GENERALIZED COMPUTER PROGRAM

STREAMFLOW ROUTING OPTIMIZATION (OPROUT)

USERS MANUAL

JANUARY 1982

HEC HYDROLOGIC ENGINEERING CENTER

Water Resources Support Center U.S. Army Corps of Engineers

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DRAFT
STREAMFLOW ROUTING OPTIMIZATION
(OPROUT)

January 1982

The Hydrologic Engineering Center
U.S. Army Corps of Engineers
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Davis, California 95616


STREAMFLOW ROUTING OPTIMIZATION
(OPROUT)

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INTRODUCTION

1. ORIGIN OF PROGRAM

The computer program "Streamflow Routing Optimization" (OPROUT) was developed at the Hydrologic Engineering Center (HEC) by Vernon R. Bonner. The program consists of optimization routines developed originally by Dr. Anthony Slocum and Ramesk Danekar of Anderson-Nichols & Company, Inc., as a portion of HEC contract, "Evaluation of Streamflow Routing Techniques with Special Emphasis on Determining Nonlinear Routing Criteria," October 1975, (Contract No. DACW05-75-C-0027). These routines were linked with routing and plotting routines from the computer program HEC-5, "Simulation of Flood Control and Conservation Systems," into one program, OROUT, which this manual describes.

2. PURPOSE OF PROGRAM

This program can be used to determine Modified Puls or Muskingum routing criteria by optimizing parameters for a single reach using observed upstream and downstream hydrographs for one to five events. The main advantage to the program is that the user can develop routing criteria from several events by making one computer program execution.
3. TECHNICAL APPROACH

a. Modified Puls Routing Method. In this routing method, outflow is a unique function of storage. The following relationships apply:

\[
\frac{\Delta S}{\Delta t} = I - O \quad (1)
\]

where

I = average inflow in the reach during time interval \(\Delta t\)
O = average outflow from the reach during time interval \(\Delta t\)
\(\Delta S\) = change in storage during time interval \(\Delta t\)

\[
O = \frac{O_1 - O_2}{2} \quad (2)
\]

where \(O_1\) and \(O_2\) = reach outflow at start and end of time interval, respectively

\[
\Delta S = \frac{S_2 - S_1}{2} \quad (3)
\]

where \(S_1\) and \(S_2\) = reach storage at start and end of time interval, respectively

substituting (2) and (3) in (1) and rearranging,

\[
\frac{S_2}{\Delta t} + \frac{O_2}{2} = \frac{S_1}{\Delta t} - \frac{O_1}{2} + I \quad (4)
\]

Let \(SI = S + \frac{O}{2}\) = storage indication and \(\Delta t = 1\) then,

\[
SI_2 = SI_1 + I - O_1 \quad (5)
\]

equation (5) can be solved using a storage indication-outflow (SI vs O) relationship and knowing reach inflow.
can be seen from the described relationships, modified Puls routing requires a storage-outflow relationship for the downstream end of the routing reach. The relation indicates the amount of flow occurring at the downstream end of the reach for a given amount of water stored in the reach between the upstream and downstream ends.

Starting with the given information, an observed hydrograph at the upstream end of the reach and an observed hydrograph at the downstream end of the reach, the problem is associated with defining the proper storage-outflow relationship. The proper relationship when used with modified Puls routing will generate a routed hydrograph (observed upstream hydrograph routed to the downstream end) which is the same as would occur in the real river reach. If there were zero local flows, the routed hydrograph would be equal to the observed downstream hydrograph. In reality there will be local flow entering the reach during at least part of the time period of the observed hydrographs. If this local flow was gaged (all local flow coming from a gaged tributary), the local flow could be subtracted from the downstream observed hydrograph. The result would provide the upstream routed hydrograph. Unfortunately, in the majority of cases, the local flow is ungaged and not known. In this situation, the observed upstream hydrograph can be routed to the downstream end and subtracted from the observed downstream hydrograph to generate the local flow hydrograph. If the routed hydrograph is reasonable, no negative local flows will be generated by this procedure (i.e., for all time periods, the routed hydrograph is always less than or equal to the downstream observed hydrograph). This fact is used to form the objective function for the optimization routine. It is stated:
Objective Function - Minimize the Sum of Negative Local Flow in a given routing reach by proper definition of the storage-outflow relationship and number of routing subreaches using Modified Puls with upstream and downstream observed hydrographs.

One form for the storage-outflow relationship is as follows:

\[ S = K O^M \]  

(6)

where

- \( S \) = total storage in the routing reach
- \( O \) = reach outflow
- \( K, M \) = are constants which cause the function to represent the storage-outflow relationship of the river reach under study

With this function a gradient search approach can be used to achieve the stated objective function. Computationally, a beginning \( K \) and \( M \) are selected from the observed hydrograph information (\( M = 1 \) and \( K \) equal travel time of peak flow). The number of subreaches is set to one. A modified Puls routing is performed based upon the selected \( S = K O^M \) function. The routed hydrograph is subtracted from the observed downstream hydrograph which determines the sum of the negative local flow. Either \( K \) or \( M \) is changed following a gradient search procedure and a new sum negative local flow is computed which can be compared to the last value. This procedure is continued until the objective function can no longer be improved. The number of routing subreaches is incremented by one and the gradient search procedure is continued. The result provides the optimum \( K, M \) and number of subreaches for the given routing reach with the given observed hydrograph. The selected exponent usually is in the
following range:

\[ 0.6 < M < 0.8 \]

and the number of subreaches usually equals 2.

A curve warping routine was written to overcome the computational difficulty and the inflexibility of using only \( S = KOM^M \) to represent storage-outflow. This routine is very simple and surprisingly effective.

The optimization routine still begins with a macro gradient search \( S = KOM^M \) to obtain a beginning storage-outflow function which is reasonable. Then the curve warping routine is called. The computed storage-outflow relationship is divided into 17 piece-wise linear segments (this is also used in other HEC programs using modified Puls). This forms a table of storage versus outflow for equally spaced flow segments starting at zero and ending at the peak flow of the observed downstream hydrograph. The number of segments can be input by the user up to a maximum of 18 segments.

The curve warping routine works in the following manner. One cycle consists of testing each point in the storage-outflow table beginning with the lowest point above zero. The flow is held constant and the storage is stepped up, down or not changed depending if the objective function is improved. Storage is never stepped greater than the value for the next higher point in the table or less than the next lower point in the table to keep the function single valued. If an improvement was made during the last cycle, a new cycle is performed. This is continued until no more improvement can be obtained. The step size is reduced and the process is repeated. When no more improvement can be be made, the number of subreaches is incremented by one and the curve warp routine is recalled. The final result provides the optimum number of subreaches and the storage-outflow function. The several additional degrees of freedom in this function enable a solution which works well for all magnitudes of flood events within those used to derive the storage-outflow relationship.
The program also employs an optional curve fit routine for smoothing the developed storage-outflow function after the curve warping routine. The program also incorporates several other components of the objective function described previously to improve the reasonableness of the local flow hydrograph and to force the routed hydrograph toward the recession side of the given, observed downstream hydrograph. The total routing objective function is defined as follows:

\[
\text{MINIMIZE } \text{SUMNL} = \text{SUM} (\text{SUM1} + \text{SUM2} + \text{SUM3}) \tag{7}
\]

where the three components are defined as,

1) For all time periods,

\[
\text{SUM1} = \text{SUM} (\text{negative local flows}) \times \text{WT1}
\]

2) For the recession limb of the routed hydrograph defined as from 85% of the routed hydrograph peak discharge to 15% of the observed downstream hydrograph peak discharge, and where the routed flow is less than 95% of the observed downstream flow (indicating how early this portion of the routed hydrograph is),

\[
\text{SUM2} = \text{SUM} (\text{routed hydrograph minus observed downstream hydrograph}) \times \text{WT2}
\]

and

3) For all time periods following the peak discharge of the routed hydrograph (indicating how late this portion of the routed hydrograph is),

\[
\text{SUM3} = \text{SUM} (\text{negative local flows}) \times \text{WT3}
\]

Weighting of the individual components of the objective function (WT1, WT2 and WT3) can be input by the user on the .IT card as described in Exhibit 2, Input Description. One or both of the second (SUM2) and the third (SUM3) can be eliminated by default values of zero for WT2 and/or WT3 thereby changing the basis of the objective function. The program output lists the value (error)
of each of the three components and the total (SUM1, SUM2, SUM3 and SUMNL) for each iteration as NEG LOCAL, TOO EARLY, TOO LATE and TOTAL, respectively.

b. Muskingum Routing Method. In this method, outflow from a routing reach is a linear function of the sum of prism and wedge storage in the reach. The basic routing equation is:

\[ O_n = C_1 I_n + C_2 I_{n-1} + C_3 I_{n-2} \ldots \]  

where:

- \( O_n \) = Ordinate of outflow hydrograph at time \( n \)
- \( I_n, I_{n-1}, \ldots \) = Ordinates of inflow hydrograph at times \( n, n-1, \ldots \)
- \( C_1, C_2, \ldots \) = Routing coefficients, as coefficients of inflow

Equations used to determine the coefficients \( C_1, C_2, \ldots \) are as follows:

\[ C_1 = \frac{(\Delta t - 2XK)}{(2K(1-X) + \Delta t)} \]  

\[ CC = \frac{(2K(1-X) + \Delta t) - 2\Delta t}{(2K(1-X) + \Delta t)} \]  

\[ C_2 = C_1 \cdot CC + \frac{(\Delta t + 2KX)}{(2K(1-X) + \Delta t)} \]  

\[ C_i = C_{i-1} \cdot CC \text{ for } i > 2 \]  

where

- \( \Delta t \) = Routing time increment
- \( K = \) Muskingum routing parameter having units of time
- \( X = \) Muskingum dimensionless routing parameter between 0 and .5

The program has the capability of optimizing Muskingum routing coefficients using the same techniques and search procedures as described for the modified Puls method. The \( M \) in equation (6) is equal to 1 for the linear Muskingum method and the same objective function is used to optimize Muskingum routing constants and \( K \) and \( X \).
From the above relationships it can be seen that the following relationship between \( K \) for each subreach and \( \Delta t \) must be true to avoid negative coefficients.

\[
\frac{1}{2(1-X)} \leq \frac{K}{\Delta t} \leq \frac{1}{2X}
\]

If a Muskingum routing optimization produces negative coefficients, the user should increase the number of subreaches, thereby reducing \( K \), so that the above limits are met. The method for defining the number of subreaches (RT.3, 3rd field of the RT Card) is described under paragraph 4, Program Capabilities and illustrated in Exhibit 1.
4. PROGRAM CAPABILITIES

The program will provide solutions to the following problems:

a. Determine Muskingum K and X and the number of routing subreaches for a single reach with up to five sets of given upstream and downstream observed hydrographs. Each hydrograph set is given equal weight in the optimization objective function.

b. Determine Modified Puls storage-outflow relationship and number of routing subreaches for a given reach with up to five multiple sets of given upstream and downstream observed hydrographs.

c. Determine routing criteria for a given number of subreaches in either cases a or b above.

d. Determine the storage-outflow curve, as in case b above, with a given coefficient X (Working R&D routing) or an additional lag of the routed hydrograph.

Under any of the above options, a complete trace feature is available to monitor the progress of the optimization computations. This feature is written in the same manner as exists in HEC-5; therefore, a source listing is required to interpret results.

The program can be used to solve the more difficult problem when two or more upstream gages and routing reaches flow to a common downstream gage. This currently cannot be solved automatically by the program; however, the user can develop routing criteria for this situation by multiple executions of the current program. In most cases, one upstream gage will have the dominant flow. The optimization routine can be operated using the dominant upstream gage as the observed upstream hydrograph and the given observed downstream hydrograph. The resulting local flow hydrograph which is computed by the Optimization Routine can be used as the observed downstream hydrograph in conjunction with the next largest upstream gage flow which becomes the observed upstream hydrograph.
This process is repeated until routing criteria is defined for all routing reaches. In most cases, some user smoothing of the local flow hydrographs will be required (while maintaining consistent volume) and a second iteration will be required beginning with the dominant upstream gage. The problem is difficult to solve due to the many additional degrees of freedom. For each additional routing reach, two basic unknowns are added, routing criteria and local flow; whereas, only one known is added, upstream observed hydrograph.

During the performance of the optimization routine, a printer plot can be requested (5th field of J1 card) which will plot the upstream observed hydrograph (values entered on IN cards), downstream observed hydrograph (values entered on IN cards), routed hydrograph (upstream hydrograph routed to downstream location using routing criteria derived by optimization routine) and the computed local flow hydrograph (difference between routed hydrograph and downstream observed hydrograph). This provides a visual check on the results developed by the optimization subroutine.

In addition, upon completion, the optimization routine prints the values for the adopted storage-outflow relationship (table of storage versus flow) and the optimum number of subreaches. The travel time indicator (inverse slope of storage-outflow relationship) is also printed for each incremental linear segment of the storage-outflow table and for the given point to the origin. The upstream hydrograph is printed as read in addition to the routed hydrograph. Incremental local flows are printed twice for each control point. The first is the computed values without adjustment and the second is the adjusted values with all computed negative values set to zero. The negative volume is proportioned to the remaining positive values. Program capabilities are illustrated in Exhibit 1 - Example Input and Output. A detailed description of the program input is presented in Exhibit 2.
EXHIBIT 1

EXAMPLE INPUT AND OUTPUT
EXHIBIT 1

EXAMPLE INPUT AND OUTPUT

Streamflow Routing Optimization (OPROUT)

The input and output for three examples are provided to illustrate the use of selected program capabilities and options and to assist in verifying the correct execution of the program. A brief description of each example is provided below. Printer plots are requested for each of the examples.

a. Example 1 - To determine modified Puls storage-outflow relationship and the number of routing subreaches for a single reach and from a single flood event.

b. Example 2 - To determine modified Puls storage-outflow relationship and the number of routing subreaches using three flood events. (J1.7)

c. Example 3 - To determine Muskingum K and X for one flood event and a user specified number of routing subreaches. (RT.3)
## Example 1 Input

### Example 1 Modified Puls Routing Optimization

**T2** SCIO TO CHILLICOTHE TO HIGBY OHIO

**T3** SINGLE EVENT - JANUARY 1959

| J1   | 100 | 1 | 0 | 0 | 0 | 1 | 1 |

| ID CHILLICOTHE TO HIGBY - JAN 1959 |

| RT | 2   | .5 | 0 | 0 | 6 | 3 | 3 | 0 |

| IN  | 2   | JAN59 |

| QO  | 3160 | 3093 | 3025 | 2940 | 3020 | 3207 | 3800 | 4660 | 5650 | 7203 |
| QO  | 8395 | 9653 | 11400| 13300| 15200| 17075| 18600| 20150| 21700| 23575|
| QO  | 25800| 31250| 42800| 64650| 99900| 126000| 140000| 143000| 138000| 130500|
| QO  | 120500| 110500| 103000| 94300| 85500| 76950| 69000| 63100| 57200| 52350|
| QO  | 47500| 43950| 40400| 37300| 34200| 31750| 29300| 27550| 25800| 24450|
| QO  | 23100| 22000| 20900| 19950| 19000| 18300| 17600| 17150| 16700| 16500|
| QO  | 16300| 16225| 16150| 16075| 16000| 15900| 15800| 15650| 15500| 15300|
| QO  | 15100| 14800| 14500| 14125| 13750| 13375| 13000| 12725| 12450| 12175|
| QO  | 11900| 11600| 11300| 11000| 10750| 10500| 10250| 10000| 9750 | 9500 |
| QO  | 9250 | 9000 | 8750 | 8500 | 8250 | 8000 | 7750 | 7500 | 7250 | 7000 |

| IN  | 3   | JAN59 |

| QO  | 4580 | 4449 | 4317 | 4277 | 4420 | 5850 | 7635 | 9595 | 11800| 14500|
| QO  | 17750| 21450| 25200| 28125| 31550| 35000| 37900| 39580| 41450| 42975|
| QO  | 44700| 47050| 49400| 53300| 59400| 74850| 97350| 121000| 143000| 156500|
| QO  | 160000| 157000| 149000| 138000| 127000| 115000| 103000| 93200| 83400| 76850|
| QO  | 70300| 64950| 59600| 55550| 51500| 47750| 44000| 40750| 37500| 34950|
| QO  | 32400| 29850| 27300| 26000| 24700| 23400| 22100| 21300| 20500| 20000|
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| QO  | 15700| 13100| 13100| 13100| 13100| 13100| 13100| 13100| 13100| 13100|
| QO  | 11200| 11200| 11200| 11200| 11200| 11200| 11200| 8600 | 8600 | 8600 |
### Example 1 Modified Puls Routing Optimization

**T2 Scioto River Chillicothe to Higby, Ohio**

**T3 Single Event - January 1959**

#### Exhibit 1 Example 1 Output

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**Exhibit 2 of 10**
## Optimisation Routine Output

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### STORAGE-OUTFLOW FUNCTION, SMOOTHED

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**SMOOTHED BY 4TH ORDER POLYNOMIAL AS FOLLOWS:**

\[
s = -2.355E+03 \, Q^0 + 9.422E+00 \, Q^1 + 1.643E+05 \, Q^2 + 2.123E-10 \, Q^3 + 6.723E-16 \, Q^4
\]

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**Optimum Number of Subreaches**: 1

**Upstream Hydrograph Routed Downstream**

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**Sum = 2989206.**

**Routed Q from M= 2 to 3**

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**Sum = 2972298.**
## INC LOCAL FLOWS COMPUTED

### COMPUTED LOCAL FLOW

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|               | 15200. 17075. 18600. 20150. 21700. 23575. 25800. |
|               | 31250. 42800. 64650. 99900. 126000. 140000. 143000. |
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|               | 9000. 8750. 8500. 8250. 8000. 7750. 7500. |
|               | 7250. 7000. |

### LOCAL FLOW ADJUSTED FOR NEGATIVE VALUES

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**Example 2**

**Exhibit 1**

**Example 2**

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Example 2
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STORAGE-OUTFLOW FUNCTION, UNSMOOTHED

SUM OF COMPUTED ERRORS = -715540.5

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STORAGE-OUTFLOW FUNCTION, SMOOTHED

COMPUTED ERRORS:

NEG LOCAL | TOO EARLY | TOO LATE | TOTAL
-----------|-----------|----------|--------
-68477.12  -832049.77  -34238.56  -934765.45

SMOOTHED BY 4TH ORDER POLYNOMIAL AS FOLLOWS:

\[
S = -.1265E+04 Q^0 + .1061E+01 Q^1 + -.8053E-05 Q^2 + .1323E-09 Q^3 + -.3000E-15 Q^4
\]

ADOPTED STORAGE-OUTFLOW TABLE

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**Optimum Number of Subreaches = 1**

**Upstream Hydrograph Routed Downstream**

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**Sum = 2541213.**

**Routed Q from Mx= 2 to 3**

| RTED | 1.30 | RTCDP | 0. | M= 0. |

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**Sum = 2484104.**
PLOTTED POINTS (BY PRIORITY) - R = INFLOW AT MX ROUTED TO MY, N = OBS OR NAT AT MY, L = LOCAL (INC) AT MY, I = INFLOW AT MX

UPSTREAM (MX) = 2
DOWNSTREAM (MY) = 3

CHILlicothe TO HigBY - 3 EVENTS

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**Sum = 2989206.**

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**Sum = 2972963.**
### PLOTTED POINTS (BY PRIORITY)
- R = INFLOW AT MX ROUTED TO MY, N = OBS OR NAT AT MY, L = LOCAL (INC) AT MY, I = INFLOW AT MX

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#### Downstream (MY) = 3

**Chillicothe to Higby - 3 Events**

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**Example 2**

Exhibit 1

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**SUM= 490964. ** **-SUM= -892. ** **-MAX= -356.**
COMPUTED LOCAL FLOW

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LOCAL FLOW ADJUSTED FOR NEGATIVE VALUES

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SUM= 2989206, -SUM= 0, -MAX= 0.
### COMPUTED LOCAL FLOW

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### LOCAL FLOW ADJUSTED FOR NEGATIVE VALUES

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| M= 3 | 907. | 1095. | 1114. | 1299. | 1365. | 1523. | 1710. |
| M= 3 | 1887. | 2013. | 1718. | 1892. | 2053. | 2211. | 2373. |
| M= 3 | 2543. | 2733. | 2949. | 627. | 903. | 1202. | 1519. |
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| M= 3 | 1284. | 1534. | 1784. | 2034. | 2282. | 2530. | 211. |
| M= 3 | 459. | 706. | | | | | |

**Sum= 810477.**  
**-Sum= -10521.**  
**Max= -2451.**
### Example 3 Input

**Example 3**

**Muskingum Routing Optimization User Specified No. of Subreaches**

**T2** SCIOTO RIVER  CHILLICOHE TO HIGBY OHIO

**T3** SINGLE EVENT - JANUARY 1959

| J1  | 100 | 3 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |

**ID CHILLICOHE TO HIGBY - JAN 1959**

| RT  | 2   | 3 | 3.6 | 0 | 0 | 6 | 3 | 3 | 3 | 0 |

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### Example 3

#### Muskingum Routing Optimization User Specified No. of Subreaches

- **T2: Scioto River Chillicothe to Higby Ohio**
- **T3: Single Event - January 1959**

#### Exhibit 1

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### Chillicothe to Higby - Jan 1959

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**Example 3 Output**
### Optimization Routine Output

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**MUSKINGUM Optimization Completed**

**MUSKINGUM K (Hours Per Subreach) = 3.70**

**MUSKINGUM X = .15**

**Number of Routing Subreaches = 3**
UPSTREAM HYDROGRAPH ROUTED DOWNSTREAM

| N= 2 | 3160. | 3093. | 3025. | 2940. | 3020. | 3207. | 3800. |
| 4660. | 5650. | 7203. | 8395. | 9653. | 11400. | 13300. |
| 15200. | 17075. | 18600. | 20150. | 21700. | 23575. | 25800. |
| 31250. | 42800. | 64650. | 99900. | 126000. | 140000. | 143000. |
| 138000. | 130500. | 120500. | 110500. | 103000. | 94300. | 85500. |
| 76950. | 69000. | 63100. | 57200. | 52350. | 47500. | 43950. |
| 40400. | 37300. | 34200. | 31750. | 29300. | 27550. | 25800. |
| 24450. | 23100. | 22000. | 20900. | 19950. | 19000. | 18300. |
| 17600. | 17150. | 16700. | 16500. | 16300. | 16225. | 16150. |
| 15075. | 16000. | 15900. | 15800. | 15650. | 15500. | 15300. |
| 15100. | 14800. | 14500. | 14125. | 13750. | 13375. | 13000. |
| 12725. | 12450. | 12175. | 11900. | 11600. | 11300. | 11000. |
| 10750. | 10500. | 10250. | 10000. | 9750. | 9500. | 9250. |
| 9000. | 8750. | 8500. | 8250. | 8000. | 7750. | 7500. |

**SUM= 298926k.**

**ROUTED Q FROM N= 2 TO 3**

| RTMD= | 3.15 | BTODF= | 0.45 | R= 0.45 | 
| COEF= | 0.00842 | 0.06388 | 0.18416 | 0.25859 | 0.20828 | 0.13217 | 0.07354 | 0.03765 | 0.01816 | 0.00820 |
| M= 2 | 0.00334 | 0.00127 | 0.00046 | 0.00000 |

| 3160. | 3159. | 3155. | 3137. | 3103. | 3062. | 3049. |
| 3117. | 3336. | 3764. | 4427. | 5327. | 6414. | 7625. |
| 8981. | 10512. | 12190. | 13942. | 15683. | 17366. | 19018. |
| 20744. | 22855. | 26184. | 32353. | 43514. | 60853. | 82315. |
| 103143. | 119199. | 128542. | 131387. | 125252. | 123577. | 115307. |
| 108337. | 100016. | 91582. | 83334. | 75617. | 68623. | 62344. |
| 56737. | 51767. | 47389. | 43491. | 39981. | 36814. | 33901. |
| 31479. | 29299. | 27402. | 25749. | 24292. | 22995. | 21825. |
| 20765. | 19814. | 18977. | 18258. | 17662. | 17187. | 16829. |
| 16569. | 16387. | 16255. | 16150. | 16055. | 15957. | 15848. |
| 15721. | 15572. | 15397. | 15189. | 14941. | 14654. | 14332. |
| 13986. | 13633. | 13290. | 12970. | 12669. | 12378. | 12090. |
| 11799. | 11508. | 11224. | 10951. | 10688. | 10431. | 10178. |
| 9926. | 9676. | 9425. | 9175. | 8925. | 8675. | 9425. |
| 8175. | 7925. | 7675. | 7425. | 7175. | 6925. | 6675. |

**SUM= 2973350.**
PLOTTED POINTS (BY PRIORITY) - R = INFLOW AT MX ROUTED TO MY, N=OBS OR NAT AT MY, L=LOCAL (INC) AT MY, I=INFLOW AT MX

UPSTREAM (MX) = 2 DOWNSTREAM (MY) = 3

CHILlicothe to Highy - Jan 1959

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Exhibit 1
Example 3
6 of 9
INC LOCAL FLOWS COMPUTED

**COMPUTED LOCAL FLOW**

| M= 2 | 3160, 3093, 3025, 2940, 3020, 3207, 3800, 4660, 5650, 7203, 8395, 9653, 11400, 13300, 15200, 17075, 18600, 20150, 21700, 23575, 25800, 31250, 42800, 64650, 99900, 126000, 140000, 143000, 130000, 130500, 120500, 110500, 103000, 94300, 85500, 76950, 69000, 63100, 57200, 52350, 47500, 43950, 40400, 37300, 34200, 31750, 29300, 27550, 258000, 24450, 23100, 22000, 20900, 19950, 19000, 18300, 17600, 17150, 16700, 16500, 16300, 16225, 16150, 16075, 16000, 15900, 15800, 15650, 15500, 15300, 15100, 14800, 14500, 14125, 13750, 13375, 13000, 12725, 12450, 12175, 11900, 11600, 11300, 11000, 10750, 10500, 10250, 10000, 9750, 9500, 9250, 9000, 8750, 8500, 8250, 8000, 7750, 7500, 7250, 7000. |

**LOCAL FLOW ADJUSTED FOR NEGATIVE VALUES**

| M= 2 | 3160, 3093, 3025, 2940, 3020, 3207, 3800, 4660, 5650, 7203, 8395, 9653, 11400, 13300, 15200, 17075, 18600, 20150, 21700, 23575, 25800, 31250, 42800, 64650, 99900, 126000, 140000, 143000, 130000, 130500, 120500, 110500, 103000, 94300, 85500, 76950, 69000, 63100, 57200, 52350, 47500, 43950, 40400, 37300, 34200, 31750, 29300, 27550, 25800, 24450, 23100, 22000, 20900, 19950, 19000, 18300, 17600, 17150, 16700, 16500, 16300, 16225, 16150, 16075, 16000, 15900, 15800, 15650, 15500, 15300, 15100, 14800, 14500, 14125, 13750, 13375, 13000, 12725, 12450, 12175, 11900, 11600, 11300, 11000, 10750, 10500, 10250, 10000, 9750, 9500, 9250, 9000, 8750, 8500, 8250, 8000, 7750, 7500, 7250, 7000. |

\[ \text{SUM} = 2989206, \quad \text{MIN} = 0, \quad \text{MAX} = 0. \]
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<th>1120</th>
<th>1290</th>
<th>1162</th>
<th>1140</th>
<th>1317</th>
<th>2788</th>
<th>4586</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6478</td>
<td>8464</td>
<td>10736</td>
<td>13323</td>
<td>16123</td>
<td>18786</td>
<td>20500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22569</td>
<td>24488</td>
<td>25710</td>
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<td>25767</td>
<td>25609</td>
<td>25682</td>
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</tr>
<tr>
<td></td>
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<td>27047</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>39587</td>
<td>37301</td>
<td>31459</td>
<td>25613</td>
<td>19847</td>
<td>14423</td>
<td>10693</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6663</td>
<td>2984</td>
<td>1618</td>
<td>66</td>
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<td>1577</td>
<td>2606</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2863</td>
<td>3763</td>
<td>4111</td>
<td>4259</td>
<td>4019</td>
<td>3936</td>
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<td></td>
</tr>
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<td></td>
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<td>3101</td>
<td>2448</td>
<td>1551</td>
<td>1708</td>
<td>1705</td>
<td>1575</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>1406</td>
<td>1523</td>
<td>1742</td>
<td>1838</td>
<td>2013</td>
<td>2196</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2343</td>
<td>2413</td>
<td>2045</td>
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<td>2343</td>
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<td>759</td>
<td>1046</td>
<td>1369</td>
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<td>2730</td>
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<td>722</td>
<td>1010</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1301</td>
<td>1592</td>
<td>1876</td>
<td>2149</td>
<td>2412</td>
<td>769</td>
<td>1022</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1274</td>
<td>1524</td>
<td>1775</td>
<td>2025</td>
<td>2275</td>
<td>2525</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td></td>
<td>425</td>
<td>675</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Sum= 810090. -Sum= 0. -Max= 0.**
EXHIBIT 2

INPUT DESCRIPTION

Streamflow Routing Optimization (OPROUT)

To determine the optimization routing criteria using modified Puls or Muskingum routing methods for a single reach, at least one set of observed hydrographs are required for the upstream and downstream ends of the reach. A maximum of five sets of observed hydrographs can be used to develop the routing criteria. The observed upstream hydrograph must be input ahead of the downstream hydrograph for each event. There is a date variable on the input cards so that the starting date of each flood can be input with the flow data.

If several floods are used to develop the routing criteria, all the flow data must have the same number of periods. This means shorter events must be extended with base flow values up to the number of periods of the longest event. The added data should be included at the end of the actual flood and the upstream values generally should be less than the downstream values.

The following INPUT DESCRIPTION provides a detailed description of data input. Input format is the standard HEC ten fields of 8 columns each with the first two card columns reserved for the card identification. Card ID is not read by the program. Three title cards are used to provide labeling information. The job card defines job options using integers (no decimal points). The identification card provides a label for plots, and the routing card provides the routing optimization information. The remaining cards contain the flow data (upstream then downstream hydrograph).
INPUT DESCRIPTION

Streamflow Routing Optimization Program (OPROUT)

T1, T2, T3 Cards - Title Cards

Job title cards; three cards required. Both alphabetic and numeric information may be placed on these cards. Information on these cards will be printed out as job title on the first page of output.

J1 Card - Job Card - all integers

<table>
<thead>
<tr>
<th>Field</th>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NPER</td>
<td>+</td>
<td>Number of values on each set of flow data cards (IN). Each set of flow data must have NPER Values (300 maximum).</td>
</tr>
<tr>
<td>2</td>
<td>IPER</td>
<td>+</td>
<td>Time interval (Δt) in hours between flow values.</td>
</tr>
<tr>
<td>3</td>
<td>INPUT</td>
<td>0</td>
<td>First input card for each flow set will have control point number in field 1 and date in field 2 and no other data. Subsequent cards contain 10 fields of flow data.</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>Flow data will be in default HEC-5 format. First two fields of first card are for control point and date with flow data on the remaining 8 fields. Subsequent cards contain 10 fields of flow data.</td>
</tr>
<tr>
<td>Field</td>
<td>Variable</td>
<td>Value</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>----------</td>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>4</td>
<td>IPRNT</td>
<td>0</td>
<td>Output will be limited to Input Data, Optimization Errors, and optimization results.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Same as above plus optimization trace.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>Same as above plus routing trace.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>Same as above plus detailed routing trace.</td>
</tr>
<tr>
<td>5</td>
<td>IPLOT</td>
<td>0</td>
<td>No hydrograph plot.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Plot hydrograph for Inflow (Routed Downstream), Observed flow downstream, Computed Local Flow, and Inflow Upstream.</td>
</tr>
<tr>
<td>6</td>
<td>IPUNCH</td>
<td>0</td>
<td>No punch cards.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Punch computed local flow data.</td>
</tr>
<tr>
<td>7</td>
<td>NFLOOD</td>
<td>0</td>
<td>One flood event will be used to optimize routing criteria.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ Number of flood events (5 maximum) requires upstream and downstream flow data for each event.</td>
</tr>
<tr>
<td>8</td>
<td>NPTSQ</td>
<td>0</td>
<td>Number of storage-outflow points to be derived from optimization routing is equal to 9.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+ Number of storage-outflow points to be derived (18 maximum). The more points used, the longer the optimization time.</td>
</tr>
<tr>
<td>9</td>
<td>ICURV</td>
<td>0</td>
<td>No adjustments will be made to the storage-outflow curve (UNSMOOTHED CURVE).</td>
</tr>
</tbody>
</table>
A fourth order polynomial curve should be fitted to the unsmoothed curve. The smooth curve will then be used for computing local flows.

<table>
<thead>
<tr>
<th>Field</th>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>IFLOW</td>
<td>0</td>
<td>Input flow data is average for the period.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>Input flow data is end of period data. Flow data will be averaged before routing.</td>
</tr>
</tbody>
</table>

Title (alphanumeric) of routing reach in columns 3-40. Title will be printed on hydrograph plots.

<table>
<thead>
<tr>
<th>Field</th>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>CPT(K)</td>
<td>+</td>
<td>Control point number of upstream end of routing reach.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Control point number of downstream end of routing reach.</td>
</tr>
<tr>
<td>6-10</td>
<td>Not used</td>
<td></td>
<td>Number of subreaches to the left of the decimal and routing method to the right of the decimal (.5 for modified Puls and .6 for Muskingum). If subreaches are not given, the number will be optimized.</td>
</tr>
</tbody>
</table>
**RT Card - Continued**

<table>
<thead>
<tr>
<th>Field</th>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
</table>
| 4     | RTCOF    | 0     | Muskingum routing coefficient "X" will be optimized if Muskingum optimization is requested (RT.3 = .6).  
                        + Coefficient X will not be optimized. The given value will be used for Muskingum or modified Puls. |
| 5     | XMUSK    | 0     | Travel time (Muskingum K) in hours will be optimized if Muskingum optimization is requested. |
| 6     | LAG      | 0     | No lag in addition to routing.  
                        + In addition to routing, lag outflow by the number of periods shown. |
| 7     | WT1      | 0     | Weighting of negative local flow equals one (1.0).  
                        + Weighting factor for negative local flow. Use any number. |
| 8     | WT2      | 0     | Weighting factor (penalty) for recession leg being too early equals zero (0).  
                        + Weighting factor for recession leg being too early. (Suggested value near 1.0.) |
| 9     | WT3      | 0     | Weighting factor of error on recession leg of hydrograph being too late equals zero (0).  
                        + Weighting factor for recession leg being too late. Use in conjunction with WT2. (Suggested value near 4.0.) |
| 10    | METRIC   | 0     | English units.  
                        + Metric units. |
IN Cards - Flow data for upstream and then downstream station.*

<table>
<thead>
<tr>
<th>Field</th>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MM</td>
<td>+</td>
<td>Control point number for input hydrograph. First hydrograph for the upstream location, and then the downstream location.</td>
</tr>
<tr>
<td>2</td>
<td>DATE</td>
<td>+</td>
<td>Starting date of flow data for identification only. Can be alphanumeric data.</td>
</tr>
<tr>
<td>3-10</td>
<td>QII</td>
<td>+</td>
<td>Flow data in cfs or m³/SEC if INPUT (J1.3) equals 5. Remaining data starts in field 1 of succeeding cards. (NPER values.)</td>
</tr>
<tr>
<td>or</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-10</td>
<td>QII</td>
<td>+</td>
<td>Flow data starts in field 1 of the second card if INPUT (J1.3) equals 0 (NPER values).</td>
</tr>
</tbody>
</table>

*Repeat IN cards for both control points. Two sets of flow data in turn for each flood up to the number of floods prescribed (NFLOOD on J1.7).
SUMMARY OF INPUT CARDS
STREAMFLOW ROUTING OPTIMIZATION PROGRAM (OPROUT)

* IN MM DATE QII QII ... 
RT RTFR RTTO RTMD RTCOF XMUSK LAG WT1 WT2 WT3 METRIC
ID Title of routing reach (cols 1-40)
J1 NPER IPER INPUT IPRNT IPLT IPUNCH NFLOOD NPTSQ ICURV IFLOW
T3
T2
T1 Output title information, three cards required

*Include IN cards for inflow then outflow of reach for each flood event.