic pesticides, nutrients, and sediment bound pollutants such as phosphorus can be exported from agricultural land and into major waterways or aquifers (Walter et al. 1978; Goolsby et al. 1993; Roy et al. 1995; Heimann et al. 1997).

To manage the use of floodplain soils effectively, the scheduling and extent of agricultural practices need to be quantified based on some magnitude of return period flow determined to be of unacceptable risk. Return period frequency analysis is

often used to quantify cataclysmic or very rare events on the magnitude of 50–500-year return periods. These large return period flows are used to design safe hydraulic structures (e.g., bridges and levees) and to delineate floodplains for insurance purposes. James and Hall (1986) investigated economic loss as a function of large return period flows in one drainage basin. However, in the case of agricultural land uses, smaller return period flows and floodplains are of concern for management purposes (McCuen 1998).

One important example in the Catskills is the need to develop dairy manure scheduling schemes (i.e., timing and placement of field spread manure) that restrict potentially polluting manure spreading in floodplains from periods of the year susceptible to flooding. The ubiquitous current practice is daily manure spreading primarily on fields most easily accessed or closest to the barn regardless of hydrological sensitivity (Walter et al. 2000). Hydrological sensitivity is dependent upon both spatial location and season. Obviously, there are times during the year when flooding potential is higher (November through April) and times when it is lower (May through October). Interfacing this hydrological knowledge with information about changes in pollutant loading will help develop environmentally safer farm management practices. This study is only part of a fully holistic analysis of floodplain management that takes into account additional criteria including economic, engineering, environmental, and societal factors surrounding development or use of these areas (Penning-Rowsell et al. 1987). Hannan and Goulter (1988) used seasonal flood analysis to model the best economic management practices of a floodplain agricultural system by determining crop damage from flooding by considering the joint probabilities of crop growth stage and monthly return period flooding.

This study provides quantitative framework for a water quality based farm management practices on floodplain soils. Specifically, the hydrological risks of floodplain management systems are quantified by investigating the monthly variance of streamflows for various size watersheds in the Delaware River Basin. Monthly and annual frequency analyses were performed for each catchment to determine the time variance of flood flows. A combination of maximum series and partial duration series (these are defined in the next section) analyses were used to determine monthly flow probability for each catchment. Because each series has strengths and weaknesses relevant to this study, both were used to provide a probabilistic envelope; the maximum series provides a lower probabilistic boundary and the partial duration series an upper boundary.

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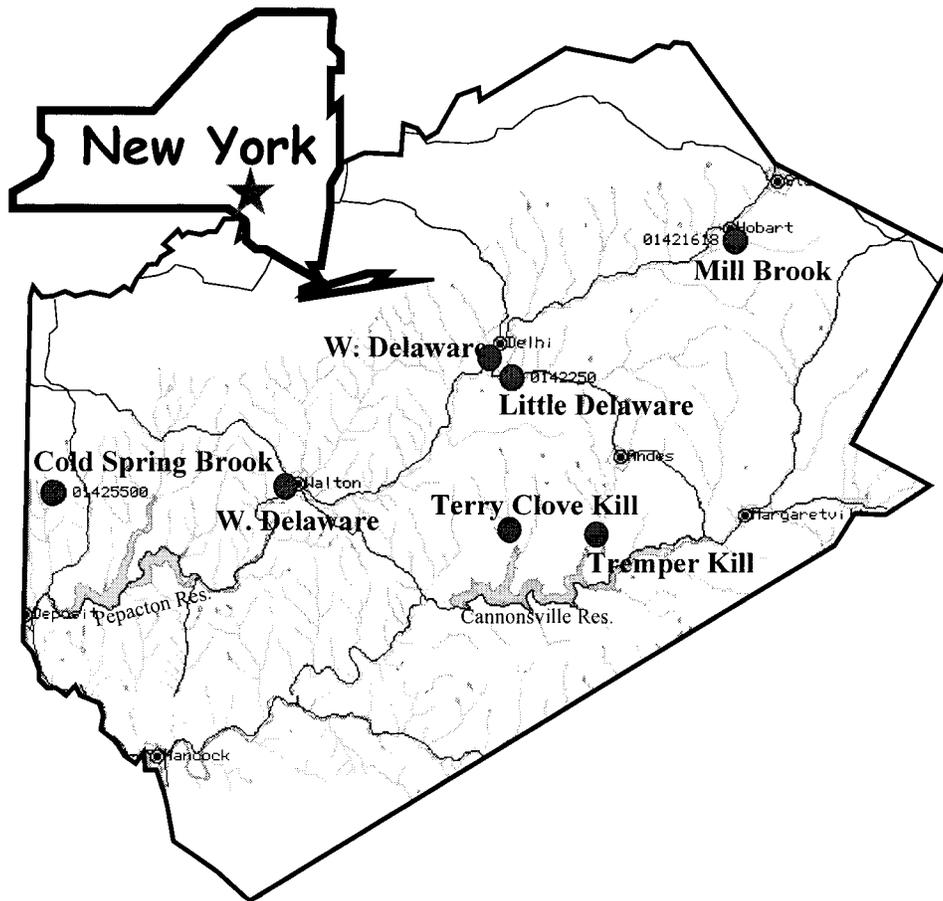


FIG. 1. Stream Gauge Locations; Map Shows Upper and East Delaware River Systems in Delaware County, N.Y. (Star Shows Location of Delaware County)

This is explained in the next section. From monthly frequency curves, monthly flood or bank-full probabilities were determined for risk analysis purposes.

STATISTICAL METHODOLOGY

Seven catchments, or stream gauging locations (Fig. 1) were chosen for this study based on their drainage areas. A range of drainage areas was chosen so that some comparison could be made between the time variability of smaller and larger watersheds. Table 1 presents the general characteristics of the seven stream gauging locations. Hourly flow data were downloaded from the USGS's World Wide Web page (<http://www.dnyalb.er.usgs.gov/swr/NY/>). The data sets were large, generally longer than 40 years (Table 1).

Two statistical approaches to flood frequency analysis were used in this study, namely, maximum series and partial duration series. The maximum series is commonly used for flood frequency analysis, and, because only one event per year is used, sample independence is relatively certain. This type of analysis is typical for obtaining flood magnitudes for infrequent events like those of concern when designing hydraulic structures (e.g., spillways and dams) (Chow et al. 1988; McCuen 1998). However, flood-related contaminate transport poses a high potential hazard during any flood regardless of flow rate (e.g., even during very short, frequent floods). The partial duration series is more appropriate for this kind of analysis because it is well suited to analyzing frequent recurrence intervals (Bedient and Huber 1987; Stedinger et al. 1992; McCuen 1998). However, unlike the maximum series, numerous hydrologists have made statements regarding the difficulty of assuring sample independence in partial duration series, largely due to the complexity of process interactions within

TABLE 1. Characteristics of Catchments Analyzed

Station (1)	Location (2)	Drainage area (km ²) (3)	Record period (4)
West Delaware River	Walton, N.Y.	860	1950–1994
West Delaware River	Delhi, N.Y.	367	1937–1970
Little Delaware River	Delhi, N.Y.	129	1937–1970
Tremper Kill	Andes, N.Y.	85.9	1937–1994
Mill Brook	Dunraven, N.Y.	65.2	1937–1994
Terry Clove Kill	Pepacton, N.Y.	35.2	1937–1962
Cold Spring Brook	China, N.Y.	3.86	1934–1968

hydrological systems [e.g., Chow et al. (1988), Stedinger et al. (1992), and McCuen (1998)]. The criteria used in this study are explained in the next paragraph. Given that these two series have complimentary strengths and weaknesses, using both provides a complete range of probability. The maximum series will underpredict low return period floods thus providing a lower probabilistic boundary. The partial duration series should provide more realistic probabilities of frequent events, but, if the data are not completely independent, it may overpredict flow probability, providing an upper boundary. Sample independence is relatively certain in the maximum series and comparing trends in the two approaches will provide internal corroboration of the results.

Before the data were analyzed, each station's records were disaggregated by month and ranked such that monthly partial duration and monthly maximum series were found. The partial duration series for any monthly group of data consist of the n largest values within that data, where n is the number of years of record, irrespective of whether two or more values occur in

the same month. This type of partial duration series is often referred to as an annual exceedance series (Chow et al. 1988). In an attempt to establish independence among largest values, the peak over threshold approach was utilized (Shaw 1988) using the criteria loosely suggested by McCuen (1998) that no two sample peaks occur in the same well-defined hydrograph nor within 1 week of each other. A discharge threshold was established such that only n peak flows in a monthly group exceeded it, and thus the threshold was different for different monthly groups. The maximum series for any group of monthly or yearly data consist of the largest flow per month or per year for each of n years. Thus for a set of n years of data, 13 subsets were generated (12 monthly and 1 yearly series) for each station and for each type of series (partial duration and maximum series).

Although many theoretical distributions exist for frequency analysis of hydrologic variables (Gumbel 1942; Chow 1954; Escalante-Sandoval and Raynal-Villasenor 1994), the log-Pearson Type III (LP3) distribution is recommended by the Water Resources Council (WRC) (1967) for the analysis of flood flows. LP3 analyses have been extensively used to model the frequency distribution of flood flows (Bobee 1975; Kite 1978; Kuczera 1982). The data sets in this study generally had large sample skew coefficients (third moments about the mean), which made them unsuited to the popular log-normal analysis (Chow 1954). An LP3 analysis was performed on the data for each given month and on the entire yearly record to determine flow frequency curves.

The flow data were log-transformed, and the mean, standard deviation, and skew coefficient were found for each set of data. With these statistical moments, it is possible to determine the return period flows using tabulated frequency factors (WRC 1967) or calculated frequency factors (Naghavi and Yu 1996) and the equation

$$\log Q_T = (\overline{\log Q}) + \sigma_{\log Q} K(\gamma, T) \quad (1)$$

where Q_T = desired return period flow; T = return period in years; σ = standard deviation of the log transformed flow; γ = skew coefficient; and K = frequency factor, which is a function of the skew coefficient and the return period.

To compare relative flow magnitudes for stations encom-

passing a large range in drainage area, the calculated flow values using (1) were normalized to flow depths using the drainage area of the given catchment as the normalizing factor. The return period flow depths were given as depth per day.

Some quantification of risk or probability of flooding in each month is necessary for this evaluation to be useful to planners or farmers. The most direct approach to this task is to use a stream rating curve for each location of measurement and a measurement of bank-full flow corresponding to the flood level. To no avail, the writers spent considerable time and effort trying to locate this type of information from the appropriate agencies. Nonetheless, some hydrologists have indicated that rating curves are often too dynamic over time and therefore not necessarily well suited to this kind of analysis because the bank-full stage is susceptible to change (Dunne and Leopold 1978). Thus, lacking enough information, and questioning the utility of the "rating curve" approach, the assumption was made, based on Dunne and Leopold (1978), that a river's annual maximum flow corresponds to the 1.5-year return period flow based on a yearly analysis using a yearly maximum series. This estimate is independent of stream cross section and gives a general, quantifiable risk level. Using this assumption, the 1.5 year maximum series annual flow was determined for each catchment, and, using the monthly maximum and partial duration series analyses, the monthly probabilities of bank-full flow were determined.

RESULTS

Seasonal Return Period Flows

Results from the monthly frequency analysis were graphed in 3D form to show flow variation as a function of return period and month. Figs. 2(a-c) and 3(a-c) show the partial duration and maximum series results, respectively, for three of the gauging stations, Cold Spring Brook, the Little Delaware River, and the West Delaware River at Walton, N.Y. The y-axes in Figs. 2 and 3 have units equal to watershed outflow volume divided by watershed area. Significantly higher flows are found for the spring months, especially March, and the fall months, September, October, and November, and significantly smaller flows are found for May through July. Isoflow lines

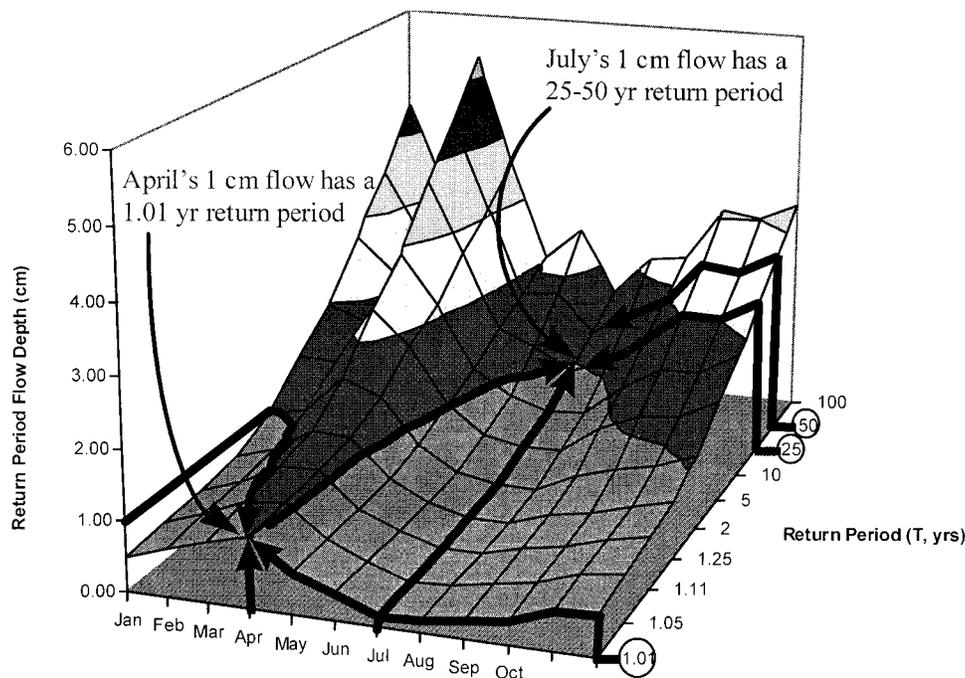


FIG. 2(a). Partial Duration Series Analysis for West Delaware River at Walton, N.Y. (Boundaries between Shaded Areas Correspond to Marked Divisions on Vertical Axis; Bold Lines Show Return Periods for April and July Corresponding to Flow Depth of 1 cm)

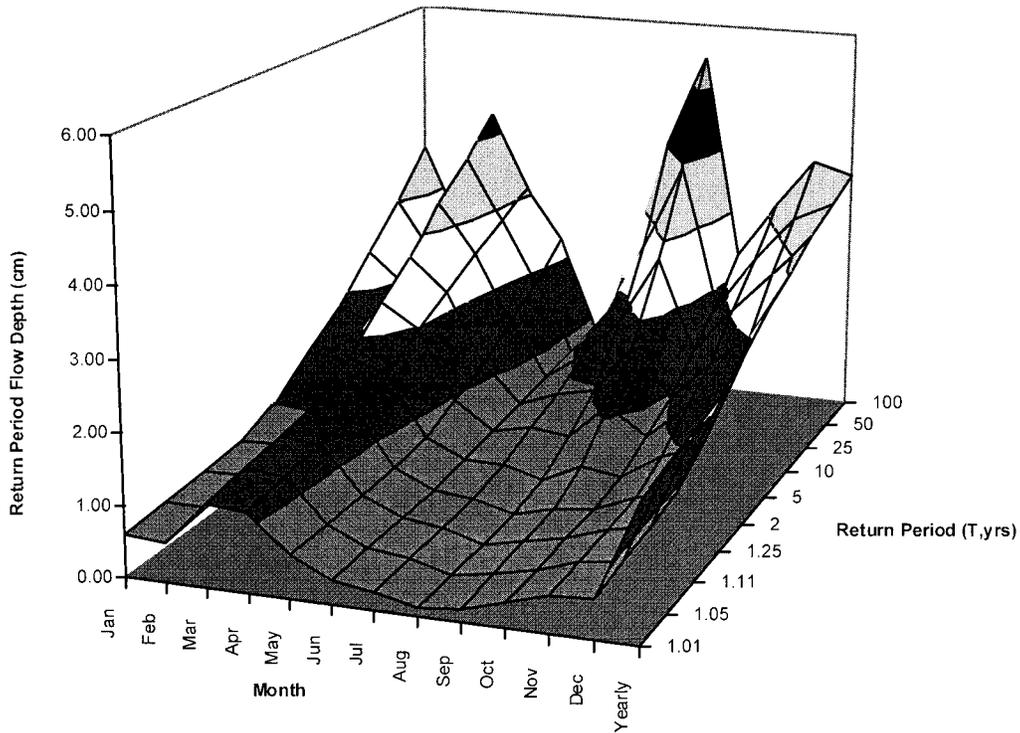


FIG. 2(b). Partial Duration Series Analysis for Little Delaware River at Delhi, N.Y. (Boundaries between Shaded Areas Correspond to Marked Divisions on Vertical Axis)

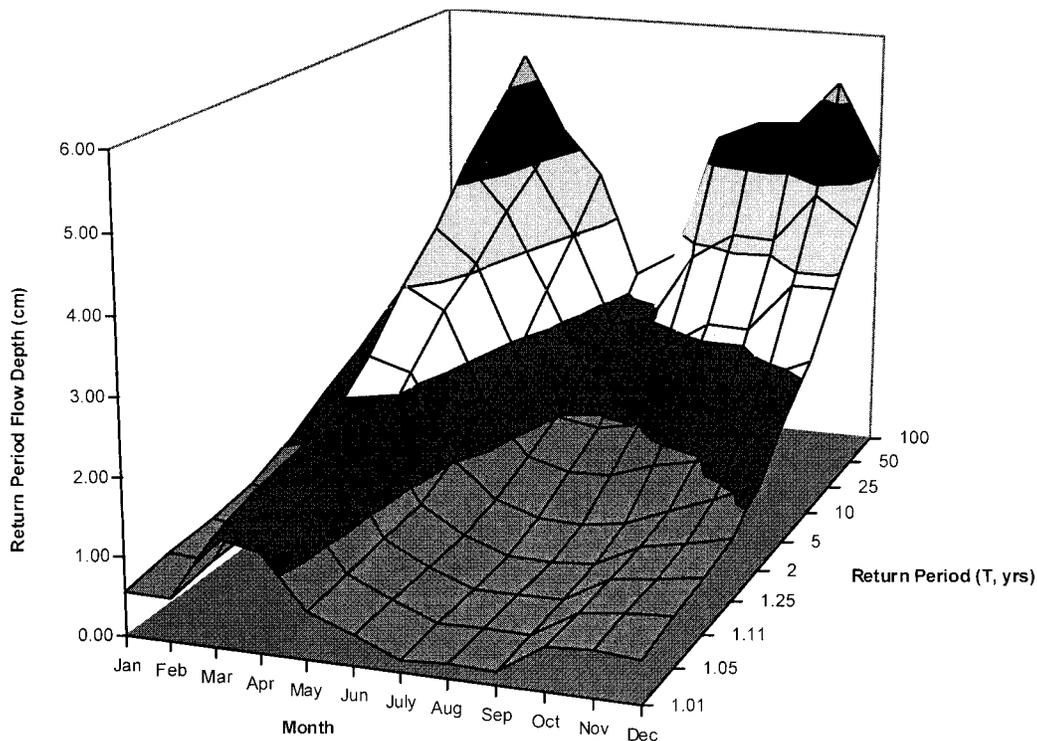


FIG. 2(c). Partial Duration Series Analysis for Cold Spring Brook at China, N.Y. (Boundaries between Shaded Areas Correspond to Marked Divisions on Vertical Axis)

(lines of equal flow), shown as boundaries between shaded zones on these figures, show that the return period associated with a given flow depth, can vary greatly from month to month. For example, in Fig. 3(a) it can be seen that a flow depth of 1.3 cm has only a 1.01-year return period in April, and the same flow corresponds to a 10–25-year return period in June and July. These striking differences illustrate the need to properly quantify the temporal variation of flows as a func-

tion of season so that floodplain managers can plan potentially polluting activities around periods of the year most likely to incur flooding.

For the partial duration series analysis, Figs. 2(a–c) show similar shapes and normalized magnitudes among highly dissimilar watershed areas (over two orders of magnitude difference). This is striking in the lower return period ranges, where the figures show almost identical results. At higher return pe-

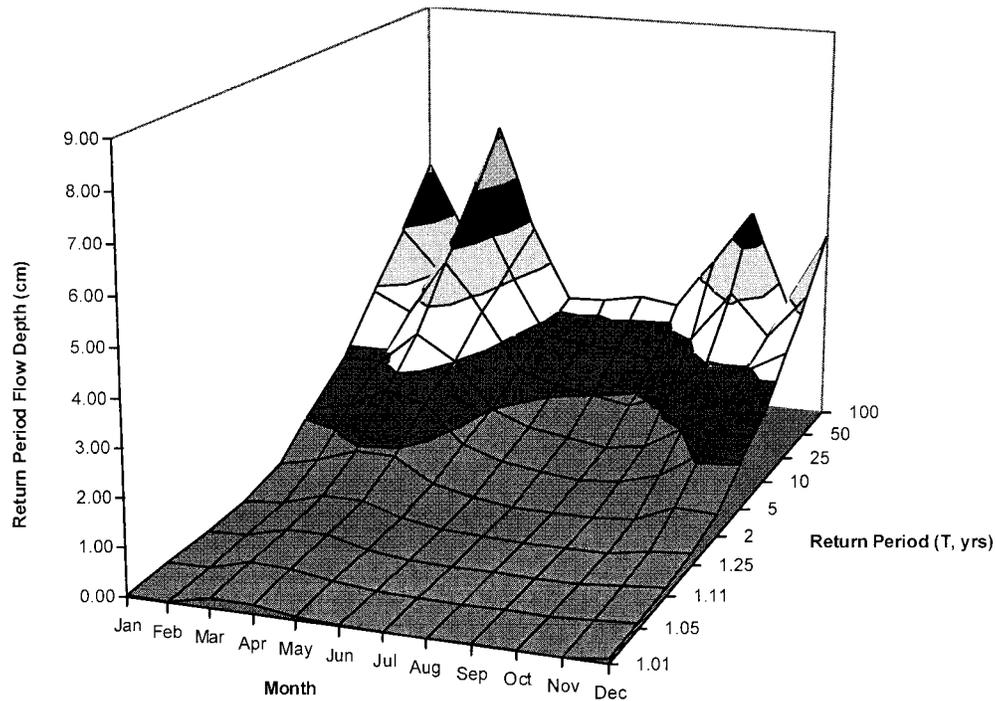


FIG. 3(a). Maximum Series Analysis for West Delaware River at Walton, N.Y. (Boundaries between Shaded Areas Correspond to Marked Divisions on Vertical Axis)

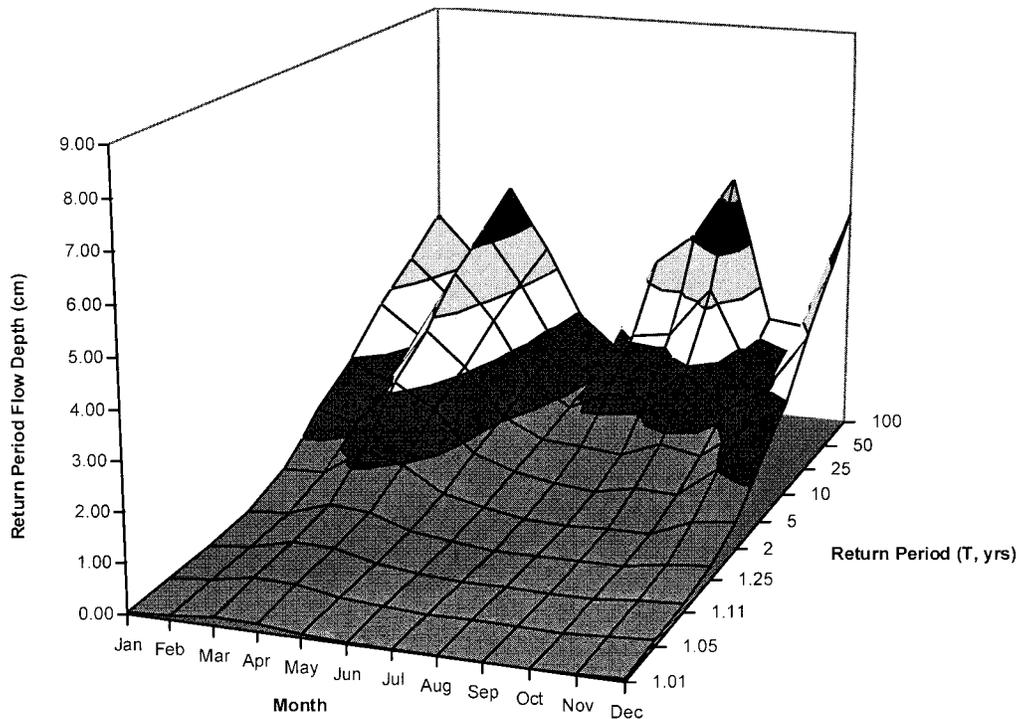


FIG. 3(b). Maximum Series Analysis for Little Delaware River at Delhi, N.Y. (Boundaries between Shaded Areas Correspond to Marked Divisions on Vertical Axis)

riods, more rare events cause the curves to deviate slightly because the smaller watersheds react more strongly to anomalous events in the fall season than does the larger West Delaware watershed.

Figs. 3(a-c) show the analogous results for the monthly maximum series. The similarity between the partial duration [Figs. 2(a-c)] and maximum [Figs. 3(a-c)] series graph shapes lends credence to the statistically less certain partial duration analysis. Although the shapes of the curves for the three stations in Figs. 3(a-c) are generally the same as Figs.

2(a-c), at low return periods, lower flows are seen using the maximum series, and at the high return periods, slightly higher flows are seen. The low flow results are generally expected from the comments of Bedient and Huber (1987) mentioned earlier. The lower return period flow differences are due to the maximum series containing relatively low flows during dry years, and the partial duration series will only contain flows from wet periods. The higher return period flow differences are much smaller and are most likely due to statistical curve-fitting differences (differences in skew, mean, and standard

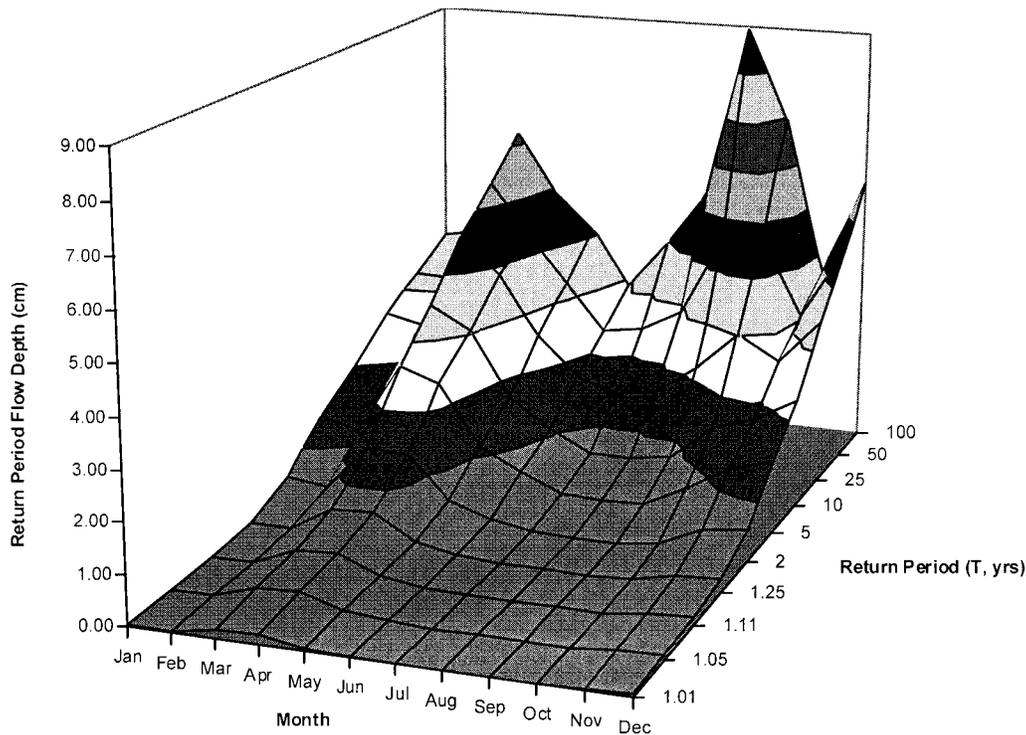


FIG. 3(c). Maximum Series Analysis for Cold Spring Brook at China, N.Y. (Boundaries between Shaded Areas Correspond to Marked Divisions on Vertical Axis)

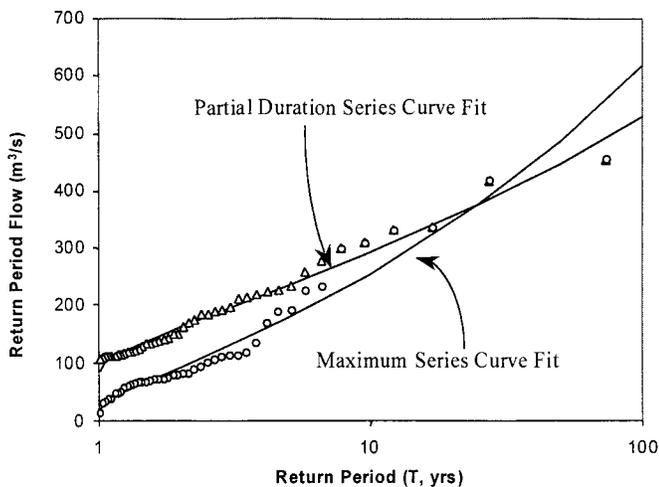


FIG. 4. Comparison of Curve-Fitting for Partial Duration and Maximum Series Analyses for West Delaware at Walton, N.Y. (Δ , are Partial Duration Data; \circ , Maximum Series Data)

deviation) and/or possible non-independence among some partial duration series data. Fig. 4 illustrates the curve-fitting technique used with the maximum and partial duration series from a given month at a given station. In this figure the flow values in each series are plotted using the plotting position formula recommended by Cuanne (1978) for an LP3 analysis

$$T = \frac{n + 0.2}{m - 0.4} \quad (2)$$

where n = number of years in the record; m = flow rank (with $m = 1$ the largest flow and $m = n$ the smallest flow); and T = return period in years. In this figure it can be seen how, although the high return period flows are equal for both series, the curve-fitting technique causes the maximum series to predict higher flows at the high return periods. Although inconclusive, the good visual fit for the partial duration curve lends credence to the partial duration series methodology.

TABLE 2. Bank-Full Flow Depths and Calculated Yearly Flood Probabilities for Analyzed Catchments

Station (1)	Drainage area (km ²) (2)	Bank-full flow depth (cm) (3)	Calculated P_y (4)
West Delaware River ^a	860	1.62	0.63
West Delaware River	367	1.49	0.70
Little Delaware River	129	1.65	0.69
Tremper Kill	85.9	1.63	0.66
Mill Brook	65.2	2.17	0.68
Terry Clove Kill	35.2	1.94	0.68
Cold Spring Brook	3.86	2.14	0.72
Average	221	1.81	0.68

^aAt Walton, N.Y.

Bank-Full Probability

Table 2 presents the bank-full flow depths, or 1.5-year return period flow depth (Dunne and Leopold 1978), for the analyzed stations. The flows are very similar with an average of 1.81 cm of normalized flow depth and a coefficient of variation of 15%. There is a slight negative correlation between drainage area and bank-full flow, but in our analysis the number of stations limits any robust interpretation of this trend.

Fig. 5 illustrates the technique for finding monthly, bank-full probabilities for a given station. In Fig. 5, the return period (using the maximum series) flows for each month and for the yearly analysis are presented for Tremper Kill. The horizontal line drawn on the graph indicates the 1.5-year return period flow and the return period values where it crosses an individual month's frequency curves directly relate to the bank-full probability in a given month by

$$P_m = (1/T_m) \cdot 100 \quad (3)$$

where P_m = bank-full probability (%) for a given month m ; and T_m = associated return period (year) for month m .

Figs. 6 and 7 show the bankfull probabilities for each month

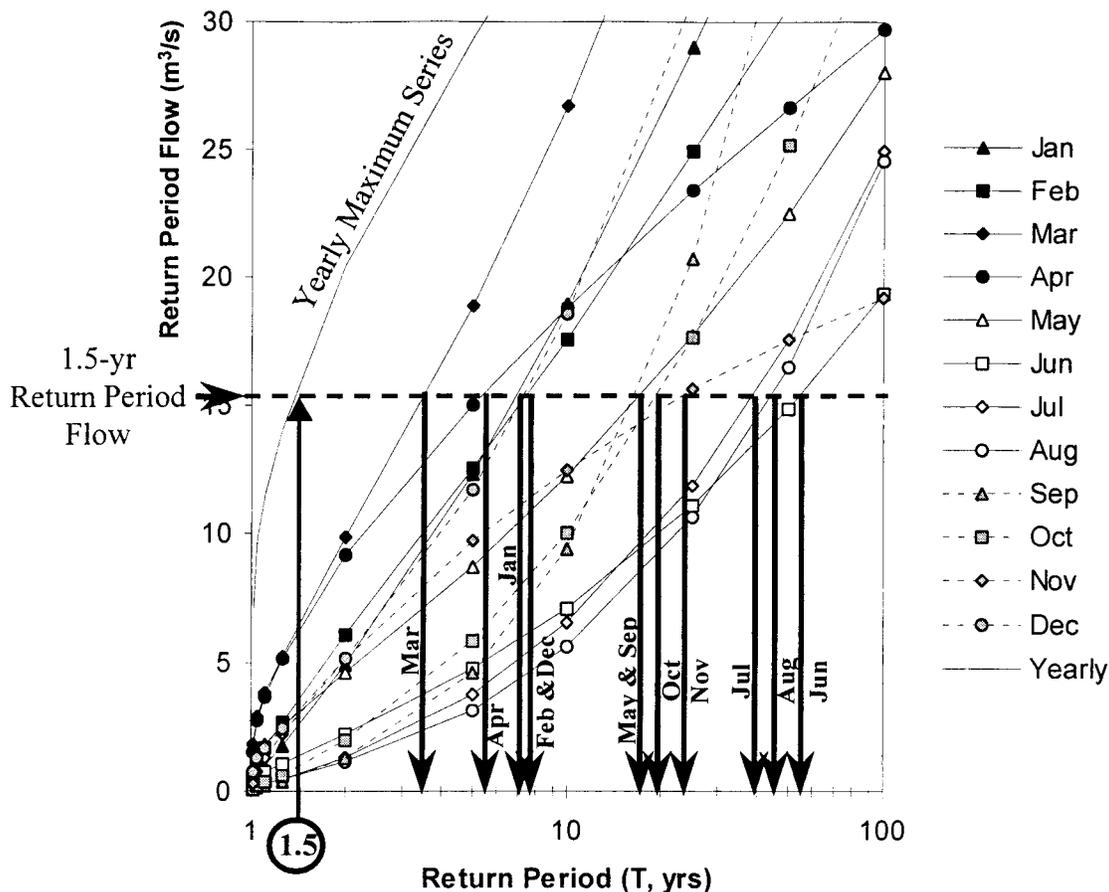


FIG. 5. Determination of Monthly Bank-Full Return Periods for Tremper Kill Assuming 1.5-Year Annual Flow Is Bank-Full Flow (Downward-Oriented Arrows Show Return Periods Corresponding to Intersection of Monthly Frequency Curves and Bank-Full Flow)

and for each station, using the partial duration and maximum series frequency curves, respectively. The relative trends are similar for both analyses and for all catchments (i.e., high probability of flooding in the spring and low probability in the summer). Fig. 8 shows the average bank-full probabilities of all of the stations (error bars ± 1 standard deviation) based on maximum and partial duration series. Bank-full probabilities based on the partial duration series are generally over 50% in March and similarly high in April (Figs. 6 and 7). As expected from the earlier discussion, the probabilities based on the maximum series frequency curves (Fig. 7) are lower for the same months.

DISCUSSION

Applicability of Results

The results of this study are applicable to a broad variety of floodplain activities, especially those potentially contributing to non-point-source pollution. Consider the dairy manure-spreading example discussed in the Introduction section. Because of the relatively high cost, there is understandable resistance on the part of Delaware Basin dairy farmers to construct manure storage facilities. This analysis clearly shows that there are relatively distinct periods of hydrological sensitivity (i.e., prone to flooding) and insensitivity. Fig. 8 suggests that incorporating manure storage into a manure-spreading strategy such that manure produced in April and May is stored and applied in June may reduce the risk of associated surface water contamination by 28–55%, depending on the type of analysis considered. Quantifying the risk reduction in this way allows planners to better assess the costs and benefits of management practices such as manure storage.

Because farm planners typically attach hydrological sensitivity to a parcel of land regardless of season, this analysis provides benefits for farmers as well as for reducing water quality risks. Namely, this approach may indicate that land traditionally classified as too sensitive for some agricultural activities may have seasonal flooding characteristics like those investigated in this paper that make the land insensitive (i.e., suitable for activities such as manure spreading) during some parts of the year (e.g., June and July).

Bank-Full Probability Interpretation

The statistical explanation for consistently higher partial duration series derived probabilities relative to the maximum series (Fig. 8) resides in the technical difference between results yielded by a maximum series and results produced by a partial duration series. Strictly speaking, a maximum series analysis for bank-full flow will result in a return period that represents the average number of years between when the monthly maximum flow will equal or exceed the bank-full condition. Thus, considering Fig. 8, March has an average bank-full probability of 28%, corresponding to a return period of approximately 3.6 years [(3)]. In contrast, the return period yielded by the partial duration series analysis represents the average amount of time, in years, between bank-full or greater conditions for a given month, irrespective of whether multiple flood flows occur in a single month.

The difference in the results between the maximum and partial duration series can be interpreted as the susceptibility of a given month to multiple flooding events. The percent difference between the two series results is a direct measurement of the likelihood that more than one flood will occur in a month, given that a flood has already occurred in that month.

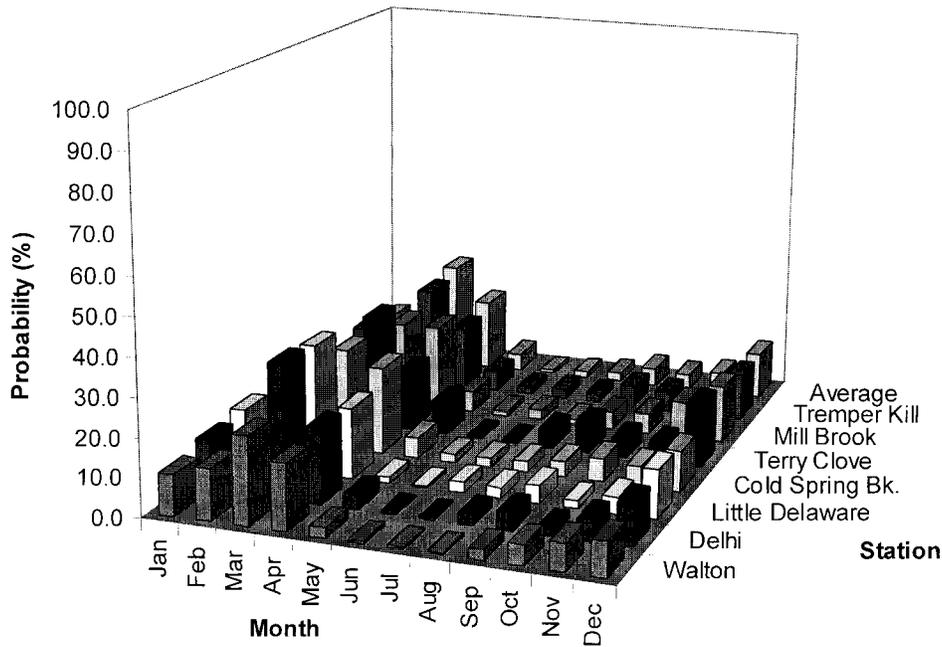


FIG. 6. Probability of Monthly Bank-Full Flow for All Gauging Stations Based on Partial Duration Series Analysis

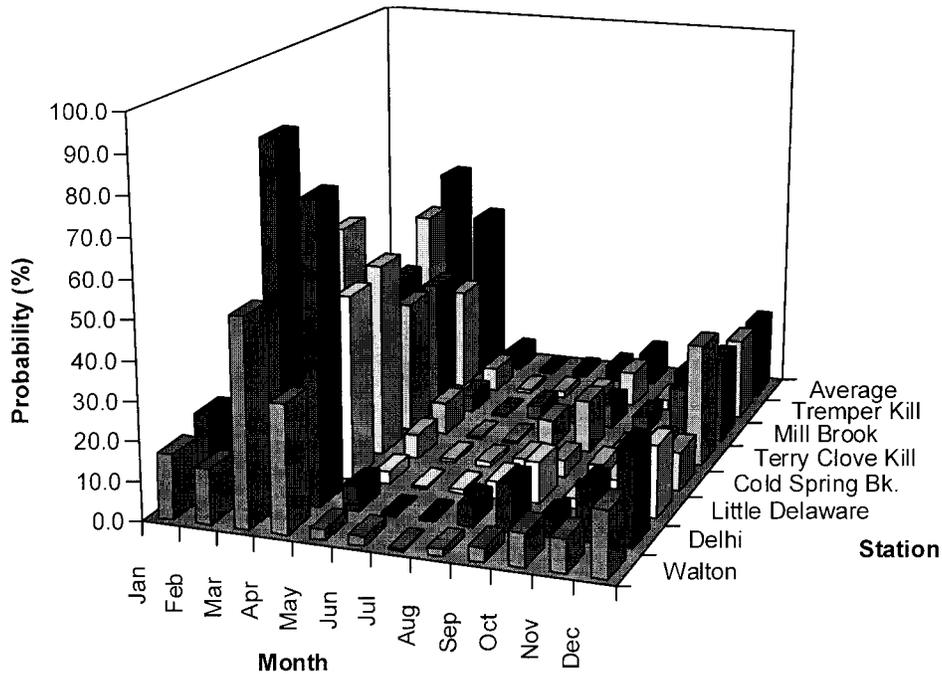


FIG. 7. Probability of Monthly Bank-Full Flow for All Gauging Stations Based on Maximum Series Analysis

The partial duration series represents the entire population of floods, and the maximum series represents only the single highest events in a given month. Thus the probability that encompasses all floods past the first in a month is the difference between the two probabilities given by the series and the probability that more than one flood will occur, given that one has already occurred is given by

$$P_{mul} = \frac{(P_{pd} - P_{max})}{P_{pd}} \cdot 100 \quad (4)$$

where P_{mul} = probability of multiple flood flows; P_{pd} = probability of bank-full flow based on the partial duration series; and P_{max} = probability of bank-full flow based on the maximum series. Fig. 9 shows the results of this based on the average values seen in Fig. 8. As expected, the very dry months

of June and July show a negligible chance of a second flood in a month when one has already occurred. This fact is important to planners, implying that floods will only be discrete, occurring for short periods of time during the summer months in this area and will not extend over days.

Statistical Significance and Limitations of Results

A simple check can be performed to determine the theoretical accuracy of the flood predictions based on the maximum series values. From the definition of the 1.5-year return period flow, the probability that flooding will occur at least once in a given year is approximately 67%. Given the probabilities that flooding will occur at least once in the individual months, the yearly probability can be back-calculated by

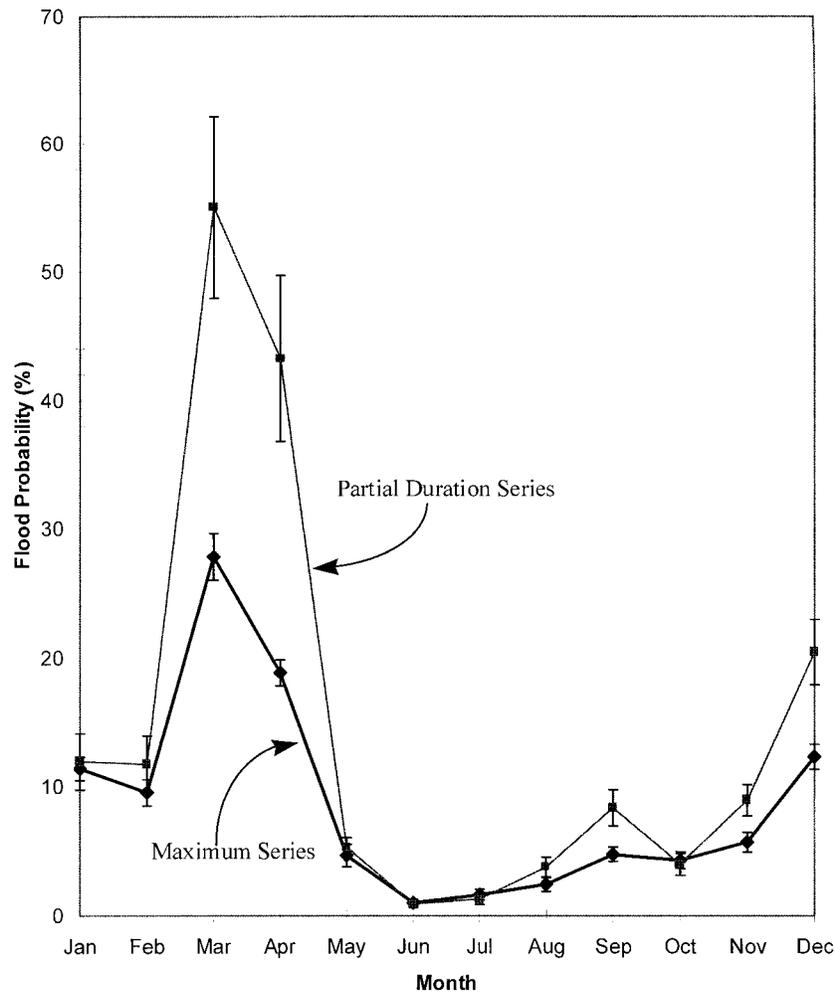


FIG. 8. Average Monthly Probabilities for All Delaware River Basin Catchments Used in This Study

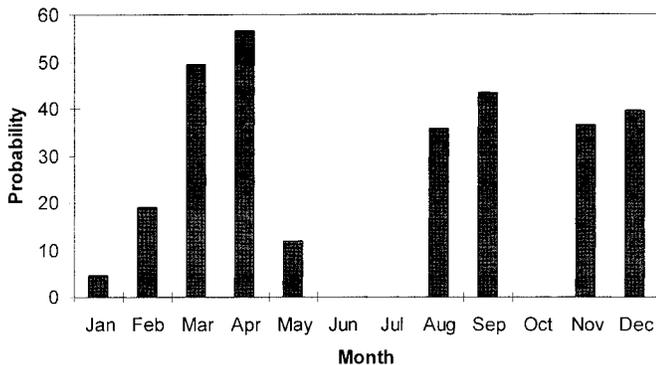


FIG. 9. Probability of Multiple Floods, Given That One Flood Occurs in Each Month Based on Average for All Seven Catchments

$$P_y = 1 - (1 - P_1)(1 - P_2) \cdots (1 - P_{12}) \quad (5)$$

where P_y = yearly probability (with a theoretical value of 0.67 on a decimal basis); and P_1, P_2, \dots, P_{12} represent the probabilities of the respective months based on the maximum series analysis. For the average probabilities found in Fig. 8, (5) yields a yearly probability of 0.68. Table 2 gives the results for the individual stations.

Obviously, statistical approaches to predict return period flows and thus to predict temporal variation in return period flows has limits. The curve-fitting procedure used with the LP3 analysis can result in statistical prediction anomalies (Fig. 4).

The following discussion is devoted to some limitations of the statistical approach put forward in this study.

The LP3-fitting procedure is particularly useful in that it allows ample shape flexibility by including the skew coefficient of the data, or the third moment of the distribution about the mean. An LP3 weakness is that the skew is dependent on the cubed deviation of sample values from the mean. Thus a small error in approximating the population mean can result in a large error in the skew coefficient estimate. This error will naturally decrease with increased sample size. Tasker and Steedinger (1986) derived a multiplicative, bias correction factor for the skew coefficient as follows:

$$Sk_2 = Sk_1 \left(\frac{n+6}{n} \right) \quad (6)$$

where Sk_2 = corrected skew coefficient; Sk_1 = original skew coefficient; and n = sample size. As n approaches infinity, Sk_2 approaches Sk_1 , as would be expected. To determine the effect of this correction factor, it was applied to the Walton, N.Y., station data for the month of March. Fig. 10 shows the predictions based on the original and corrected skew coefficients. As can be clearly seen in this graph, with a sample size of 44, the skew correction has little effect on the predicted return period flows. There is some divergence seen at the upper end. This upper end divergence should not affect the temporal variation in return period flows because it should apply relatively uniformly over the months. Also, because the core of this study focuses on bank-full flow, the divergence at high return periods is somewhat irrelevant.

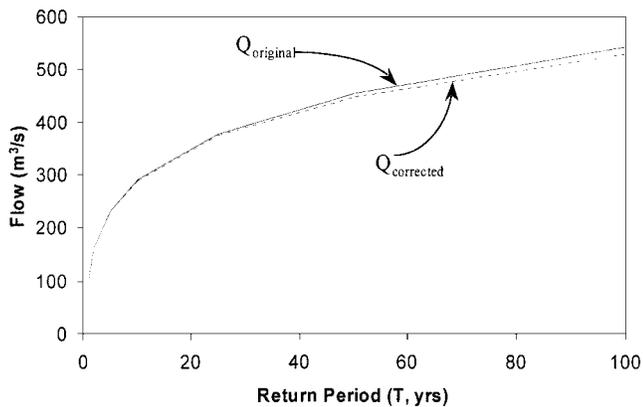


FIG. 10. Comparison of Predicted Flows with Corrected and Uncorrected Skew Coefficients for Walton, N.Y.

CONCLUSIONS

This study analyzed the temporal variation in return period flows and flood probabilities for seven stream gauging stations within the Delaware River Basin, the source of drinking water for New York City. These seven stations were chosen based on the range in their drainage area [3.86–860 km² (1.5–332.0 mi²)]. Historical data, taken from the USGS Surface Water Resources Web page for New York State, were disaggregated into monthly groupings. The LP3 analyses were performed on each month's partial duration and maximum series, resulting flow frequency curves. The results of these analyses show significantly larger flows for a given return period during March, April, and December, regardless of drainage area.

Using the 1.5-year return period flow as the bank-full flow probabilities that a bank-full condition would occur in a given month were determined based on monthly partial duration and maximum series. The maximum series analysis found that March had the highest probability of a flood in any given year (28.8%), followed by April and December with 18 and 12% probabilities, respectively. The relative risk of flooding among months was the same for the partial duration series as for the maximum series, although probabilities of flooding in a given month as determined by the partial duration series were sometimes much greater than those given by the maximum series. This discrepancy may be attributed to the probability of multiple floods occurring in a given month. These two analyses are perhaps best viewed as flood probability envelopes. Analysis showed that the theoretical yearly probability of flooding matches calculated values from individual months well, with a maximum deviation of only 5%.

This study concludes that agricultural management practices need to take into account the temporal or seasonal variation in flooding frequency regardless of return period. By allowing agricultural management to take into account extremely low flooding periods (typically May through August) larger portions of agricultural land will be suitable for sensitive use during large portions of the year.

APPENDIX. REFERENCES

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