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12

Flood Routing Through a Flat, Complex Flood Plain Using a One-Dimensional Unsteady Flow Computer Program

by

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FLOOD ROUTING THROUGH A FLAT, COMPLEX FLOODPLAIN USING A ONE-DIMENSIONAL UNSTEADY FLOW COMPUTER PROGRAM[1]

John C. Peters[2]

ABSTRACT: The routing of flood waves through the Central Basin of the Passaic River in New Jersey is complex because of flat gradients and flow reversals. The one-dimensional unsteady flow program DWOPER, developed by the National Weather Service, was used to simulate flood wave movement through the Basin. A historical event was used for calibration and two synthetic events were simulated. Boundary conditions consisted of discharge hydrographs at inflow points to the study area, local flow hydrographs at interior points, and a stage discharge relation for flow over the crest of a diversion dam at the basin outlet. Manning's n values were adjusted based on stage and discharge data for the historical event; however, verification data were not available for events comparable in magnitude to the synthetic events. Aspects of the investigation reported include techniques for characterizing the flow system, model calibration, techniques for representing a tunnel diversion, and simulation results.
(KEY TERMS: unsteady flow; flood routing; Passaic River.)

INTRODUCTION

This paper describes application of a one-dimensional unsteady flow program to analyze flood wave movement through the Central Basin of the Passaic River in New Jersey. The Central Basin is characterized by flat, wide floodplains. Flow reversals occur at tributary junctions. Because of the complex flow characteristics, the traditional application of hydrologic routing procedures, such as the Modified Puls method, in conjunction with steady flow water surface profile computation, was subject to question. The unsteady flow analysis described in this paper was made in conjunction with traditional approaches and provided a basis for improved representation of flood wave movement. The computer program used is the Dynamic Wave Operational Model (DWOPER) developed by the National Weather Service (Fread, 1978). A historical flood event was used for calibration, and two synthetic events were simulated. Aspects of the investigation reported herein include techniques for characterizing the flow system, model calibration, techniques for representing a tunnel diversion, and simulation results.

BACKGROUND

The unsteady flow analysis described in this paper was made in connection with a congressionally authorized investigation of structural and nonstructural flood control measures for the Passaic River Basin being performed by the New York District, Corps of Engineers. The Central Basin contains substantial natural flood storage capacity. The unsteady flow analysis was made to ascertain the nature of flood wave movement through the Central Basin and to provide a basis for modification of hydrologic routing criteria being used in another model for basinwide estimation of the impacts of predicted land-use or project induced changes on flood damage potential.

STUDY AREA

The Passaic Central Basin is a flat, oval shaped area about 10 miles wide and 20 miles long that contains an intermediate reach of the Passaic River. Figure 1 is a perspective representation of the topography of the Basin and surrounding areas. Approximate locations of the Central Basin boundary and major streams are shown. The Passaic River enters the Basin from the south and meanders generally to the north and east until it passes out of the Basin at Beatties Dam.

Streams entering the Basin include the Passaic River above Chatham Township and the Whippany, Rockaway, and Pompton Rivers. The drainage area of each at the point of entry to the study area is 29 square miles for the Whippany, 128 square miles for the Rockaway, and 355 square miles for the Pompton. The drainage area of the Passaic is 100 square miles at the point of entry and 762 square miles at Beatties Dam. Pompton River inflows therefore constitute runoff from approximately 50 percent of the total drainage area at Beatties Dam. Stream slopes through much of the Basin are of the order of 1.5 feet/mile.

The confluence of the Pompton and Passaic Rivers occurs at a location called Two Bridges (Figure 1). During large flood

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Figure 1. Perspective Representation of Passaic River Central Basin.

events, peak discharge on the Pompton at Two Bridges tends to occur at least 12 hours prior to the arrival of the crest of the flood wave coming from the remainder of the drainage area. This is due to the relatively rapid runoff response characteristics of the Pompton watershed. The reach of the Passaic River between Two Bridges and Beatties Dam restricts outflow from the Central Basin. When a flood wave passing through the Pompton reaches Two Bridges, some of the flow moves upstream on the Passaic and ponds until a sufficient depth of water is developed for the flow to reverse direction and discharge from the Basin. Flow reversals occur to a lesser extent at the Whippany-Rockaway and Rockaway-Passaic junctions.

CAPABILITIES OF DWOPER

Computer program DWOPER was developed by the Hydrologic Research Laboratory of the National Weather Service (Fread, 1978). It is based on the one-dimensional St. Venant equations for gradually varied unsteady flow. A weighted four-point implicit scheme is used to establish a set of nonlinear finite difference equations, and these are solved with a Newton-Raphson iteration method. Irregular cross-sections located at unequal distances on a single stream or on a dendritic river system can be accommodated. Discharge and stage continuity at confluences is achieved using an iterative method. Manning's n values can vary with location and stage or discharge. A variety of boundary conditions, including temporally varying lateral inflows, can be specified. Other program capabilities, including an option for calibration of Manning's n values, are described by Fread (1978).

FLOW SYSTEM REPRESENTATION

Figure 2 shows the river system configuration used for the Central Basin analysis. The "main river" consists of the Rockaway River to its confluence with the Passaic, and the Passaic from that point to the Beatties Dam. The tributaries are the

Whippany, Upper Passaic, and Pompton Rivers. By configuring the river system in this fashion, all tributaries are first order; there is no tributary to a tributary. DWOPER cannot handle second and higher order tributaries.

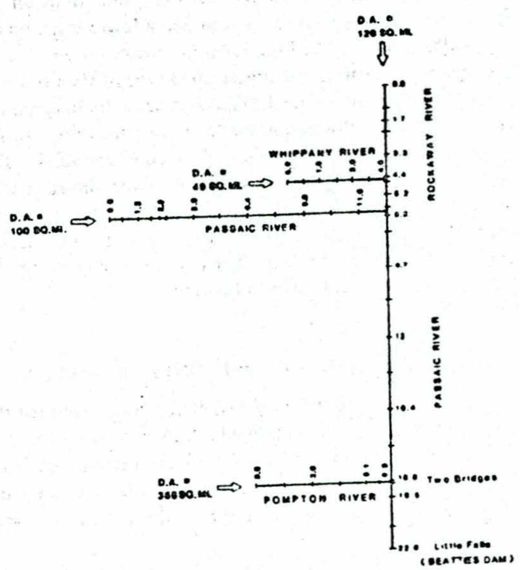


Figure 2. Schematic Map of River System.

A cross section spacing of approximately one cross section per mile was considered adequate to represent river geometry and to provide reasonable spacing for the "computation net" used in solving the St. Venant equations. The numbers of cross sections used are 22 on the main river, 7 on the Whippany, 14 on the Upper Passaic, and 7 on the Pompton, as shown in Figure 2. The cross section geometry was based on topographic maps having a scale of 1 inch = 200 feet and a 2-foot contour interval, and cross section data available in the format for computer program HEC-2 (Hydrologic Engineering Center, 1981a).

Cross sections are specified in terms of elevation and width. Two sets of widths may be specified for a cross section one set for active flow and a second set for off-channel storage. Roughness was defined in terms of composite n value as a function of elevation. In the Central Basin analysis, off-channel storage was not used; that is, entire cross sections were considered to be active. The limited conveyance of the floodplain was reflected by appropriately large composite n values.

Most of the available cross section and roughness data were in a format for the HEC-2 program – that is, cross sections in terms of X-Y coordinates and n values which vary horizontally across a cross section. The computer program Geometric Elements from Cross Section Coordinates (Hydrologic Engineering Center, 1976) was used to develop cross section widths and composite n values for use in DWOPER. The composite n values were developed in such a way as to preserve the elevation conveyance characteristics of the original (HEC-2) cross sections.

BOUNDARY CONDITIONS

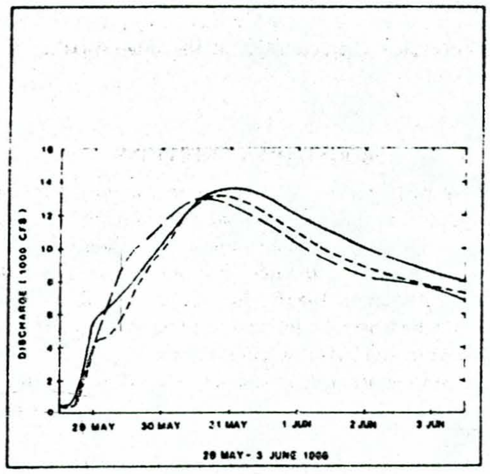
Inflow hydrographs were developed for the points of entry to the study area based on gaged streamflow data for the historical event and based on simulation of precipitation runoff processes with computer program HEC-1 (Hydrologic Engineering Center, 1981b) for the two synthetic events. Local flow hydrographs for 25 locations in the interior of the Central Basin were also developed using HEC-1 for all three events. An elevation discharge rating curve for the overflow crest of Beatties Dam was used as a downstream boundary condition.

CALIBRATION

The basis for calibrating the DWOPER model was reproduction of a flood that occurred in May-June 1968. Although it is generally advisable to use several events for calibration/verification, availability of data and study resources precluded the analysis of additional events. Peak discharges associated with the 1968 event have a recurrence interval of the order of 10 years. Available data include a discharge hydrograph at Beatties Dam and high water marks for ten locations in the Basin. Parameters that were adjusted in the calibration process are the composite n values.

Figure 3 shows hydrographs at Beatties Dam for the pre-calibration and post-calibration runs, as well as the observed hydrograph. Fifteen runs were made for calibration purposes. As may be seen in Figure 3, the precalibration run produced a hydrograph that peaks 12 hours too early. It was found that the magnitude and timing of computed runoff at Beatties Dam was strongly influenced by the contribution from the Pompton River, and that a significant improvement could be achieved by increasing overbank n values for the Pompton, perhaps to reflect the real but not explicitly modeled delay that occurs as flow moves laterally to fill and empty the wide floodplain that extends to the right side of the River. The post-calibration run reflects an approximate doubling of overbank n values for the Pompton River and a 10 percent increase of all other n values over those used in the precalibration run.

As may be noted from Figure 3, the simulated hydrograph reflects less runoff volume than the observed hydrograph. Because most of the inflow to the Central Basin is based on gage measurements, the missing volume is probably due to underestimation of local runoff within the Basin, which was calculated by precipitation runoff simulation using HEC-1. The computed peak discharge at Beatties Dam for the post-calibration run is 13,100 cfs, which is about 3 percent less than the observed peak of 13,500 cfs. The computed peak occurs five hours prior to the observed peak. Computed peak stages were generally within ± 1 foot of measured high water marks.



LEGEND:

- ———————— OBSERVED
- .... RUN 15 (DWOPER)
- — — — — RUN 1 (DWOPER)

Figure 3. May-June 1968 Flood Discharge Hydrographs, Passaic River at Beatties Dam.

SIMULATION RESULTS

In addition to the May-June 1968 event, two synthetic events were simulated. Computer program HEC-1 was used to generate inflow and local flow hydrographs for the events. One event is an "intermediate" flood generated with a 100-year storm applied to the entire drainage area above Beatties Dam. The event is referred to as an intermediate event rather than a 100-year event because runoff parameters such as loss rates were not adjusted to ensure that computed peak discharge at Beatties Dam corresponds to the 0.01 exceedance probability peak discharge indicated by a statistically derived frequency curve. Also, the recurrence intervals for computed peak discharges at upstream locations, with smaller drainage areas, can be expected to be less than the recurrence interval for the computed peak discharge at Beatties Dam because the equivalent of only one storm centering was used.

The second synthetic event was a Standard Project Flood (SPF) generated by applying a Standard Project Storm to the drainage area above Beatties Dam. A Standard Project event is intended to represent the largest event that is reasonably characteristic of the region in which it occurs and is used as a design standard for situations where protection of human life and high valued property is involved.

The simulation results for the historical and two synthetic events were ultimately used for comparison with results for the same events obtained with hydrologic (coefficient) routing criteria, to enable adjustment of the criteria. Therefore it was not necessary to associate specific recurrence intervals with the synthetic events.

The relationship between stage and discharge for a flood event is an indicator of the "unsteadiness" of the flow. If flow were steady, the relationship would be single valued and monotonically increasing. For unsteady flow, the relationship is looped as illustrated in Figure 4. The energy gradient for a given discharge is greater on the "rising" side than on the "falling" side of a flood wave, resulting in a lower stage on the "rising" side. A flat falling limb reflects slow drainage.

In order to determine the upstream extent of the effects of Pompton River runoff on peak stage and peak discharge, a run of the intermediate flood was made in which inflows to the Pompton were set to an arbitrarily low constant value. Figure 5 shows computed peak stage profiles for the runs with and without the intermediate flood inflows to the Pompton. Computed peak stage 14 miles upstream from Two Bridges is affected by as much as 0.5 feet. The corresponding computed peak discharge profile is shown in Figure 6.

CHARACTERIZATION OF A TUNNEL DIVERSION

One of the flood control measures being considered for the Central Basin is a tunnel that would transport excess runoff out of the Central Basin. It was desired, for preliminary planning purposes, to estimate the Basin wide impacts of a tunnel on peak stage and discharge, assuming unlimited tunnel capacity.

The location for one of the tunnels considered is shown in Figure 7. The DWOPER program does not contain an option specifically for simulating a tunnel diversion. However, the "weir flow bifurcation" capability of the program provides a means for simulating lateral outflow over a weir between two cross sections.

To employ this option, the user must specify the cross sections defining the two ends of the weir, as well as the crest elevation and discharge coefficient for the weir. The length of the weir is equal to the distance between the two cross sections. Hence the distance between cross sections can be chosen to define a length of weir that would serve as a control for the tunnel. The average of the water surface elevations at the two cross sections is used to determine the head over the weir crest at any point in time.

In addition, it is necessary to specify a location on a tributary where the diverted flow reenters the flow system. The computed water surface elevation for the reentry reach of the tributary is monitored to determine if a program defined submergence correction is to be applied to the calculated weir flow. In order to simulate the required reentry condition, a dummy tributary with four cross sections was created. The dummy tributary junction is just upstream from Beatties Dam, as illustrated in Figure 7. Flows diverted over the weir at a desired tunnel location reenter the flow system between the two upstream cross sections on the dummy tributary. However, extremely wide off-channel storage widths were specified for these cross sections so that diverted water enters and remains in storage and does not flow out of the dummy tributary. The elevation at which the artificial storage occurs is

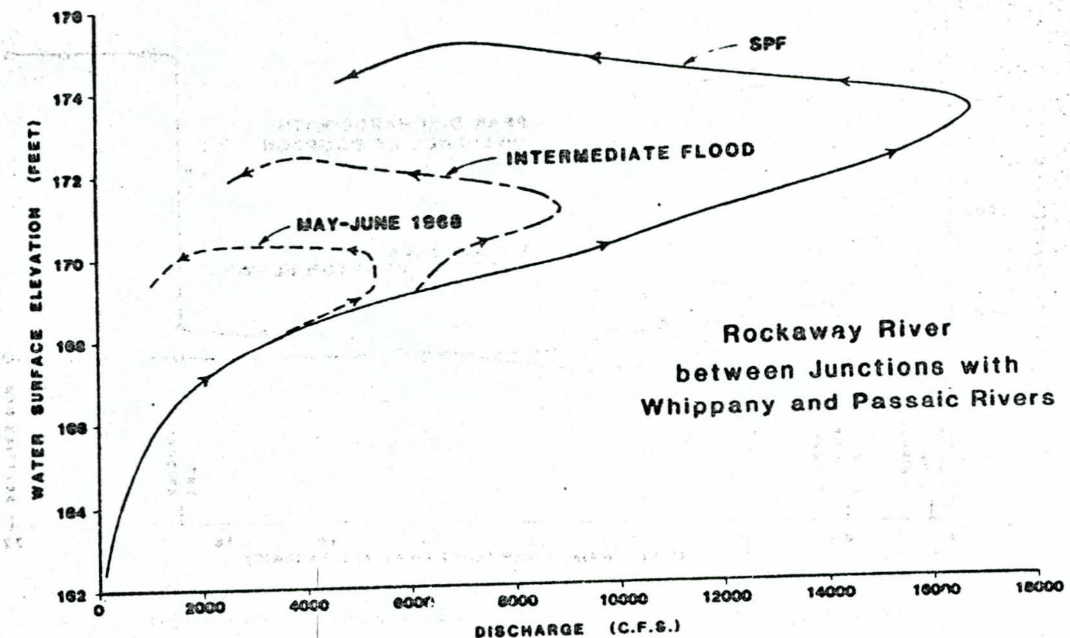


Figure 4. Elevation-Discharge Rating Curves ("Main" River at Mile 5.2).

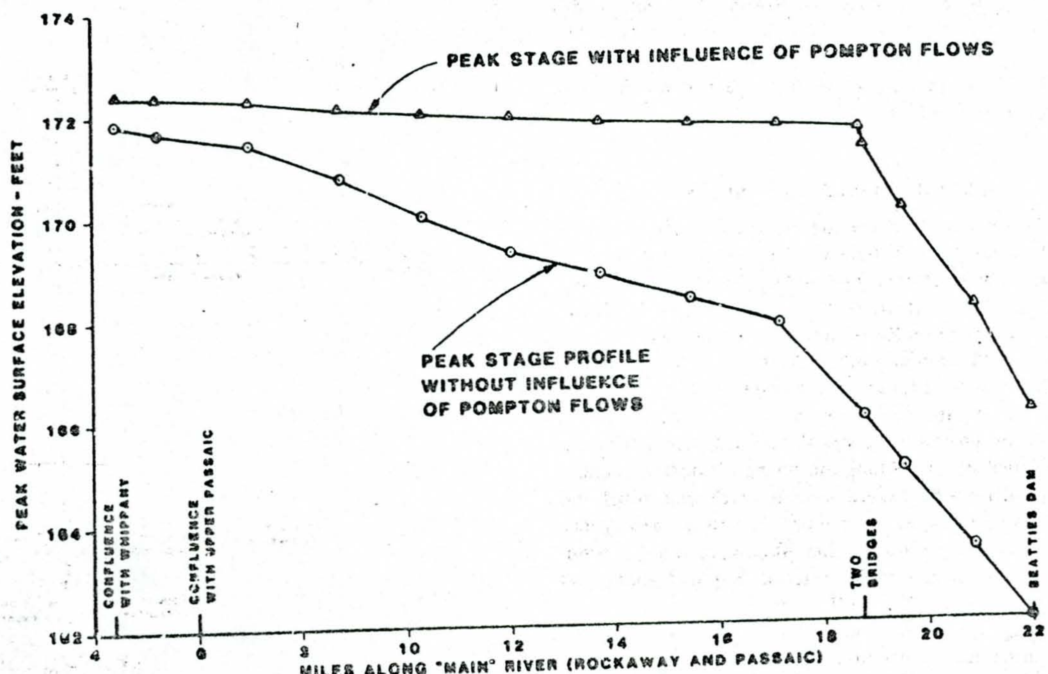


Figure 5. Intermediate Flood – Peak Stage Profiles Illustrating Influence of Pompton River.

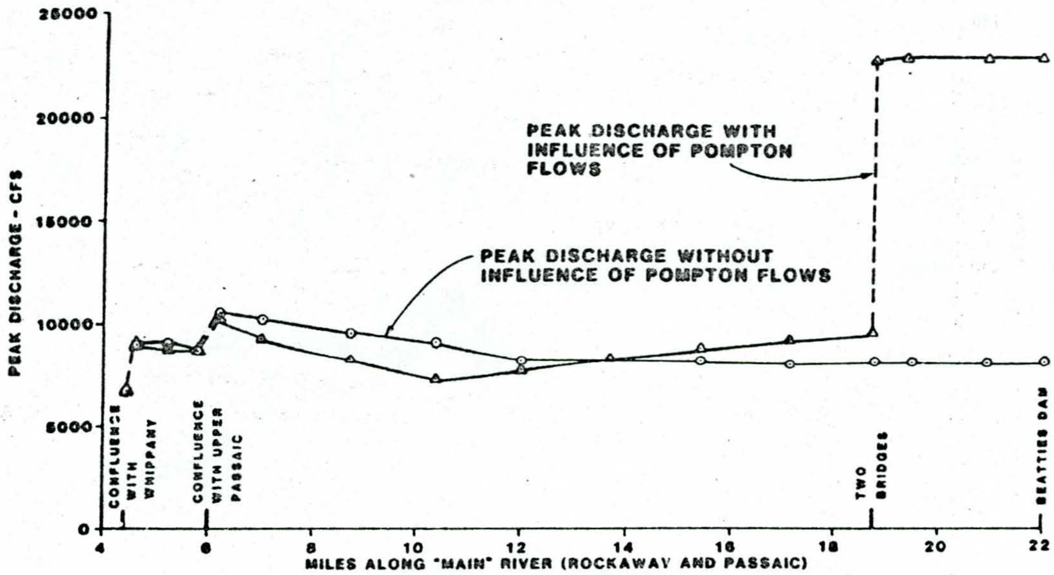


Figure 6. Intermediate Flood – Peak Discharge Profiles Illustrating Influence of Pompton River.

sufficiently low that submergence corrections are not made to the calculated weir flow. Also, arbitrarily large n values were input for the reach between the two downstream cross sections to restrict computed tributary discharge at the junction with the main river to negligibly small amounts. Figure 8 shows the impact of the tunnel on the peak stage profile for the intermediate flood, and Figure 9 shows the impact on the discharge hydrograph at Beatties Dam.

SUMMARY AND CONCLUSIONS

Flood wave movement through the Central Basin is complicated by mainstream tributary interactions and flow reversals. Relationships between stage and discharge tend to exhibit a substantial "loop" effect, as illustrated in Figure 4. The influence of the Pompton River on main river stage extends well upstream from the tributary junction, as shown in Figure 5.

DWOPER was used for analyzing unsteady flow in the Central Basin. Once data preparation was completed, application of the program proved to be straightforward except for difficulties experienced in learning the program's input structure. Minor difficulties were experienced in developing initial and boundary conditions to overcome numerical convergence problems. A typical run involving 50 cross sections, 3 tributaries, and 145 one-hour time intervals required about 200 Computing Units on a CDC 7600 computer.

A limitation on results of this study is the lack of data for additional historical events that could be used for validation purposes. For a complex flow system such as exists in the Central Basin, stage hydrograph or peak stage data at interior locations is essential for calibration/verification. The data available for this study were, however, typical of many "real world" situations in which analyses of complex problems are required.

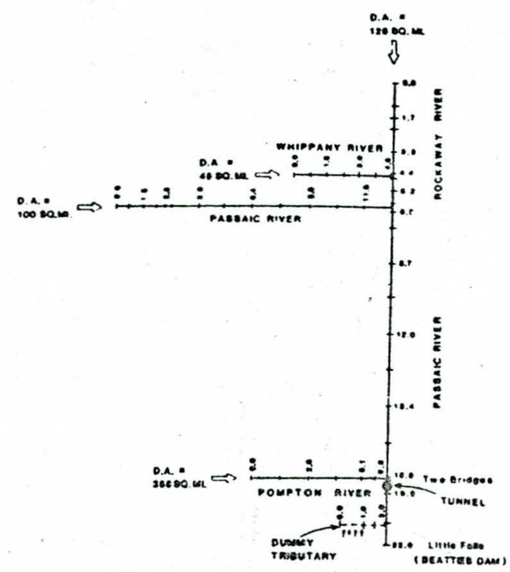


Figure 7. Schematic Map of River System with Proposed Tunnel.

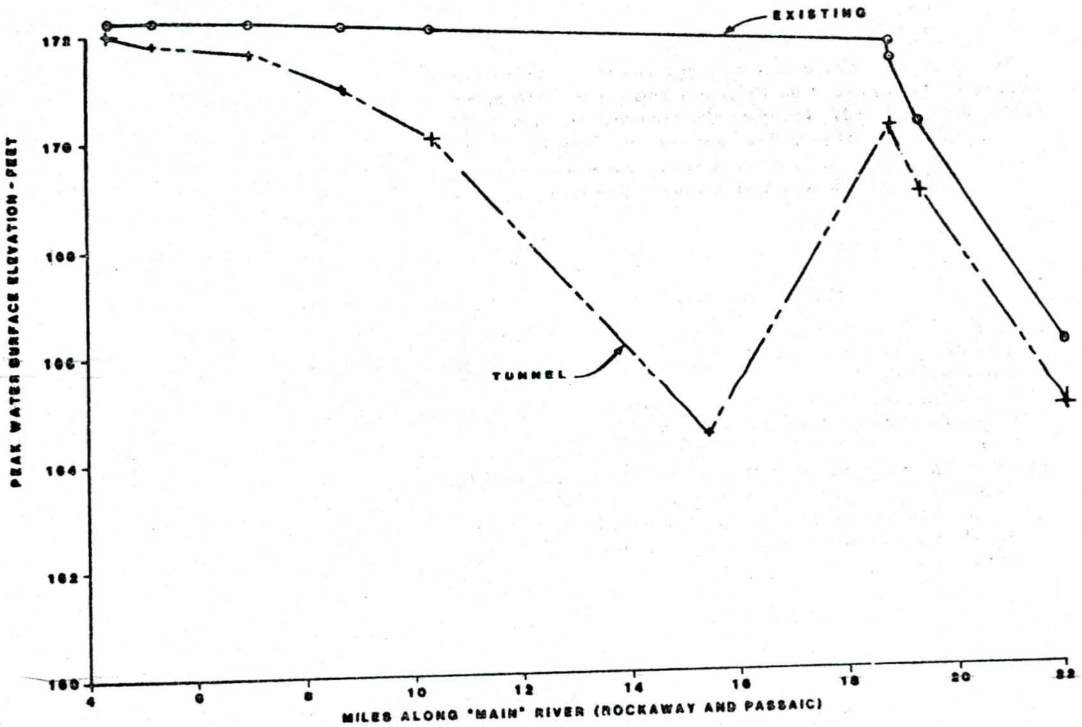


Figure 8. Peak Stage Profile – Intermediate Flood.

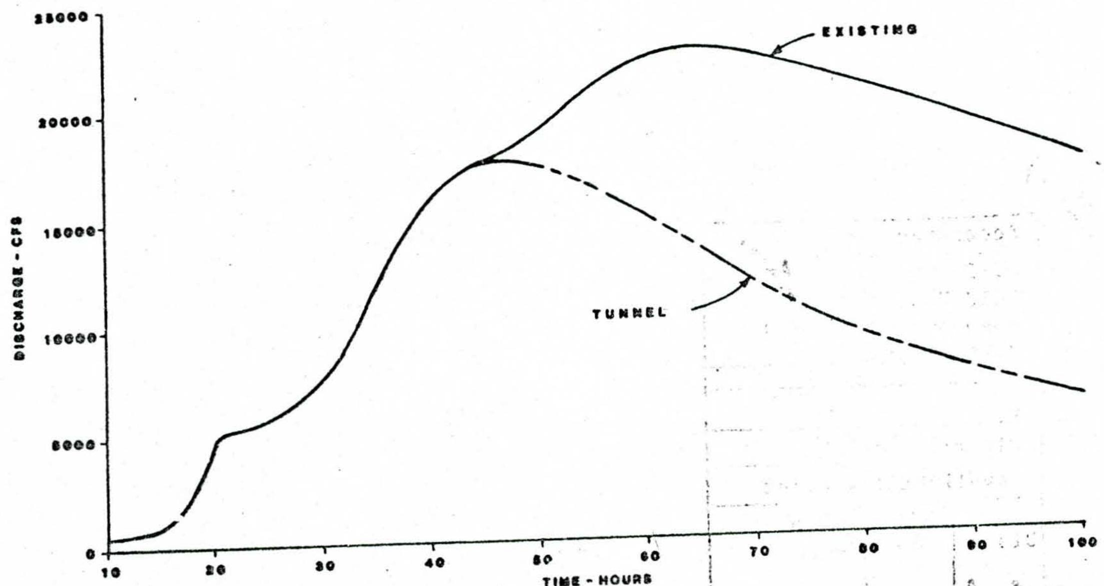


Figure 9. Intermediate Flood Discharge Hydrographs – Passaic River at Beatties Dam.

ACKNOWLEDGMENTS

The writer acknowledges assistance and valuable comments provided by D. Michael Gee of the Hydrologic Engineering Center in performing the subject study. The application of computer program HEC-1 to generate inflows and local flows was made by Camp Dresser and McKee Inc. The study was performed under the auspices of the Passaic River Study Group of the New York District, U.S. Army Corps of Engineers.

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Unsteady Flow; Flood Routing; Passaic River

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The routing of flood waves through the Central Basin of the Passaic River in New Jersey is complex because of flat gradients and flow reversals. The one-dimensional unsteady flow program DWOPER developed by the National Weather Service, was used to simulate flood wave movement through the basin. A historical event was used for calibration and two synthetic events were simulated. Boundary conditions consisted of discharge hydrographs at inflow points to the study area, local flow hydrographs at interior points, and a stage discharge relation for flow over the crest of a diversion dam at the basin outlet.

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