Flood Analysis in DuPage County Using Hydrological Simulation Program—FORTRAN Model

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Most counties across the United States use design storm approaches with single-event rainfall–runoff models and steady-state hydraulic models for flood analysis and design. DuPage County, Illinois, has recently adopted a different approach. A continuous simulation model, the Hydrological Simulation Program—FORTRAN model, has been used to simulate 40 years of runoff for 35 land segments that represent the variations in land cover conditions and historical precipitation across the county. Engineers use the runoff as input to the full equations model, an unsteady flow model, to simulate county streams. Results from these simulations are used to estimate flood probabilities by a new statistical technique. DuPage County has taken this new approach to deal with the complicated flood design and analysis problems that exist in its large and urbanizing watersheds.

For most problems in flood analysis and design, stream flow data are not available at the site of interest. It is often necessary to evaluate conditions under past, future, or hypothetical conditions. As a result hydrologic and hydraulic models are frequently used to simulate flows and water levels on the basis of precipitation and other meteorological information. Usually, a single-event rainfall–runoff model is used to simulate runoff with a design storm as input. A steady-state hydraulic model is then used to convert simulated peak discharges into water levels.

Flood analysis techniques in DuPage County, Illinois, are unlike those typically used across the United States. The Hydrological Simulation—FORTRAN (HSPF) model, a continuous simulation hydrologic model, is used to simulate long continuous records of runoff for analysis and design work. The full equation (FEQ) model, an unsteady flow routing model, takes simulated runoff and produces river stage and flow estimates. PVSTATS, a statistical analysis program, uses results from FEQ model simulations to estimate flood probabilities by a new statistical technique.

This paper describes in detail the hydrologic and hydraulic methods used for flood analysis in DuPage County. The next section gives a background on urban development and existing flood problems in DuPage County. The subsequent sections describe the hydrologic and hydraulic simulation models used in the county. The new statistical methods used to estimate flood frequencies are described, and an application of the county methods for Ginger Creek are provided. The final section discusses the motivation and historical evolution of continuous simulation modeling in DuPage County.

BACKGROUND

DuPage County, in northeastern Illinois, is part of the expanding Chicago Metropolitan area. The county has three major watersheds: Salt Creek and the East Branch and the West Branch of the DuPage River (Figure 1). Salt Creek is an urbanized watershed. The East Branch of the DuPage River is now experiencing rapid urban development. The West Branch is largely undeveloped.

Today, Salt Creek has serious flooding problems. Early development during the 1950s and 1960s occurred without storm water detention or floodplain regulations. Rapid development in the 1970s and 1980s converted much of the remainder of the watershed to urban land uses (*1*). Now, many people live and work in flood-prone areas. Average annual flood damages on the main stem of Salt Creek exceed $1 million a year (*2*). To reduce damage from floods several major flood control projects are planned for Salt Creek.

In August 1987 a night of extreme rainfall (>9 in. at O'Hare Airport) caused record flooding on Salt Creek. This flood galvanized regional support for strong storm water management and flood control measures. The Illinois General Assembly soon passed legislation authorizing county governments to mitigate the effects of urban development through the use of countywide storm water management planning. By 1991 DuPage County had developed a storm water and floodplain ordinance. To prevent future problems within the county's urbanizing watersheds, the ordinance requires significant on-site detention storage for new development, compensation for lost depressional storage, and no increase in flood elevations and damages off-site. The ordinance also requires that new hydrologic and hydraulic methodologies be used for estimating floodplain limits. The following sections describe these methods.

HYDROLOGIC SIMULATIONS MODELS

The hydrologic model now used in DuPage County is the HSPF model (*3*). Earlier work used the LANDS module of the Hydrocomp Simulation Program (HSP) (*4*). The HSPF model is a public-domain model written by Hydrocomp, Inc., in the late 1970s for the Environmental Protection Agency. The LANDS model is a proprietary version developed by Hydrocomp in the mid-1970s.

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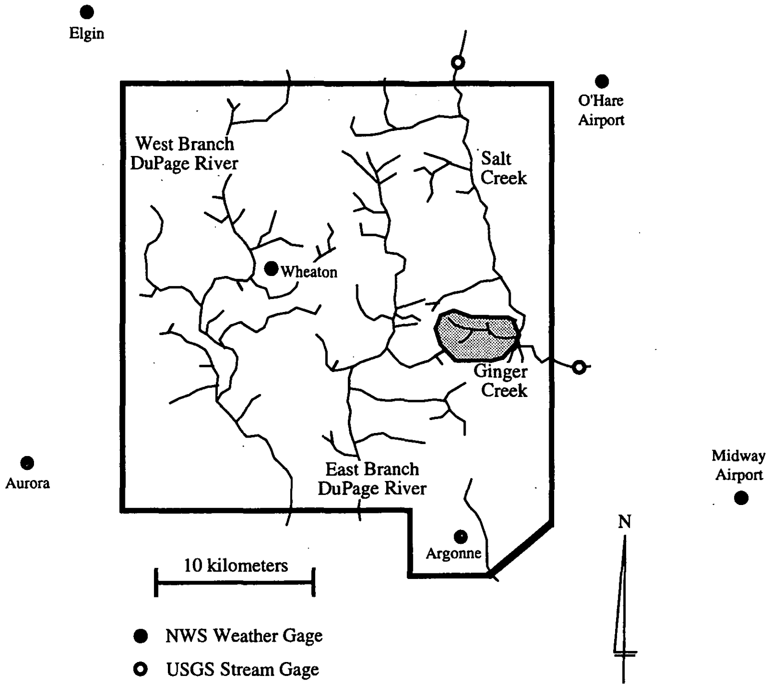

FIGURE 1 DuPage County, Illinois, showing three major streams and Ginger Creek watershed. Precipitation gauge used to simulate headwaters of Salt Creek (north of DuPage County) is not shown.

These models continuously simulate the land surface hydrology of a catchment, including infiltration, evapotranspiration, snow accumulation and melt, soil moisture storage, and surface, interflow, and groundwater discharge. Both models use the same methodology, which is based on the Stanford Watershed Model IV (*5*).

The hydrologic model takes historical meteorological records and produces a continuous time series of runoff for individual land segments. A land segment represents the unit area rainfall–runoff response for a single combination of land cover and meteorological input. Five different land cover categories have been established for DuPage County: impervious area, flat-slope grassland, moderate-slope grassland, steep-slope grassland, and forestland. A network of seven precipitation gauges with 40 years of record are used to represent the spatial and temporal variabilities of precipitation throughout the county (Figure 1). Thirty-five land segments are used to model runoff in the county, one for each precipitation gauge and land cover combination. Model parameters are the same for land segments with the same land cover category.

Model parameters for the five land cover categories were estimated on the basis of a regional hydrologic calibration of Salt Creek. Five of the network precipitation gauges were used for the regional calibration. The Wheaton precipitation gauge, located near the center of the county, also supplied data on air temperature. The O'Hare Airport precipitation gauge, located near the northeast corner of the county, supplied data on dew point temperature, wind speed, and cloud cover. From these records continuous time series of solar radiation and potential evapotranspiration were generated by using the UTILITY module of HSP.

The land segment parameters were estimated for a calibration period from 1978 to 1988. Although land use changes did occur during the calibration period, most of the Salt Creek watershed was urbanized by this time. The percentage of watershed area in each land cover category was found by using 1985 land use information. LANDS-simulated runoff was compared with stream flow measurements for gauges at Rolling Meadows [drainage area of 79 km^2 (30.5 mi^2)] and Western Springs [drainage area of 298 km^2 (115 mi^2)]. Comparisons were made on an annual, monthly, and individual storm event basis. Parameters for different land segments were adjusted until the best match between simulated and observed flows was obtained. Figures 2 through 5 show calibration results at both stream gauges. Naturally, there is a better match for annual flows than for single events. The mismatch between simulated and observed flows occurs because of deficiencies in the model and in the data (e.g., precipitation and stream flow). Note, however, that an exact match is not required to accurately reproduce the statistical characteristics of flows for flood analysis.

HYDRAULIC SIMULATION MODEL

The hydraulic model used in DuPage County is the FEQ unsteady flow routing model (*6*). The FEQ model is designed to take land segment runoff and simulate the flood wave moving through river reaches and hydraulic structures. As with steady-state hydraulic models such as HEC-2 (*7*), the FEQ model requires detailed information on river cross sections and hydraulic structures. However, the FEQ model uses a complete one-dimensional solution to the St. Venant equations. As a result the FEQ model can simulate the complicating backwater effects that commonly occur on the low-gradient streams in DuPage County.

Each stream requires unique FEQ model input to represent the stream's hydraulics. For Salt Creek hundreds of surveyed cross sections were needed. Three recent floods were used to calibrate the Salt Creek FEQ model. Runoff simulated by LANDS for these events was routed with the FEQ model. Because many tributary streams are ungauged, simulated peak water levels were compared

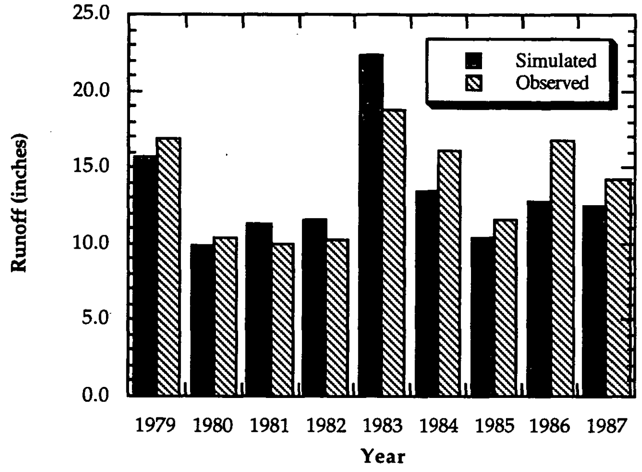

FIGURE 2 Simulated and observed annual runoff for Salt Creek at Rolling Meadows [30.5 mi² (79 km²)].

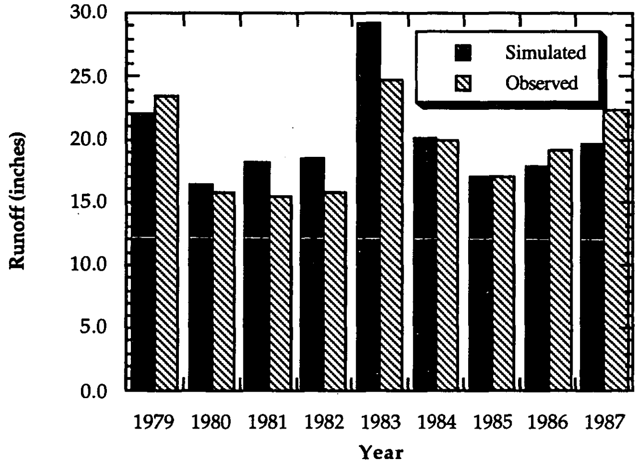

FIGURE 3 Simulated and observed annual runoff for Salt Creek at Western Springs [115 mi² (298 km²)].

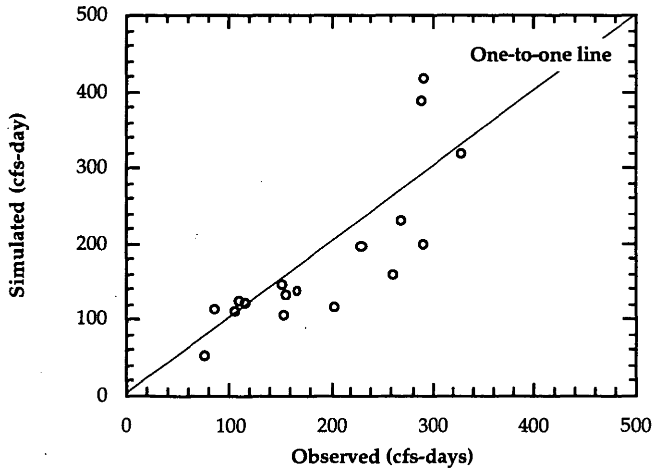

FIGURE 4 Simulated versus observed storm event runoff for Salt Creek at Rolling Meadows [30.5 mi² (79 km²)].

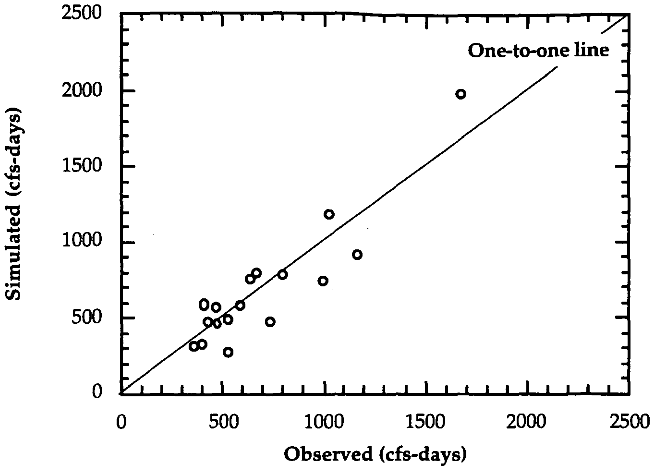

FIGURE 5 Simulated versus observed storm event runoff for Salt Creek at Western Springs [115 mi² (298 km²)].

with reported high water marks compiled by the DuPage County Stormwater Management Division. Because of its high magnitude, one flood (August 1987) weighed heavily in the hydraulic calibration. Where results from the simulation with the FEQ model were inconsistent with the high water information, the model of the creek was modified to improve the match between simulated and observed high water levels.

FLOOD FREQUENCY ANALYSIS METHODS

With continuous simulation modeling, the typical approach to flood frequency analysis is to treat simulated flows just like a stream gauge record (*8*). A probability distribution is chosen to model the frequency of floods, and the distribution is fitted to the simulated peak discharges by statistical methods. Yet for flood analysis on large urban watersheds, continuous simulation models are often used to simulate the effects of urban development, storm drainage systems, detention ponds, levees, and dams. These land-use and structural changes selectively alter flows. Flood distributions for such conditions are complicated. However, conventional techniques fit relatively simple distributions to the flood data. When conventional techniques are applied, the results can be misleading. The following is an example.

The HSPF model was used to simulate flows for conditions before and after urbanization in a small catchment [7.3 km² (2.8 mi²)] in the Salt Creek watershed (*9*). Flood probabilities were estimated by fitting a log-Pearson type III distribution to the simulated annual peak discharge series. Figure 6 shows the relationship between estimated flood quantiles before and after development. A disturbing feature of the curve is that the ratio of flood quantiles is less than 1 at longer return periods. This implies that urban development is decreasing the frequency of large floods. This contradicts what is known about urban development and flooding; it also contradicts what is shown by the simulated flood data. The ratios between peak discharges are never less than 1 for any simulated storm event. The extrapolation of estimated flood frequency curves is responsible for this inconsistent result (*10*).

Because of the problems encountered with conventional frequency analysis, a new statistical method called the peak-to-volume

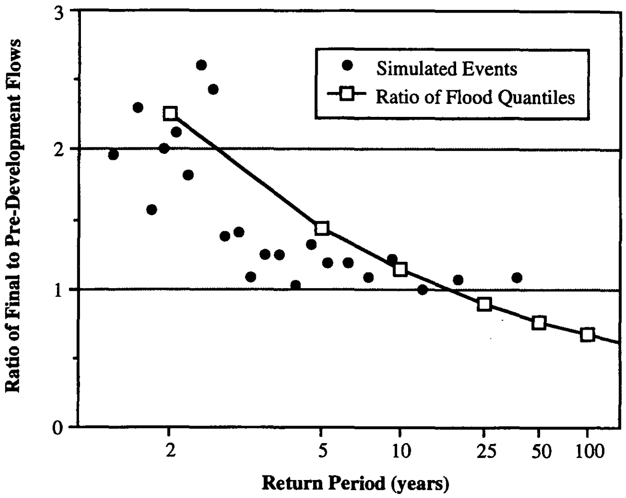

FIGURE 6 Ratio of peak discharges before and after urban development. Circles show ratios for individual events; curve with boxes shows ratio of flood quantiles estimated using log-Pearson Type III distribution.

approach was developed for use with model-simulated flows (*11*). DuPage County uses a computer program, PVSTATS, to do the peak-to-volume calculations. Another program automatically takes outputs from the FEQ model simulations of continuous simulation and extreme storm events and creates the input files needed by PVSTATS.

The idea behind the peak-to-volume approach is to estimate both the distribution of flood volume and the distribution of flood peaks conditioned on flood volume. At the site of interest, flood volumes are extracted from the continuous simulation for storms that produce a flood peak above a specified threshold u. A probability distribution $G_u(x)$ is then fitted to the flood volumes. This step exploits the fact that flood volumes often conform to commonly assumed probability distributions, even when the flood peaks are affected by flow regulation and other complications. PVSTATS allows users to choose between four theoretical probability distributions for $G_u(x)$.

The next step is to estimate the distribution of flood peak Y conditioned on flood volume X. First, a statistical model is developed for the relationship between flood peaks and flood volumes. The relationship is assumed to have the form of a nonlinear regression model:

$$\ln Y = W(\ln X) + \epsilon \quad (1)$$

The regression model errors ϵ are assumed to be independent and normally distributed with mean zero and constant variance σ_ϵ^2. The distribution of flood peak conditioned on flood volume is then a lognormal distribution truncated below the threshold u, or

$$F_{Y|X}(y|x) = \frac{\Phi[Z(y)] - \Phi[Z(u)]}{1 - \Phi[Z(u)]}, x \geq 0, y \geq u \quad (2)$$

where $\Phi(\ )$ is the cumulative distribution function for a standard normal random variable, and

$$Z(y) = \frac{\ln y - W(\ln x)}{\sigma_\epsilon} \quad (3)$$

The critical innovation in this step is the use of information from extreme storms that have occurred in a meteorologically homogeneous region containing the watershed. These storms are used to simulate large floods, and the results are used to define the upper tail of the relationship between flood peak and volumes.

Finally, the probability distribution of flood peaks is found by combining the estimated distribution of flood volume with the estimated distribution of flood peak conditioned on flood volume. The distribution of flood peaks is given by

$$F_u(y_p) = \exp\{-\Lambda[1 - H_u(y_p)]\} \quad (4)$$

where Λ is the mean number of floods annually, and $H_u(y_p)$ is the conditional distribution of flood peaks. A flood is defined as an event in which the flood peak exceeds a fixed threshold, u. $H_u(y_p)$ is defined as

$$H_u(y_p) = \int_0^\infty F_{Y|X}(y_p|x)\, g_u(x)\, dx \quad (5)$$

where $g_u(x)$ is the flood volume density function corresponding to the distribution $G_u(x)$.

In essence, the peak-to-volume approach combines appealing aspects of both continuous simulation and design storm approaches. Continuous simulation allows engineers to see the effects of land-use changes and flood mitigation measures for a variety of realistic storms. However, the peak-to-volume approach avoids problems in flood estimates that arise when conventional frequency analysis is applied. As with design storm approaches, large floods are simulated using extreme rainfall. However, the peak-to-volume approach uses actual storm events and incorporates the simulation results within a sound probabilistic framework.

Another clear advantage of the approach is that for floodplain mapping the statistical analysis can be carried out directly on peak flood stages (instead of peak discharges). This is especially important when there are backwater and floodplain storage effects that produce a nonunique relationship between peak stage and discharge. In a case study comparing the peak-to-volume approach with the design storm approach and conventional frequency analysis, the peak-to-volume approach produced the most credible estimates for floodplain mapping (*12*).

GINGER CREEK EXAMPLE

The Ginger Creek floodplain mapping study was the first application of the new DuPage County flood analysis techniques. Ginger Creek is a tributary to Salt Creek (Figure 1) and has a drainage area of 15.0 km^2 (5.8 mi^2). The watershed contains low-density residential housing, two golf courses, a major Interstate highway, and some undeveloped wetlands. Two lakes on the main stem and several culvert and bridge crossings regulate flows during floods. To develop the FEQ model input for Ginger Creek, survey crews measured 77 cross sections and all significant hydraulic structures. Comparisons between simulated and observed water levels were made for a single flood (August 1987) to calibrate the model.

In practice, land-use conditions are easier to determine than land cover. As a result, DuPage County has developed regional conversions between land use and land cover for hydrologic modeling. Table 1 shows the distribution of impervious land, grassland, and

TABLE 1 Land-Use to Land Cover Conversions

Land-Use Categories	Land Cover Categories Impervious (%)	 Grassland (%)	 Forest (%)
Hydraulically-connected Residential:			
1/4 acre lots	28	67	5
1/3 acre lots	20	75	5
1/2 acre lots	15	80	5
1 acre or greater	10	85	5
Non-hydraulically-connected Residential:			
1/4 acre lots	6	89	5
1/3 acre lots	4	91	5
1/2 acre lots	3	92	5
1 acre or greater	2	93	5
Multi-family residential	50	40	10
Commercial/Industrial	85	15	0
Major road corridors	50	50	0
Other roads	100	0	0
On-line surface water	100	0	0
Office/Research	80	15	5
Open space	determined case-by-case		

forestland for a variety of land-use categories. Local slopes are used to distinguish between the three grassland types. For Ginger Creek, areas were assigned to each land segment on the basis of future land-use conditions. Land segment unit area runoff is then multiplied by the land segment area to produce catchment runoff for future conditions.

From the 40-year simulation record, 58 significant runoff events were found. Simulated runoff for these 58 events was routed through the Ginger Creek stream network by using the FEQ model. For the statistical analysis the top 40 flood peaks were determined at each cross section. A log-Pearson Type III distribution was then fitted to the 3-day flow volumes for these events. Note that 3-day flow volume can be used as a surrogate for flood volume with this approach (*11*). Figure 7 shows the estimated volume distribution for an example cross section.

Extreme storms that occurred in Illinois or bordering states were used in the extreme storm simulations. Each storm was simulated three times by using the dry, average, and wet initial moisture conditions determined for the month when the extreme storm occurred. Peak stage and 3-day flow volume results for the extreme storm simulations were combined with a sample from the continuous simulation. A nonparametric regression technique called LOWESS (*13*) was used to find the relationship between peak stage and 3-day flow volume. Figure 8 shows the fitted curve at the example cross section. Finally, the peak-to-volume curve was numerically integrated with the estimated volume distribution to estimate the peak stage distribution. Figure 9 shows the estimated 100- and 500-year return period water surface profiles for the lower stem of Ginger Creek.

HISTORY AND MOTIVATION FOR CONTINUOUS SIMULATION MODELING

Continuous simulation modeling has a long history in the Chicago metropolitan area. The first application of continuous simulation

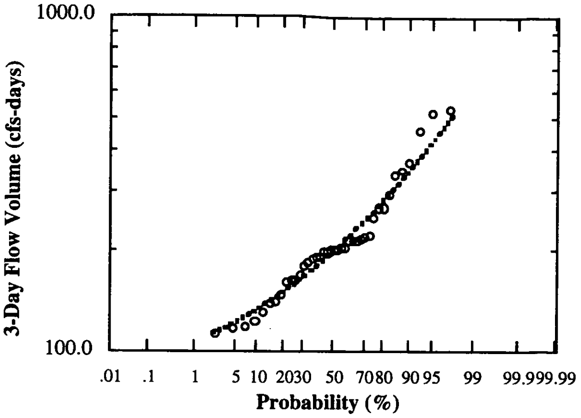

FIGURE 7 Three-day flow volume distribution for Ginger Creek cross section. Log-Pearson Type III distribution was fitted to sample by method of moments.

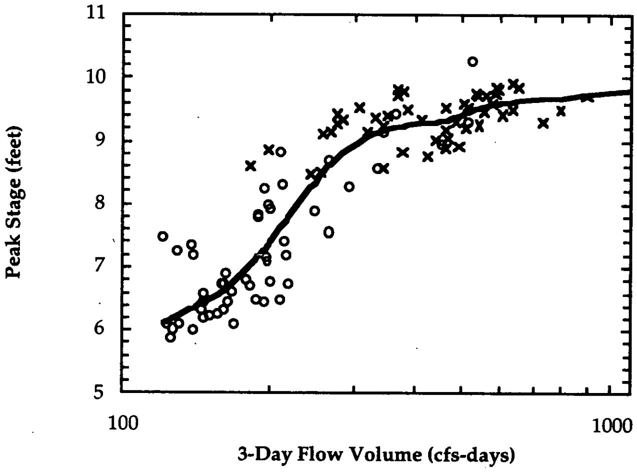

FIGURE 8 Peak stage and 3-day flow volume for Ginger Creek cross section. Circles show results from 40-year continuous simulation; crosses show results from simulations with extreme storms; solid curve shows regression made using LOWESS. Notice leveling off of peak stages for large floods due to floodplain effects.

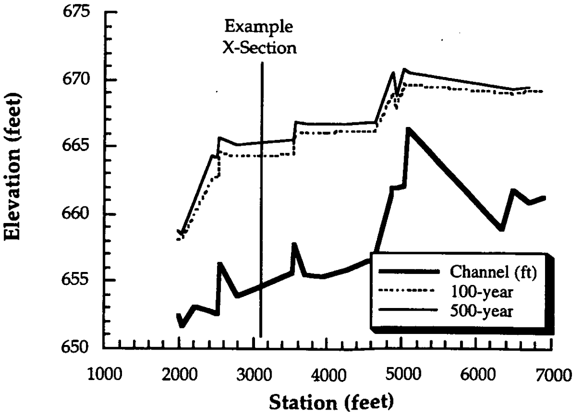

FIGURE 9 Estimated 100- and 500-year return period water levels for lower stem of Ginger Creek.

was in the late 1960s, with a study of the West Branch Chicago River. The 208 water quality studies of the late 1970s applied continuous simulation to many watersheds in northeastern Illinois (*14*). DuPage County's involvement with continuous simulation began in the 1980s with a study of Winfield Creek, a tributary to the East Branch of the DuPage River.

A study of Salt Creek in the late 1980s showed the utility of continuous simulation modeling for flood design in DuPage County. The study included analysis of the effects of modified outlet structures on Busse Woods, major flood control reservoir (*2*). Many were concerned that changing the outlet would increase the duration that sensitive woodlands in a bordering wilderness preserve would be inundated. Continuous simulation allowed engineers to estimate and compare flood inundation durations for many outlet designs.

Other major flood control projects now planned for Salt Creek also involve complicated hydraulic structures and operating schemes. A new flood control reservoir is being built; an abandoned quarry is being converted for flood storage along the main stem; a floodgate is being constructed to prevent Salt Creek backwater from flooding a tributary stream. The temporal and spatial patterns of rainfall, as well as the sequence of storm events, can significantly affect the operation of these flood control structures. Floodplain storage and backwater effects are also important on the low-gradient streams in the county. These complicated watershed conditions motivated DuPage County to choose a continuous simulation approach to provide the critical information needed for flood design (*1*). Recently adopted ordinances now require this approach for flood analysis and floodplain mapping on all major streams in the county.

CONCLUSION

DuPage County has turned to a continuous simulation modeling approach to handle the complicated flood analysis problems encountered in its large urban watersheds. The DuPage County method uses the HSPF model, a continuous simulation hydrologic model that has been calibrated to local conditions by using available stream gauge records. Land segments were created to represent the rainfall–runoff response for the five dominant land cover categories found in the county. Forty years of runoff have been generated for each land segment. Engineers simulate individual streams in the county using the FEQ model, an unsteady flow routing model. Based on an analysis of land-use conditions for the stream, the FEQ model multiplies land segment runoff by the appropriate segment area and simulates flows and water levels for the stream. PVSTATS takes FEQ model simulation results and estimates flood probabilities by the peak-to-volume approach.

In most counties across the United States, the design storm method is the standard approach for flood analysis. The design storm method is popular because it is easy to apply and has been widely accepted for flood analysis. Clearly, one of the greatest obstacles to implementing DuPage County's method has been the natural reluctance of some to accept new approaches. In the past continuous simulation approaches have been criticized for technical, financial, and administrative reasons (*15*). Yet the authors believe that many of the old criticisms of continuous simulation do not apply here.

By using DuPage County methods, the land-use data required to estimate land segment areas are the same as those required for other hydrologic methods. The cross-sectional input data required for the FEQ model are also the same as those required for steady-state hydraulic models. Instead of running a single design storm event, engineers now run the FEQ model with data files containing the runoff for the continuous simulation and extreme storm events. Computer programs take simulation results and prepare inputs for the peak-to-volume flood frequency analysis. Unsteady flow modeling does require more time and technical expertise. Still, the huge financial expenditures needed to mitigate the severe flooding problems in DuPage County warrant the additional time required to do a more detailed flood analysis.

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REFERENCES

1. Sikora, J. H., and J. H. Steffen. The Use of Continuous Simulation and Unsteady Flow Modelling in DuPage County, Illinois, In *Urban Hydrology* (M. E. Jennings, ed.), American Water Resources Association, 1991.
2. *Busse Woods Reservoir—The Benefits and Costs of Additional Flood Control.* Division of Water Resources, Illinois Department of Transportation, 1989.
3. Johanson, R. C., J. C. Imhoff, J. L. Kittle, Jr., and A. S. Donigian, Jr. *Hydrological Simulation Program—FORTRAN (HSPF): Users Manual for Release 8.0.* Report EPA-600/3-84-066. Environmental Protection Agency, 1984.
4. *Hydrocomp Simulation Programming: Operations Manual.* Hydrocomp, Palo Alto, Calif., 1976.
5. Crawford, N. H., and R. K. Linsley, Jr. *Digital Simulation in Hydrology: Stanford Watershed Model IV.* Technical Report 39. Department of Civil Engineering, Stanford University, Calif., 1966.
6. Franz, D. D. *Unsteady Flow Solutions, Input Description for FEQ: Version 6.1.* Linsley, Kraeger Associates, Ltd., Mountain View, Calif., 1990.
7. *HEC-2 Water Surface Profiles, User's Manual.* Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif., 1982.
8. Thomas, W. O., Jr. Comparison of Flood-Frequency Estimates Based on Observed and Model Generated Peak Flows. *Proc., International Symposium on Flood Frequency and Risk Analysis*, Louisiana State University, Baton Rouge, 1986.
9. Dreher, D. W., G. C. Schaefer, and D. Hey. *Evaluation of Stormwater Detention Effectiveness in Northeastern Illinois.* Northeastern Illinois Planning Commission, Chicago, 1989.
10. Bradley, A. A., and K. W. Potter. Flood Frequency Analysis for Evaluating Watershed Conditions with Rainfall–Runoff Models. *Water Resources Bulletin*, Vol. 27, No. 1, 1991, pp. 83–91.
11. Bradley, A. A., and K. W. Potter. Flood Frequency Analysis of Simulated Flows. *Water Resources Research*, Vol. 28, No. 9, 1992, pp. 2375–2385.
12. Bradley, A. A., P. J. Cooper, K. W. Potter, and T. Price. Floodplain Mapping Using Continuous Hydrologic and Hydraulic Simulation Models. *Water Resources Bulletin*, submitted for publication.
13. Cleveland, W. S. Robust Locally Weighted Regression and Smoothing Scatterplots. *Journal of the American Statistical Association*, Vol. 74, 1979, pp. 829–836.
14. *Areawide Water Quality Management Plan.* Northeastern Illinois Planning Commission, Chicago, 1979.
15. Franz, D. D. Hydrologic Design: Extending Traditional Methods. In *Hydraulic Engineering '93* (H. W. Shen, S. T. Su, and F. Wen, eds.), ASCE, 1993.

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