US Army Corps of Engineers
Hydrologic Engineering Center

HEC-5C, A Simulation Model for System Formulation and Evaluation

March 1974

TP-41

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
March 1974

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
HEC-5C, A Simulation Model for System Formulation and Evaluation

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bill S. Eichert

5d. PROJECT NUMBER

5e. TASK NUMBER

5F. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center (HEC)
609 Second Street
Davis, CA 95616-4687

8. PERFORMING ORGANIZATION REPORT NUMBER
TP-41

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/ MONITOR'S ACRONYM(S)

11. SPONSOR/ MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Presented at the Hydrologic Engineering Center, Seminar on Analytical Methods in Planning, 26-28 March 1974, Davis, California.

14. ABSTRACT
Overview of generalized computer model (HEC-5) for simulation operation of multipurpose reservoir system and evaluating economic consequences for flood control and hydropower purposes.

15. SUBJECT TERMS
simulation, flood control, system analysis, computer modeling, hydropower, reservoir regulation, flood damage reduction, multipurpose reservoirs, water resources project

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	34	19b. TELEPHONE NUMBER

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HEC-5C, A SIMULATION MODEL[1] FOR SYSTEM FORMULATION AND EVALUATION

by Bill S. Eichert[2]

1. Need for Hydrologic and Economic Simulation Model

Because of the great expenditure of funds required to construct structures to reduce flooding in a river basin, it is important to make sure that each project built is justified and is more desirable than any other alternative. In a complex river basin where numerous system components exist or are required to reduce flooding, the evaluation of each alternative requires a large number of calculations. Until recently all such evaluations had to be done by rather crude techniques or by laborious manual procedures, although a few simple computer models could be used on parts of the study. For example, a study made 10 years ago, required that 10 flood control reservoirs be considered in firming up the design of a few new reservoirs in a flood control system. The hydrology required in operating the system (after the historical flows throughout the basin were known) for several historical floods required three men working full time for about 4 months at a cost of about $25,000. In spite of the large time and cost, many simplifying assumptions had to be made, no economic evaluation was made and no alternative solutions were investigated because of the manpower, funds, and time limitations. The same job can be done today with greater detail and accuracy with a simulation model such as HEC-5C with less cost and manpower and, in addition, each alternative can be studied with a few hours of work and a $20 computer run which will show the average annual damages at all damage centers and the net system flood benefits. The initial work in assembling the reservoir data in the required computer format for the system requires about one man-week of work. The determination of the historical flows for all major floods of record throughout the system is the major task and has to be done by either manual or computer techniques, but could be done with about 3-man months of effort for this basin. The verification of the model on historical floods can be done in a couple of man months. Once the above tasks are completed, detailed simulations can be made easily and with little expense for numerous combinations of reservoirs, and other alternatives including nonstructural alternatives.

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[1]Presented at The Hydrologic Engineering Center, Seminar on Analytical Methods in Planning, 26-28 March 1974 at Davis, California.

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2. Purpose of Water Resources System Simulation Model - HEC-5C

This program was developed to assist in planning studies required for the evaluation of proposed changes to a system and to assist in sizing the system components for flood control and conservation requirements for each component recommended for the system. The program can be used in studies made immediately after a flood to calculate the preproject conditions and to show the effects of existing and/or proposed reservoirs on flows and damages in the system. The program should also be useful in selecting the proper reservoir releases throughout the system during flood emergencies in order to minimize flooding as much as possible and yet empty the system as quickly as possible while maintaining the proper balance of flood control storage among the reservoirs.

The above purposes are accomplished by simulating the sequential operation of various system components of any configuration for short interval historical or synthetic floods or for long duration nonflood periods, or for combinations of the two. Specifically the program may be used to determine:

a. Flood control and conservation storage requirements of each reservoir in the system.

b. The influence of a system of reservoirs, or other structures on the spatial and temporal distribution of runoff in a basin.

c. The evaluation of operational criteria for both flood control and conservation for a system of reservoirs.

d. The average annual flood damages, system costs, and excess flood benefits over costs.

e. The determination of the system of existing and proposed reservoirs or other structural or nonstructural alternatives that results in the maximum net benefit for flood control for the system by making simulation runs for selected alternative systems.

3. Computer Requirements

The program, written in FORTRAN IV, was developed on a UNIVAC 1108 computer with 64,000 words of storage. The UNIVAC version can simulate the operation of 15 reservoirs, 25 control points, 5 diversions, and 9 power plants, using up to 50 time periods in each flood or nonflood event. Dimension limits have been increased for a CDC 7600 computer which allows the simulation of 35 reservoirs, 75 control points, 11 diversions, and 9 power plants for up to 100 time periods for each runoff event.

4. General Capabilities of Program

a. Configuration of system - any system configuration may be used as long as dimension limits are not exceeded for number of reservoirs, number of control points, number of diversions, etc.

(1) Reservoirs which have flood control storage may be operated to minimize flooding at any number of downstream control points.

(2) Reservoirs with conservation storage will be operated for their own requirements (power or low flow) and can be operated for any number of downstream control points.

(3) Reservoirs may be easily deleted from the system.

(4) Reservoirs in system are kept in balance (in the same degree of trouble) as much as possible.

b. Outflows can be specified for any number of reservoirs for any or all time periods and program will adjust other reservoir releases as necessary; otherwise program will determine all reservoir releases.

c. Effects of forecast errors can be evaluated by specifying the number of forecast periods and a corresponding contingency allowance (i.e., error in forecasting).

d. Local flows can be calculated from observed discharges and reservoir releases; system operation can be performed or omitted after flows are determined.

e. The multiflood option may be used to operate the system for a continuous period of record (for example, 5 events each containing 4 years of monthly data may be used for a total of 20 years). Also a mixture of computational intervals may be used such as running a monthly operation for a few years (assuming no routing if desired) and then operating for daily or hourly flows during a major flood (with detailed flood routing) and then back to a weekly or monthly routing interval, etc. An unlimited number of events can be simulated in this manner.

f. Evaporation and a monthly variation in reservoir operating levels can be considered in the routings if desired.

g. Voluminous output can be suppressed by requesting only a summary output. Detailed output for a few selected control points can also be obtained.

h. Stream routing may be accomplished by the following methods:

(1) Modified Puls, Working R/D, Muskingum, Straddle Stagger, and Tatum.

(2) Each routing method may be used several times for each reach.

(3) Actual releases that are routed by nonlinear (storage-outflow is not a straight line) methods (Modified Puls or Working R/D) use a linear approximation for determining reservoir releases.

(4) Natural and cumulative local flows are calculated.

i. Reservoir routing is based on:

(1) Accounting methods (release is determined based on desired operation, storage is equal to inflow less outflow plus previous storage).

(2) Surcharge routing - when desired release is greater than physical outlet capacity, the arithmetical method, which is a trial and error method, is used which will provide the same results as the Modified Puls method.

(3) Emergency releases - when desired release for current period plus channel capacity releases for future periods (up to limit of foresight specified) would cause reservoir to exceed maximum flood storage in current or future periods, a release is made for the current period (up to channel capacity or the outlet capacity) so that the reservoir does not exceed top of flood pool in future period.

j. Multifloods

(1) Read and operate an unlimited number of floods for a reservoir system.

(2) The series of floods can each start at different reservoir storages or from same storages or can be continued using the storages from the previous flood.

(3) Operate up to 9 ratios of any or all floods read.

(4) Long floods may be routed by dividing the flood into flow events which are each less than the dimension limit of the time array. This may be done by manually setting in several sets of flow data (with each less than the dimension limit) or by allowing the computer to generate separate floods (when the data read exceeded the dimension limit). A minimum of a 10 period overlap between floods is used to preserve continuity.

(5) Period of record analysis may be made by analyzing a series of floods consisting of monthly or weekly data during nonflood periods and daily or multihourly data during flood periods.

k. Diversions

(1) Diversions can be made from any reservoir or control point. Only one diversion from each control point or reservoir is allowed.

(2) Diversions can be made to any downstream control point or reservoir or out of the system.

(3) Diversions may be routed using any linear method allowed and multiplied by a constant representing the percent of return flow.

(4) Types of diversions

(a) Diversions can be a function of inflows.

(b) Diversions can be functions of reservoir storages.

(c) Diversions can be constant.

(d) Diversions can be constant for certain periods such as 50 cfs for January, 40 cfs for February, etc.

(e) Diversions can be made for all excess water above the top of conservation pool up to the diversion pipe capacity.

5. Reservoir Operational Criteria

a. Reservoirs are operated to satisfy constraints at individual reservoirs, to maintain specified flows at downstream control points, and to keep the system in balance. Constraints at individual reservoirs are as follows:

(1) When the level of a reservoir is between the top of conservation pool and the top of flood pool, releases are made to attempt to draw the reservoir to the top of conservation pool without exceeding the designated channel capacity at the reservoir or at downstream control points for which the reservoir is being operated.

(2) Releases are made equal to or greater than the minimum desired flows when the reservoir storage is greater than the top of buffer storage, and or equal to the required flow if between level one and the top of buffer pool. No releases are made when the reservoir is below

level one (top of inactive pool). Releases calculated for hydropower requirements will override minimum flows if they are greater than the controlling desired or required flows.

(3) Releases are made equal to or less than the designated channel capacity at the reservoir until the top of flood pool is exceeded, then all excess flood water is dumped if sufficient outlet capacity is available. If insufficient capacity exists, a surcharge routing is made. Input options permit channel capacity releases (or greater) to be made prior to the time that the reservoir level reaches the top of the flood pool if forecasted inflows are excessive.

(4) The reservoir release is never greater (or less) than the previous period release plus (or minus) a percentage of the channel capacity at the dam site unless the reservoir is in surcharge operation.

b. Operational criteria for specified downstream control points are as follows:

(1) Releases are not made (as long as flood storage remains) which would contribute to flooding at one or more specified downstream locations during a predetermined number of future periods except to satisfy minimum flow and rate-of-change of release criteria. The number of future periods considered is the lesser of the number of reservoir release routing coefficients or the number of local flow forecast periods.

(2) Releases are made, where possible, to exactly maintain downstream flows at channel capcity (for flood operation) or for minimum desired or required flows (for conservation operation). In making a release determination, local (intervening area) flows can be multiplied by a contingency allowance (greater than 1 for flood control and less than 1 for conservation) to account for uncertainty in forecasting these flows.

c. Operational criteria for keeping a reservoir system in balance are as follows:

(1) Where two or more reservoirs are in parallel operation above a common control point, the reservoir that is at the highest index level, assuming no releases for the current time period, will be operated first to try to increase the flows in the downstream channel to the target flow. Then the remaining reservoirs will be operated in a priority established by index levels to attempt to fill any remaining space in the downstream channel without causing flooding during any of a specified number of future periods.

(2) If one of two parallel reservoirs has one or more reservoirs upstream whose storage should be considered in determining the priority of releases from the two parallel reservoirs, then an equivalent index level is determined for the tandem reservoirs based on the combined storage in the tandem reservoirs.

(3) If two reservoirs are in tandem (one above the other), the upstream reservoir can be operated for control points between the two reservoirs. In addition, when the downstream reservoir is being operated for control points, an attempt is made to bring the upper reservoir to the same index level as the lower reservoir based on index levels at the end of the previous time period.

6. Average Annual Flood Damage Evaluation

Average annual damages (AAD) or damages for specific floods can be computed for up to 9 different categories for any or all control points (nonreservoirs) using one or more ratios for each of several historical or synthetic floods. They will be computed for the following three conditions:

a. Natural or unregulated conditions.

b. Regulated conditions due to the reservoir system assumed.

c. Full regulation at those reservoir sites (uncontrolled local flows).

Damages calculated for base conditions (normally natural flows) using selected floods and ratios are adjusted to average annual damages, computed by integrating the base conditions damage frequency curve or by using a predetermined average annual damage. The corresponding adjustment is printed out to help verify the appropriateness of the floods and ratios selected in integrating the damage curve for base conditions. Damages for modified conditions are based on the cumulative product of the damages associated with the modified peak flow for each flood (for a certain damage center) times the probability interval assigned to each flood from the base condition integration. See figure 1 for an example of the AAD integration. The damage for the uncontrolled local flows are also calculated in a similar manner to the modified conditions.

The damage reduction due to the proposed system is based on the difference between the AAD for the base conditions and the modified conditions. If an existing reservoir system exists the damage reduction can be based on the difference between the base conditions and the modified conditions where the base conditions were determined from another simulation run (existing reservoirs only).

A separate set of damage data can be used if the modified condition damages do not follow the base condition discharge-damage curves as would be the case for a levee, channel improvement or nonstructural alternative such as flood proofing, relocation, purchase, flood plain zoning, etc.

7. Multiflood Selection and Operation

The selection of the floods used in operating the system, is of paramount importance in the determination of the average annual damages. The floods selected must generate the peak flows at the damage centers (particularly the key ones) which represent the full range of the flow-frequency-damage relationship for base conditions as well as for modified conditions.

Even using all historical floods of record may introduce some bias in the average annual damage if most historical floods centered over a certain part of the basin by chance and not over other areas. For instance one dam site may have several severe historical floods while another dam site immediately adjacent to that area may, due to chance, not have had any severe floods.

While it is possible in the program, HEC-5C, to use only a single flood and several ratios of that flood in computing average annual damages, this procedure could introduce considerable bias in the results. It would be far better to use several historical floods with storm centerings throughout the basin and to use several ratios of those floods to obtain flows at the damage centers representing the full range of the flow-frequency-damage relationship for base conditions and for regulated conditions. A good idea of the adequacy of the selected floods and ratios for reproducing base conditions can be obtained by looking at the correction factor printed out at each damage center for each damage category. This correction factor is the ratio of average annual damage computed by integrating the input frequency-damage curve (or from input on DA card) to the average annual damage computed by assigning probability intervals to the system flows computed by HEC-5C. When the correction factor is close to 1.0, it represents the base conditions very well, but may not represent the modified condition if only one or two regulated floods cause damage. It is desirable to have one flood that does not cause damages so that the smallest flood with damage doesn't receive too large a probability interval. It is also necessary to have several modified historical floods produce damages spread out over the modified frequency curve since the integration of the damage-frequency curve is based on rectangular blocks for each flood using the probabilities from the base condition curve.

Studies are currently being made at The Hydrologic Engineering Center to help establish criteria for the selection of the floods and ratios to use.

8. Evaluation of Alternative Reservoir Systems

If this computer program is to be used to evaluate proposed reservoirs, then the data cards should be assembled so that all proposed reservoirs are included, even if some of them would serve as alternatives of others. Control points should be selected and coded for all damage centers, control points for reservoir operation, and information points. Once the entire system is coded, a single card can be used to delete reservoirs from the system for each alternative system selected. This card can be used to delete any reservoir in the system except for downstream tandem reservoirs (these reservoirs can be deleted by removing the reservoir cards). Flood damages for a single flood (or average annual flood damages) can be evaluated at any number of control points. Reservoir costs can also be evaluated by showing how the costs vary with reservoir storage based on the top of flood control storage. If costs and average annual flood damages are calculated, the net system flood benefits will be printed out for each alternative system operated. By careful selection of alternative systems, the system that produces the maximum net flood benefits can be determined by a reasonable number of separate computer runs.

9. Evaluation of Nonreservoir Alternatives

Structural and nonstructural alternatives to certain reservoirs can also be evaluated in the system simulation with or without reservoirs in the system. The existence of a levee or channel improvement can be reflected in the reservoir system operation by changing the channel capacity if appropriate. At the present time only one set of routing criteria can be read for each reach and thus the natural and modified routings use the same criteria. This limitation requires that when the routing criteria is different between natural and modified conditions, the natural flows must be calculated by a separate computer run and entered on cards for modified conditions. Costs of nonreservoir alternatives can be shown as functions of the channel discharges. For a given design discharge an interpolation is made to determine the capital cost applicable to the control point. The average annual flood damages can be evaluated in the same manner as for reservoir alternatives. However, the zero damage point can be automatically changed to the design discharge for modified conditions if a control point cost card is read. Two sets of damage cards can be read as an alternative to the above procedure, in representing natural and regulated conditions, so that the entire damage curve can be changed for regulated conditions.

Nonstructural alternatives (flood proofing, flood plain zoning, etc.) can be handled in the same manner as structural alternatives (usually by using two sets of damage cards), however the nonstructural alternative will require defining the upper limit of the flood proofing, zoning, etc. as a channel capacity or design discharge.

10. Use of HEC-5C in Flood Control System Selection

As can be seen in table 1, quite a few reservoir systems have been simulated using HEC-5. Most of these systems have used the flood control version which was released in May 1973. The version which also includes conservation operation (HEC-5C) has not been officially released yet, but it has been used for flood control simulation and average annual damages have been calculated for the Susquehanna, Red River of the North, and the Grand (Neosho) River basins. Monthly conservation operation has been used on the Pajaro River, the Red River of the North, the Hudson River Basin and several hypothetical systems. Of the studies conducted to date by HEC using this model, five of them have been for preliminary planning studies and have been used for the sole purpose of determining the regulated flows throughout the basin for various historical and synthetic floods. Each one of these basins also had a HEC-1 rainfall runoff data model developed in order to calculate the runoff from synthetic floods and to use rainfall to get a better distribution of runoff for historical floods. The study of the 15 reservoir system for the Trinity River was made in connection with Design Memorandum studies for the Tennessee Colony reservoir in order to determine the flood control storage in that downstream project (14 reservoirs above it) and to evaluate various alternative plans of channel improvements below the project. The work on the existing five reservoir Merrimack basin is expected to use HEC-5 in a real-time operation mode using forecasting routines and automatic data collection by July of 1975.

The Susquehanna River Basin has 12 reservoirs existing or under construction, and another 22 potential reservoir sites are being investigated along with other structural and nonstructural alternatives in a preliminary plannning study being conducted by the Baltimore District office of the Corps, the HEC and a private consulting firm Anderson-Nichols of Boston, Massachusetts. The decision for selection of the desired system will make important use of the average annual damage reduction and net benefits of the alternative systems which will be printed out for each alternative evaluated by HEC-5C.

11. Model Data Requirements and Output

The input data requirements for HEC-5C can be minimal for very preliminary planning studies or it can be very detailed for modeling existing systems. The minimum data requirements are as follows:

a. General Information (4 cards)

(1) Title cards for Job (3 cards)

(2) Six miscellaneous items including the number of periods of flow data, time interval of flows, etc.

b. Reservoir Data (4 cards per reservoir)

(1) Reservoir capacities for top of conservation and top of flood control elevations.

(2) Downstream control points for which reservoir is operated

(3) Reservoir storage/outflow tables

c. Control Point (including reservoirs) Data (3 cards per control point)

(1) Identification number and title

(2) Channel capacity

(3) Channel routing criteria

d. Flow Data

Inflow or local flow data for each control point for one or more historical or synthetic floods.

Additional input information useful for planning studies:

a. Average Annual Damage Data (a minimum of 4 cards per damage center)

Peak discharge-damage-frequencies tables

b. Cost Data (1 card per control point)

(1) Reservoir capital costs vs storage <u>or</u>

(2) Control point capital costs vs channel discharge <u>and</u>

(3) Capital recovery factor

(4) Annual operation and maintenance costs

The output available from the program includes

a. Listing of input data

b. Results of system operation arranged by downstream sequence of control points.

c. Results of system operation arranged by sequence of time periods

d. Summary of flooding for system

e. Summary of reservoir releases and control point flows by period

f. Summary of conservation operation if monthly routing was made

g. Summary of maximum flows, storages, etc., for each flood event

h. Summary of maximum and minimum data for all floods

i. Summary of average annual damages

j. Summary of system costs (annual and capital) and net benefits. Examples of some of the summaries are shown as figures 2-12.

12. Strategy for Selection of Alternative Systems

For systems with only a few possible components the strategy for determining the best alternatives can be quite simple since each possible alternative can be evaluated. For systems with a large number of possible alternatives, the strategy can be difficult to predetermine and the best available procedure to follow may be to simply select alternatives to be evaluated one at a time following a careful review of information obtained from previous runs.

Certain economic criteria must be observed for the final system selected. The incremental cost of the new components of the proposed system must be less than the damage reduction accomplished by the new components. In addition, each project must be justified on the basis of the last increment added. That is to say, the cost of each project must be less than the difference between the average annual damages of the proposed system with and without that project.

A certain minimum performance criteria is also necessary. This philosophy says that if a certain level of protection can not be provided by the system then it would be better not to build any structures than to give the public a sense of false security.

With the above ideas in mind it seems necessary to first determine a minimum system that will provide an acceptable level of protection. Next see if various alternatives can be used to get a larger value of the maximum net benefits. When the maximum net benefits appears to be obtained (and it is positive) then each project should be deleted in turn to see if that project prevented more damages than it cost to build. The process of maximizing the net benefits by selecting alternatives and evaluating using HEC-5C, at present, can only be based on good engineering judgment. After a few studies are completed using this new tool, perhaps more definite guidance will be available.

13. Future Use of Model for Multipurpose Systems

The current version of the program does have capabilities for multipurpose operation of reservoir systems, but does not have multipurpose economic evaluation routines. While the program can operate for low flows at one or more downstream points, for flood control operation and for individual hydropower requirements, the conservation capabilities have not been tested on a sufficient number of systems to provide the necessary confidence. When a few more systems have been successfully operated for conservation and flood control together, that confidence will be obtained.

The major additions necessary for the future are in the area of hydropower systems, multipurpose benefit evaluation and extensive testing.

14. Conclusions

It appears that the HEC-5C simulation model should be a useful tool for planners to evaluate the effects of water resource projects and nonstructural alternatives in most river basins because it can accurately, quickly, and inexpensively simulate the hydrologic and economic responses of the system. While much of the detailed analysis of hydrology, reservoir regulations, and economics can be accomplished by the model, considerable engineering ingenuity will be required to insure that the proper data is used in the model, that the model is giving valid results, and that the proper sequence of alternatives are evaluated in order to determine the best plan for the reduction of damages in a basin.

It also seems probable that the model will be useful for simulating multipurpose reservoir operation. In this connection considerable work will be required to develop economic and social parameters to allow multipurpose evaluation of the system alternatives similar to flood control.

Considerable experience and research will be required to develop procedures, techniques and/or optimization subroutines which will enable the program to be used in the most efficient manner in the selection of the best multipurpose alternatives for the basin.

TABLE 1

SYSTEMS SIMULATED BY HEC-5

River Basin	Location	Number Reservoirs	Number Control Points (including res)	Time Increment (hrs)	Approximate Drainage Area square miles
1. Trinity	Texas	15	28	24	18,000
2. Merrimack	New England	5	11	3	4,400
3. Susquehanna	Pennsylvania	34	75	4	24,000
4. Schulkill	Pennsylvania	12	26	3	1,900
5. Potomac	Virginia Maryland Pennsylvania	26	39	2	12,000
6. Red River of North	Minnesota	13	29	24 720	40,000
7. Feather	California	3	4	2	5,900
8. Pajaro	California	3	6	1 720	400
9. Grand (Neosho)	Oklahoma	24	86	2	5,900
10. James	Virginia	22	35	6	6,800
11. Red River 1st Phase	Texas Arkansas	14	28	6	12,000
12. Hudson	New York Pennsylvania	3	5	720	500

DAMAGE - FREQUENCY CURVES

AAD CALCULATIONS

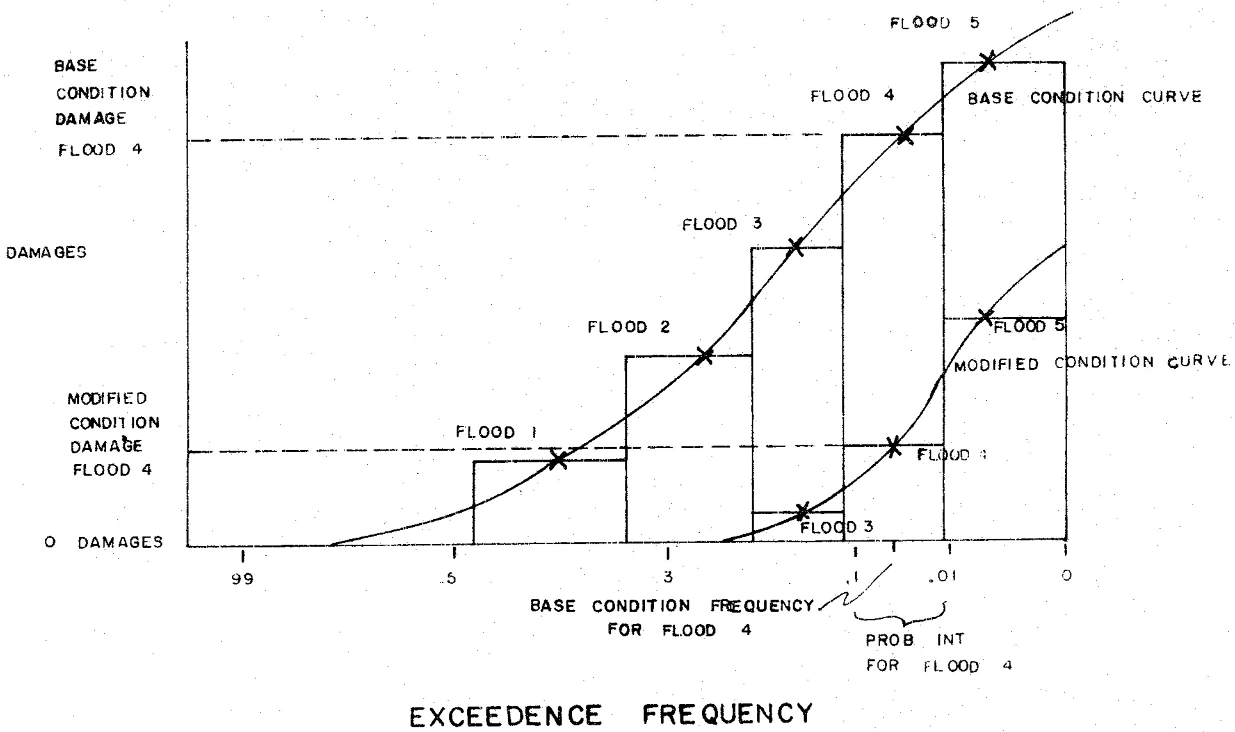
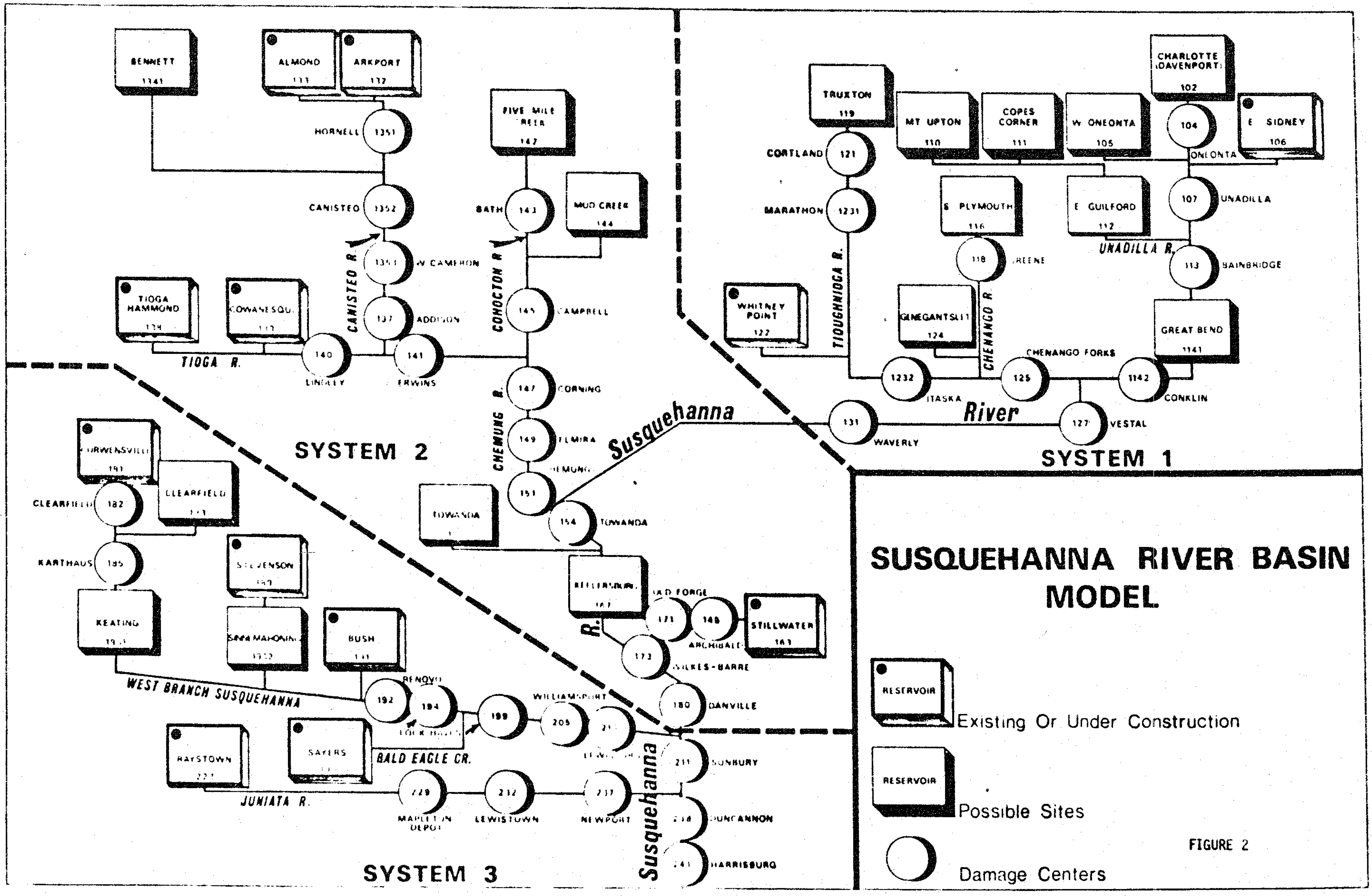


FIGURE 1. EXAMPLE OF AAD INTEGRATION FOR MULTIPLE FLOODS

(Important values for flood 4 are indicated)

Note: This figure is not for same example as figures 2-12.


SUSQUEHANNA RIVER BASIN MODEL
RESERVOIR
Existing Or Under Construction
RESERVOIR
Possible Sites
Damage Centers
FIGURE 2
SYSTEM 1
SYSTEM 2
SYSTEM 3
TRUXTON 119
MT UPTON 110
COPES CORNER 111
W ONEONTA 105
CHARLOTTE DAVENPORT 102
E SIDNEY 106
CORTLAND
MARATHON
ONEONTA
UNADILLA
BAINBRIDGE
S PLYMOUTH 116
E GUILFORD 112
UNADILLA R.
WHITNEY POINT 122
TIOUGHNIOGA R.
CHENANGO R.
GREAT BEND 1141
CHENANGO FORKS
ITASKA
CONKLIN
River
VESTAL
WAVERLY
Susquehanna
BENNETT 1341
ALMOND
ARKPORT
HORNELL
CANISTEO
CANISTEO R.
W CAMERON
FIVE MILE
MUD CREEK 144
BATH
COHOCTON R.
CAMPBELL
TIOGA HAMMOND
TIOGA R.
CORNING
CHEMUNG R.
TOWANDA
STILLWATER
WILKES-BARRE
DANVILLE
CLEARFIELD
KARTHAUS
KEATING
BUSH
WEST BRANCH SUSQUEHANNA
RENOVO
BALD EAGLE CR.
HAYSTOWN
SAYERS
JUNIATA R.
LEWISTOWN
NEWPORT
SUNBURY
HARRISBURG
Susquehanna

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**** LOC   180  DANVILLE                        SERVED BY  -138  -139  -132  -133 -1341  -142  -144  -102  -105  -106  -112 -1141
                                    -119  -122  -116  -124  -155  -163

CUM LOCAL Q    18419   18388   18289   18132   17942   17719   17505   17662   19390   25169
W/O DIVS       38793   63416   97316  133676  166674  195267  221061  245012  266872  286677
              304794  320879  333584  340942  341104  333323  318482  298582  275908  252375
              229185  206967  186030  166571  148748  132671  118381  105842   94945   85533
               77425   70436   64386   59113   54478   50363   46672   43330   40281   37480
               34895   32501   30279   28212   26289   24498   22831   21277   19830   18482
                                                                                          AVG=  141688  MAX=  341104
NATURAL FLOW   20938   20906   20807   20650   20460   20236   20020   20174   21900   27682         MIN=   17505
               41336   66059  100203  137030  170730  200135  226671  251378  274625  297479
              321337  346435  371168  392236  405513  407645  397506  376423  347512  314543
              280830  248684  219375  193384  170716  151139  134332  119952  107663   97151
               88134   80360   73613   67708   62491   57836   53643   49834   46350   43142
               40178   37430   34878   32503   30292   28234   26316   24528   22864   21313
                                                                                          AVG=  138410  MAX=  407645
                                                                                                        MIN=   20020
ACTUAL FLOW    20938   20906   20807   20650   20460   20236   20020   20174   21900   27674
               41293   65903   99781  136118  169101  197693  223496  247465  269346  289156
              307234  323211  335741  342800  342854  334934  320072  300348  278141  255426
              233396  212573  193123  175129  158701  143941  130880  119473  109632  101254
               94201   88280   83279   79015   75350   72158   69296   66629   64091   61697
               59498   57508   55684   53933   52160   50294   48303   46203   44053   41934
                                                                                          AVG=  132261  MAX=  342890
Q SPACE       113062  113094  113193  113350  113540  113764  113980  113826  112100  106326         MIN=   20020
( 134000=CC)   92707   68097   34219   -2118  -35101  -63693  -89496 -113465 -135346 -155156
             -173234 -189211 -201741 -208890 -208854 -200934 -186072 -166348 -144141 -121426
              -99396  -78573  -59123  -41129  -24701   -9941    3120   14527   24358   32746
               39799   45720   50721   54985   58650   61842   64704   67371   69909   72303
               74502   76492   78316   80067   81840   83706   85697   87797   89947   92066
                                                                                          FLOOD PERIODS=       23
Q BY US RES     2518    2518    2518    2518    2518    2517    2515    2512    2509    2506  TOTAL VLL=      2708091
AND DIVS        2500    2487    2464    2441    2427    2426    2436    2454    2474    2479
                2440    2332    2157    1947    1750    1611    1590    1766    2232    3052
                4211    5607    7093    8558    9953   11270   12499   13631   14688   15722
               16776   17845   18894   19901   20871   21795   22624   23299   23810   24217
               24602   25007   25405   25721   25871   25795   25472   24926   24223   23452
                                                                                          AVG=   10573
FLOOD BY RES       0       0       0       0       0       0       0       0       0       0
                   0       0       0    2118    2427    2426    2436    2454    2474    2479
                2440    2332    2157    1947    1750    1611    1590    1766    2232    3052
                4211    5607    7093    8558    9953    9941       0       0       0       0
                   0       0       0       0       0       0       0       0       0       0
                   0       0       0       0       0       0       0       0       0       0
                                                                                          FLOOD PERIODS=       23
                                                                                          VOL FROM RES=     83055
```

EXAMPLE SEQUENTIAL OUTPUT

FIGURE 3

COMPUTATION INTERVAL IN HOURS= 4

SINGLE FLOOD SUMMARY COPY= 1

***** FLOOD NUMBER 6 *****

T1 SUSQUEHANNA RIVER BASIN - MUD CREEK AND TRUXTON RESERVOIRS
T2 AVERAGE ANNUAL DAMAGE REDUCTION EVALUATION - EXISTING < STUDY RESERVOIRS
T3 USING MULTIPLES OF DANVILLE SPF DAMAGE DATA IN 1963 DOLLARS

LOC		MAX REG Q	MAX NAT	MAX UNC	Q BY RES	NO FLOODS TOTAL	VOL FLOODS TOTAL	NO FLOODS FROM RES	VOL FLOODS FROM RES	PER FLOODS FROM RES
140	LINDLEY	18564	82252	12534	6030	0	-0	0	0	0- 0
1351	HORNELL	11128	20644	10513	615	9	17014	9	4453	10- 33
1352	CANISTEO	34539	42857	33997	542	3	25826	3	1636	11- 13
1353	W. CAMERON	39261	47169	38718	543	5	76297	5	2652	11- 15
137	ADDISON	67310	70350	67000	310	12	236555	12	5406	9- 20
141	ERWINS	90106	154438	89743	362	7	237519	7	2697	10- 16
143	BATH	16703	16703	16703	0	6	24068	0	0	0- 0
145	CAMPBELL	22322	26768	22322	0	12	96166	0	0	0- 0
147	CORNING	122243	195288	121948	295	9	386964	9	5213	11- 19
149	ELMIRA	124290	194700	123979	310	2	16945	2	706	14- 15
151	CHEMUNG	146152	207715	145799	352	21	716554	21	38590	11- 34
104	ONEONTA	29051	29051	29051	0	17	158189	0	0	0- 0
107	UNADILLA	36833	40590	36833	0	18	237569	3	689	11- 13
113	BAINBRIDGE	78741	87877	78741	0	20	572778	4	2331	10- 13
1142	CONKLIN	107753	115306	107645	108	20	811750	10	2505	12- 31
121	CORTLAND	9605	15710	9605	0	7	21035	0	0	0- 0
1231	MARATHON	15378	20592	15378	0	3	7677	0	0	0- 0
1232	ITASKA	17619	40511	17619	0	7	32367	2	6	13- 14
118	GREENE	34734	34734	34734	0	15	213271	0	0	0- 0
125	CHENANGO FORKS	63957	86044	63956	1	15	396787	10	8008	11- 25
127	VESTAL	170875	198581	170667	209	21	1381039	21	13088	11- 31
131	WAVERLY	190767	216500	190513	254	20	1605909	20	13361	12- 31
154	TOWANDA	325815	407096	324669	1146	24	2689751	24	116410	11- 34
165	ARCHBALD	3761	6812	3761	0	1	661	0	0	0- 0
171	OLD FORGE	23076	25798	23076	0	4	30742	2	8	11- 12
173	WILKES-BARRE	341301	409570	339472	1829	25	3164548	25	111091	13- 37
180	DANVILLE	342890	407645	341104	1786	23	2708091	23	83055	14- 36

EXAMPLE FLOOD SUMMARY

FIGURE 4

		RESERVOIRS		STOR1	MAX STG	MAX LEVEL	EXCEEDED TOP F.C. 1ST PER.	LAST PER.	MAX INFLOW	MAX REL.	CHAN CAP.
LOC	138	TIOGA-HAMMOND RES	EX	5000	83472	1.654	0	0	49807	12500	12500
LOC	139	COWANESQUE RES	EX	1000	68329	1.716	0	0	39822	6000	6000
LOC	132	ARKPORT RES	EX	10	1769	2.163	8	33	2388	787	1000
LOC	133	ALMOND RES	EX	150	13353	1.901	0	0	7843	4607	5200
LOC	1341	BENNETTS CK RES	US	0	0	1.000	0	0	8499	8499	2000
LOC	142	FIVEMILE CK RES	US	0	0	1.000	0	0	4243	4243	2000
LOC	144	MUD CK RES	US	38000	49804	1.738	0	0	5169	2000	2000
LOC	102	CHARLOTTE RES	US	0	0	1.000	0	0	11556	11556	2000
LOC	105	W. ONEONTA RES	US	0	0	1.000	0	0	8595	8595	2000
LOC	106	E. SIDNEY RES	EX	1700	20401	1.588	0	0	9639	3886	1900
LOC	112	E. GUILFORD RES	US	0	0	1.000	0	0	38867	38867	2000
LOC	1141	GREAT BEND RES	US	0	0	1.000	0	0	106263	106263	50000
LOC	119	TRUXTON RES	US	27000	39958	1.480	0	0	6433	2000	2000
LOC	122	WHITNEY PT RES	EX	5000	48932	1.539	0	0	18553	3933	5000
LOC	116	S. PLYMOUTH RES	US	0	0	1.000	0	0	6323	6323	2000
LOC	124	GENEGANTSLET RES	US	0	0	1.000	0	0	10525	10525	3000
LOC	155	TOWANDA RES	US	0	0	1.000	0	0	22409	22409	1000
LOC	163	STILLWATER RES	EX	343	5245	1.421	0	0	3784	400	400

MAX SYSTEM STORAGE= 331263

EXAMPLE RESERVOIR SUMMARY
FLOOD 6 (80% SPF)
FIGURE 5

***** MAX VALUES FOR MULTY FLOODS *****

			FLD.PER	MAX REG Q *	FLD.PER	MAX NAT Q *	FLD.PER	MAX LOC Q *	Q BY RES *	WEIGHTED SHORTAGE DES	INDEX REQ
LOC	140	LINDLEY	7.049	18676 *	7.014	102814 *	7.012	15667 *	10072 *		
LOC	1351	HORNELL	7.012	13809 *	7.012	25805 *	7.012	13141 *	1782 *		
LOC	1352	CANISTEO	7.012	43089 *	7.012	53571 *	7.012	42496 *	592 *		
LOC	1353	W. CAMERON	7.013	48987 *	7.013	58961 *	7.013	48397 *	590 *		
LOC	137	ADDISON	7.012	84087 *	7.012	87938 *	7.012	83750 *	337 *		
LOC	141	ERWINS	7.013	112572 *	7.013	193047 *	7.013	112179 *	489 *		
LOC	143	BATH	7.013	20878 *	7.013	20878 *	7.013	20878 *	0 *		
LOC	145	CAMPBELL	7.014	27902 *	7.013	33459 *	7.014	27902 *	1111 *		
LOC	147	CORNING	7.013	152763 *	7.014	244110 *	7.013	152435 *	2381 *		
LOC	149	ELMIRA	7.014	155322 *	7.015	243375 *	7.014	154974 *	2342 *		
LOC	151	CHEMUNG	7.016	182638 *	7.016	259644 *	7.016	182249 *	2505 *		
LOC	104	ONEONTA	7.015	36313 *	7.015	36313 *	7.015	36313 *	0 *		
LOC	107	UNADILLA	7.017	46041 *	7.016	50737 *	7.017	46041 *	0 *		
LOC	113	BAINBRIDGE	7.014	98428 *	7.014	109846 *	7.014	98426 *	1384 *		
LOC	1142	CONKLIN	7.016	134771 *	7.016	144133 *	7.016	134556 *	1495 *		
LOC	121	CORTLAND	7.013	12006 *	7.013	19637 *	7.013	12006 *	754 *		
LOC	1231	MARATHON	7.013	19222 *	7.014	25739 *	7.013	19222 *	769 *		
LOC	1232	ITASKA	7.015	22023 *	7.015	50638 *	7.015	22023 *	2360 *		
LOC	118	GREENE	7.014	43418 *	7.014	43418 *	7.014	43418 *	0 *		
LOC	125	CHENANGO FORKS	7.015	79945 *	7.015	107554 *	7.015	79945 *	2154 *		
LOC	127	VESTAL	7.017	213692 *	7.017	248226 *	7.017	213333 *	3224 *		
LOC	131	WAVERLY	7.019	238537 *	7.019	270625 *	7.019	238141 *	2860 *		
LOC	154	TOWANDA	7.018	407236 *	7.019	508870 *	7.018	405836 *	4432 *		
LOC	165	ARCHBALD	7.012	4701 *	7.012	8515 *	7.012	4701 *	399 *		
LOC	171	OLD FORGE	7.013	28845 *	7.013	32247 *	7.013	28845 *	392 *		
LOC	173	WILKES-BARRE	7.022	426428 *	7.023	511762 *	7.022	424340 *	4405 *		
LOC	180	DANVILLE	7.024	428394 *	7.026	509556 *	7.025	426380 *	4784 *		

EXAMPLE FLOOD SUMMARY
FLOODS 1-7
RATIOS OF SPF
(.2, .3, .4, .5, .6, .8, 1.0)
FIGURE 6

		RESERVOIRS		FLD.PER	MIN STG	MIN LEVEL	*	FLD.PER	MAX STG	MAX LEVEL	*	FLD.PER	MAX REL	CHAN CAP
LOC	138	TIOGA-HAMMOND RES	EX	7,001	5000	1,000	*	7,026	110556	1,880	*	7,034	12500	12500
LOC	139	COWANESQUE RES	EX	7,001	1000	1,000	*	7,023	91061	1,958	*	7,028	6000	6000
LOC	132	ARKPORT RES	EX	7,001	10	1,000	*	7,013	2387	2,220	*	7,014	766	1000
LOC	133	ALMOND RES	EX	7,001	150	1,000	*	7,019	14800	2,000	*	6,029	4607	5200
LOC	1341	BENNETTS CK RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,012	10624	2000
LOC	142	FIVEMILE CK RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,013	5304	2000
LOC	144	MUD CK RES	US	7,001	38000	1,000	*	7,027	53197	1,950	*	7,030	2000	2000
LOC	102	CHARLOTTE RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,013	14446	2000
LOC	105	W, ONEONTA RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,014	10744	2000
LOC	106	E, SIDNEY RES	EX	7,001	1700	1,000	*	7,034	25354	1,744	*	6,053	3886	1900
LOC	112	E, GUILFORD RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,013	48584	2000
LOC	1141	GREAT BEND RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,016	132864	50000
LOC	119	TRUXTON RES	US	7,001	27000	1,000	*	7,033	43544	1,613	*	3,030	2294	2000
LOC	122	WHITNEY PT RES	EX	7,001	5000	1,000	*	7,035	61557	1,694	*	7,060	4217	5000
LOC	116	S, PLYMOUTH RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,012	7905	2000
LOC	124	GENEGANTSLET RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,013	13157	3000
LOC	155	TOWANDA RES	US	7,001	0	1,000	*	7,001	0	1,000	*	7,012	28012	1000
LOC	163	STILLWATER RES	EX	7,001	343	1,000	*	7,021	6608	1,537	*	7,060	400	400

EXAMPLE RESERVOIR SUMMARY
FLOODS 1-7
FIGURE 7

EXPECTED ANNUAL FLOOD DAMAGE SUMMARY
CONTROL POINT NUMBER 180

BASE CONDITION FREQUENCY-FLOW-DAMAGE DATA
DMGE

FREQ	PEAK	SUM	DMGE 1
.999	108000	96.000	96.000
.900	120000	141.000	141.000
.680	132000	185.000	185.000
.480	145000	232.000	232.000
.330	158000	280.000	280.000
.230	172000	353.000	353.000
.160	186000	420.000	420.000
.100	201000	780.000	780.000
.070	216000	1139.000	1139.000
.042	234000	1829.000	1829.000
.027	250000	2781.000	2781.000
.015	270000	6314.000	6314.000
.012	290000	8215.000	8215.000
.008	314000	11392.000	11392.000
.005	340000	13929.000	13929.000
.004	360000	16466.000	16466.000
.003	387000	18767.000	18767.000
.003	412000	21071.000	21071.000
.002	440000	22604.000	22604.000

AVERAGE ANNUAL DAMAGES BY TYPE
-0.00

EXISTING SYSTEM AVERAGE ANNUAL DAMAGES BY TYPE
338.49

BASE CONDITION FLOOD DAMAGES
TYPE

NO.	FLOW	PROB INT	SUM	TYPE 1
1	101911	.275	17.87	17.87
2	152867	.551	127.90	127.90
3	203823	.167	125.79	125.79
4	254778	.040	130.10	130.10
5	305734	.010	91.45	91.45
6	407645	.006	116.86	116.86
7	509556	.001	21.33	21.33
		DAMAGES	631.30	631.30
EXST SYST DAMAGES			338.49	338.49

EXAMPLE AVERAGE ANNUAL DAMAGE
EXISTING SYSTEM
FIGURE 8

MODIFIED CONDITIONS FLOOD DAMAGES

NO.	FLOW	PROB INT	SUM	TYPE 1
1	90060	.275	7.02	7.02
2	131400	.551	89.56	89.56
3	172776	.167	52.94	52.94
4	215526	.040	40.47	40.47
5	257572	.010	36.57	36.57
6	342890	.006	80.83	80.83
7	428394	.001	17.74	17.74
		DAMAGES	325.13	325.13
	DAMAGE REDUCTION		13.36	13.36

UNCONTROLLED LOCAL FLOW FLOOD DAMAGES

NO.	FLOW	PROB INT	SUM	TYPE 1
1	85276	.275	2.63	2.63
2	127914	.551	83.30	83.30
3	170552	.167	51.27	51.27
4	213190	.040	38.46	38.46
5	255828	.010	33.84	33.84
6	341104	.006	79.55	79.55
7	426380	.001	17.65	17.65
		DAMAGES	306.70	306.70
	DAMAGE REDUCTION		31.79	31.79
	CORRECTION FACTOR			.89

EXAMPLE AVERAGE ANNUAL DAMAGES
EXISTING SYSTEM PLUS
TWO PROPOSED RESERVOIRS

FIGURE 9

SUMMARY OF SYSTEM'S EXPECTED ANNUAL FLOOD DAMAGES

	DAMAGES			DAMAGE REDUCTION		
CONTROL POINT	BASE (EXIST) CONDITION	MODIFIED CONDITIONS	UNCONTROL LOCAL COND	MODIFIED CONDITIONS	UNCONTROL LOCAL COND	RESIDUAL
145	236.17	189.59	169.23	46.58	66.94	20.36
147	75.02	69.66	66.33	5.36	8.69	3.34
149	99.09	84.44	83.12	14.65	15.97	1.32
151	58.02	56.25	51.60	1.77	6.42	4.65
121	20.89	7.04	6.81	13.85	14.08	.24
1232	61.83	62.15	50.58	-.32	11.25	11.56
125	87.14	84.52	74.23	2.62	12.91	10.29
127	305.64	304.70	263.46	.94	42.18	41.24
131	91.96	93.96	84.94	-2.00	7.02	9.02
154	234.09	223.32	203.99	10.77	30.10	19.34
173	3421.06	3300.77	3231.41	120.29	189.65	69.35
180	338.49	325.13	306.70	13.36	31.79	18.43
TOTAL	5029.40	4801.54	4592.40	227.86	437.00	209.14

EXAMPLE

FIGURE 10

SUMMARY OF SYSTEM COSTS

CONTROL POINT	PROJECT TYPE	CAPITAL COST	ANNUAL O,M,&R COST	TOTAL ANNUAL COST
144	RESERVOIR	17400,00	69,95	1267,07
119	RESERVOIR	11900,00	69,97	888,69
145		0,00	-0,00	0,00
147		0,00	-0,00	0,00
149		0,00	-0,00	0,00
151		0,00	-0,00	0,00
121		0,00	-0,00	0,00
1232		0,00	-0,00	0,00
125		0,00	-0,00	0,00
127		0,00	-0,00	0,00
131		0,00	-0,00	0,00
154		0,00	-0,00	0,00
173		0,00	-0,00	0,00
180		0,00	-0,00	0,00

EXAMPLE CAPITAL COSTS

FIGURE 11

SYSTEM ECONOMIC COST AND PERFORMANCE SUMMARY
(EXCLUSIVE OF EXISTING SYSTEM COSTS)

TOTAL SYSTEM CAPITAL COST * * * * * * *	29300.00	
TOTAL SYSTEM ANNUAL OPERATING MAINTENANCE, AND REPAIR COST * * * *	139.92	
TOTAL SYSTEM ANNUAL COST * * * * * * *		2155.76
AVERAGE ANNUAL DAMAGES - EXISTING SYSTEM	5029.40	
AVERAGE ANNUAL DAMAGES - PROPOSED SYSTEM	4801.54	
AVERAGE ANNUAL DAMAGE REDUCTION		227.86
AVERAGE ANNUAL SYSTEM NET DAMAGE REDUCTION BENEFITS		-1927.90

EXAMPLE NET BENEFITS

FIGURE 12

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TP-1 Use of Interrelated Records to Simulate Streamflow
TP-2 Optimization Techniques for Hydrologic Engineering
TP-3 Methods of Determination of Safe Yield and Compensation Water from Storage Reservoirs
TP-4 Functional Evaluation of a Water Resources System
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TP-42 Optimal Sizing of Urban Flood Control Systems
TP-43 Hydrologic and Economic Simulation of Flood Control Aspects of Water Resources Systems
TP-44 Sizing Flood Control Reservoir Systems by System Analysis
TP-45 Techniques for Real-Time Operation of Flood Control Reservoirs in the Merrimack River Basin
TP-46 Spatial Data Analysis of Nonstructural Measures
TP-47 Comprehensive Flood Plain Studies Using Spatial Data Management Techniques
TP-48 Direct Runoff Hydrograph Parameters Versus Urbanization
TP-49 Experience of HEC in Disseminating Information on Hydrological Models
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TP-51 Design of Flood Control Improvements by Systems Analysis: A Case Study
TP-52 Potential Use of Digital Computer Ground Water Models
TP-53 Development of Generalized Free Surface Flow Models Using Finite Element Techniques
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TP-55 The Development and Servicing of Spatial Data Management Techniques in the Corps of Engineers
TP-56 Experiences of the Hydrologic Engineering Center in Maintaining Widely Used Hydrologic and Water Resource Computer Models
TP-57 Flood Damage Assessments Using Spatial Data Management Techniques
TP-58 A Model for Evaluating Runoff-Quality in Metropolitan Master Planning
TP-59 Testing of Several Runoff Models on an Urban Watershed
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TP-62 Flood Hydrograph and Peak Flow Frequency Analysis
TP-63 HEC Contribution to Reservoir System Operation
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TP-65 Feasibility Analysis in Small Hydropower Planning
TP-66 Reservoir Storage Determination by Computer Simulation of Flood Control and Conservation Systems
TP-67 Hydrologic Land Use Classification Using LANDSAT
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