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**Final Report**

# DEVELOPMENT OF A METHODOLOGY FOR INCORPORATING FESWMS-2DH RESULTS

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**University of Kansas**
**Lawrence, Kansas**

**May 2000**

## K-TRAN

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**16 Abstract**

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**Final Report**
**K-TRAN Research Project KU-97-4**

# Development of a Methodology for Incorporating FESWMS-2DH Results


**by**

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**and**
**Shimin Zou**

**Department of Civil and Environmental Engineering**
**University of Kansas**


**for**

**The Kansas Department of Transportation**

**May 2000**

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## Abstract

This study presents the analysis of a complex flow system that contains two roadways with multiple openings – US HW 75 and the Southeast Kansas Corridor. Typical analyses of floodplains at such sites involve the use of the one-dimensional backwater models HEC-2, HEC-RAS or WSPRO. Fairly broad assumptions are made concerning the division of flow for multiple opening bridges in applying these one-dimensional models. The analysis presented herein involves the application of the two-dimensional finite element model FESWMS-2DH (Finite Element Surface-Water Modeling System: Two-Dimensional Flow in a Horizontal Plane) to the site near Neodesha, Kansas. This model was used to determine analytically (numerically) the division of flow among conveyance structures at each of the roadways. The results of the study with regard to division of flow among the structures are compared to the one-dimensional results obtained by the USGS using the WSPRO model. The methodology used in formulating and applying the FESWMS-2DH model is also presented.



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# COMPARATIVE FLOW ANALYSIS FOR SITE NEAR NEODESHA, KANSAS

**by**

**A. David Parr and Shimin Zou**

## Introduction

The analysis of flow near highway embankments with multiple openings, such as a main bridge and one or more relief structures, poses a difficult problem for engineers. Traditional one-dimensional backwater programs such as HEC-2 or HEC-RAS require an unusually high degree of judgement as to the division of flow among the structures. The newer model WSPRO employs a quasi two-dimensional stream-tube analysis in the reach extending from the bridge upstream about one bridge opening. Everywhere else it uses a 1-dimensional analysis analogous to HEC-2 or HEC-RAS. Unfortunately, WSPRO's stream-tube module is not a truly two-dimensional representation of the flow. Consequently, interpretation of the results from WSPRO relative to flow distribution is not clear and may, in fact, not give any better results that HEC-2 or HEC-RAS regarding flow distribution. This creates a good deal of uncertainty in the determination of division of flow for the design and analysis of multiple opening highway crossings. A true two-dimensional model should give better results for the analysis of multiple opening bridges.

A two-dimensional finite element model FESWMS-2DH was developed by the Federal Highway Administration for analyzing backwater and flow distribution at width constrictions and highway crossings of rivers and flood plains. While this model should provide at better tool for analyzing flow near highway embankments with multiple openings than either HEC-2 or WSPRO, it has not enjoyed widespread use due to difficulty of use and to the very limited number of actual applications for field verification.

This project analyzes a multiple opening highway crossing near Neodesha, Kansas, using FESEMS-2DH. The region of interest is west of Neodesha and is shown in Figure 1. (Figure 2 shows the study region for the USGS WSPRO modeling project of this site.) The main channel is the Fall River that passes beneath US 75 through a rainbow-arch bridge on the west edge of Neodesha. It is labeled Bridge 3 on US 75 in Figure 1. The bridge has a total waterway area of 5,820 sq.ft. Two relief structures (Bridges 1 and 2) also allow the water to pass under US 75 between the intersection of US 75 and K-96. They are a 322-ft concrete bridge with 13 piers (Bridge 2 - total waterway area = 2,217 sq. ft.) and an 11-barrel 9’ x 9’ concrete box culvert (Bridge 1). Figure 3 shows the cross section and each of the openings as presented in USGS Open-File Report 97-13. Pictures of the drainage structures for US 75 are shown in Figure 2 of USGS Open-File Report 97-13. The three structures located on the Southeast Kansas Corridor (SKC) are also modeled herein. The SKC relief structures are Bridge 1 and Bridge 2 and the SKC main-channel bridge is Bridge 3 as shown in Figure 1. Bridge 3 on SKC is approximately one mile upstream from (along the main channel) Bridge 3 on US 75. The SKC drainage structures are described as

- Bridge 1 5-barrel 12’ x 9’ x 128’ RCB,
- Bridge 2 290.5-ft bridge with a 2,595 sq. ft. total waterway,
- Bridge 3 303.5-ft bridge with a 4,580 sq. ft. total waterway.

The principal objectives of this study were to

1. Apply FESWMS-2DH to this reach for the 50-year flood,

2. Compare the results with a WSPRO analysis reported in USGS Open-File Report 97-13 entitled "Hydraulic Analysis of U.S. Highway 75 Crossing of the Fall River at Neodesha, Southeast Kansas."

3. Determine if there is justification for using the more complicated FESWMS-2DH program in the analysis of flow near highway embankments with multiple relief structures.

If there is a good deal of discrepancy in either division of flow or water surface elevations between FESWMS-2DH and WSPRO, the increased use of FESWMS-2DH may be warranted. Only the 50-year flood (the design discharge) was considered in this study since it was deemed sufficient to make a meaningful comparison between the models.

# The FESWMS-2DH Modeling System

The Finite Element Surface-Water Modeling System - Two-Dimensional Flow in a Horizontal Plane (FESWMS-2DH) was developed by the U.S. Geological Survey in cooperation with the Federal Highway Administration (FHWA) for use in analyzing highway crossings of rivers and flood plains. The two-dimensional finite-element approach to the hydraulic analysis of highway crossings of flood plains has advantages over the more common one-dimensional analysis when lateral variations in water-surface elevation and flow distribution are significant. The finite-element method is ideally suited to simulating two-dimensional flow over complex topography having spatially variable resistance. This model allows the user great flexibility in defining geometric features such as the boundaries of a water body, channels, islands, dikes, and embankments. The user of the model is able to utilize a fine network in regions where geometric or flow gradients are large and a coarse network in regions where geometry and flow are more nearly uniform.

FESWMS-2DH is a modular set of computer programs developed to simulate surface-water flow where flow is essentially two-dimensional in the horizontal plane. The programs that comprise the modeling system have been designed specifically to analyze flow at bridge crossings where complicated hydraulic conditions exist. However, the modeling system can be applied to many other types of steady and unsteady surface-water flows. The three separate, but interrelated, programs that form the core of the modeling system are (1) the Data Input Module (DINMOD), (2) the Depth-Averaged Flow Module (FLOMOD), and (3) the Analysis of Output Module (ANOMOD).

DINMOD acts as a data pre-processor in the modeling system. The primary purpose of DINMOD is to generate a two-dimensional finite element network that is error free. Functions performed by DINMOD include editing of input data, automatic generation of all or part of the finite element network, refinement of an existing network, ordering of elements to enable an efficient equation solution, and graphic display of the finite network. Processed network data can be stored in a data file for use by other FESWMS-2DH programs.

FLOMOD applies the finite element method to solve the governing system of equations using the defined network. FLOMOD can simulate both steady and unsteady (time-dependent) two-dimensional (in a horizontal plane) surface-water flow to obtain depth-averaged velocities and flow depths. The effects of bed friction and turbulent stresses are considered as are, optionally, surface wind stresses and the Coriolis force.

Pressure flow through bridges is considered if the water is in contact with the bottom of the bridge deck that is defined by a "ceiling" elevation at a node point. Flow over weirs, or weir-type structures (such as highway embankments), and flow through culverts can also be modeled. The computed two-dimensional flow data can be written to a data file and stored for future use.

Results of flow simulations are presented graphically and in the form of reports by ANOMOD. Plots of velocity and unit-flow vectors; ground-surface and water-surface elevation contours; and time-history graphs of velocity, unit flow, or stage (water-surface elevation) at a computation point can be produced. Thus, ANOMOD acts as a post-processor in the modeling system.

## Input and Output Data Files for FESWMS-2DH

Input data are classified broadly as one of the following categories: (1) program control data, (2) network data, or (3) initial and boundary condition data.

Program control data govern the overall operation of a program. These data include codes that define functions to be performed by the modeling system, and constant values that are used as coefficients in equations and apply to the entire finite element network. Each of the three programs has one primary input file, i.e., ***FLOMOD.DAT, ANOMOD.DAT AND DINMOD.DAT.***

Network data describe the finite element network in the input file ***GRID.DAT***. These data include element connectivity lists, element property type codes, node point coordinates, and node point ground-surface elevations. Also included as network data are sets of empirical coefficients that apply to a particular element property type.

Initial condition data are starting values of the dependent variables and their time derivatives at each node point in the finite element network. Boundary condition data are values of dependent variables that are prescribed at particular node points along the boundary of the network.

Output data from the modeling consists of processed network data, computed flow data (depth-averaged velocities and water depth at each node point, and the derivatives of these quantities with respect to time for unsteady flow simulations), and plots of both network data and flow data.

For the purpose of transportation and long-term storage of graphical information, graphic output from FESWMS-2DH is written in a specified format to a data file that is called a plotfile. A plotfile can be read by a utility program that displays the graphic output on a specific hardware device. Graphic output stored in a plotfile can be processed afterward as often as necessary, stored for future use, or transported from one place to another.

## Input Data for this Project

The modeling area was 7,268 feet long (X-direction) and 5,869 feet wide (Y-direction). The total number of nodes is 12,075, and the total number of elements is 2,960. The average element size in floodplain is about 110x240 $ft^2$, and the average element size in the main channel is about 55x120 $ft^2$. Because the 9-node element is used, the actual distance between nodes is about half of the element side length. The finite element grid is shown in Figure 4. Creation of this grid was extremely time intensive due to

- the desire to accurately model the meandering main channel of Fall River as well as US 75, K-96 and the bridge openings in this reach
- the lack of a digital contour map.

The bridge opening dimensions for Bridges 1, 2 and 3 on the Southeast Kansas Corridor (SKC), and Bridge 3 on the US-75 were obtained from HNTB (Howard Needles Tammen & Bergendoff) design sheets. The bridge openings for the other two relief structures on US-75 ( Bridges 1 and 2) were obtained from Booker Associates, Inc. of Kansas.

Although the pre-processor, DINMOD, can perform automatic generation of part of the finite element network or refinement of an existing network, for this project the ground-surface elevations had to be coded by hand because there was no digitized data available. Moreover, the complexity of the main channel would make it difficult to automatically generate an acceptable finite element grid. Figures 5 and 6 show the contour map created by the grid module developed herein, with and without the finite element grid. Comparison of Figure 5 with the actual contour map for the region shows fairly good agreement.

The total discharge ($Q_{50}$) for the full valley is 34,000 cfs. A constant tail water elevation of 999.25 ft was used in the modeling process for the downstream boundary condition. This value corresponds to the 50-year computed water surface elevation in this region from Figure 7 in USGS Open-File Report 97-13. The Manning's n-values used in the FESWMS-2DH modeling ranged from 0.035 to 0.055 as per the USGS WSPRO model.

The four input files FLOMOD.DAT, ANOMOD.DAT, DINMOD.DAT and GRID.DAT for the FESWMS-2DH model of the NEODESHA site are given in the APPENDIX.

# Modeling Results

After all of the input files are coded, the FESWMS-2DH programs can be run. It takes about 20 minutes (depending on computers) to complete the computations. The output file created by FESWMS-2DH provides x-and y-velocity components and water depth at every node in the system. Unfortunately, this output file is immense. Consequently, the data for the appropriate bridge opening nodes were extracted and analyzed in a spreadsheet.

The discharge through each bridge opening was determined by numerically integrating the velocity distribution at the face of the bridge using the output for the appropriate nodes. One must be careful to remember that the discharge through an area dA equals V $\cos\theta$ times dA, where V is the velocity vector and $\theta$ is the angle between the velocity vector and a line perpendicular to the bridge opening. In vector notation

$$Q = \sum(V_i \bullet A_i)$$

where Q = total discharge through a bridge, $V_i$ = velocity vector for the i-th subarea, and $A_i$ is the area vector of the i-th subarea which is directed perpendicular to the bridge opening in the downstream direction. (The total area of flow for the bridge opening is therefore $\sum(A_i)$.)

The following tables show the discharge distribution among the three bridges for SKC and US 75. Table 1 shows the actual values obtained from the FESWMS-2DH modeling and Table 2 shows the final discharge distribution after proportional adjustment was made so that the total discharge equals 34,000 cfs. Table 3 compares the FESWMS-2DH values with the USGS WSPRO results for US 75. The USGS study did not analyze SKC.

**TABLE 1. DISCHARGE DISTRIBUTIONS COMPUTED FROM FESWMS-2DH RESULTS**

| Road# | Bridge1 | Bridge 2 | Bridge 3 | Total (cfs) |
|---|---|---|---|---|
| SKC | 313. | 2156. | 31641. | 34111. |
| US75 | 2659. | 8032. | 24139. | 34829. |

**TABLE 2. DISCHARGE-DISTRIBUTION PROPORTIONS TO GIVE 34,000 CFS**

| Road# | Bridge1 | Bridge 2 | Bridge 3 | Total (cfs) |
|---|---|---|---|---|
| SKC | 312. | 2149. | 31539. | 34000. |
| US75 | 2595. | 7840. | 23564. | 34000. |

**TABLE 3. COMPARISON OF FESWMS-2DH AND WSPRO RESULTS FOR US 75**

| | Road# | Bridge1 | Bridge 2 | Bridge 3 | Total (cfs) |
|---|---|---|---|---|---|
| FESWMS: | US 75 | 2,595. | 7,840. | 23,564. | 34,000. |
| WSPRO*: | US 75 | 5,500. | 6,000. | 22,500. | 34,000. |
| $Q_{WSP}/Q_{FES}$ | | 2.12 | 0.77 | 0.95 | |

*See Table 1, page 8 of USGS Open-File Report 97-13.

The flow field generated by FESWMS-2DH can be viewed in the output plot shown in Figure 7. This is a plot of the velocity vectors for the entire flowfield. The length of the vectors corresponds to the magnitude of the velocity. Figure 8 shows the velocity field and the contour map superimposed. These plots are useful in trying to figure out what the water may actually do in complicated multiple opening bridge scenarios. Note also the large skew angles of the velocities where the water enters the bridge openings from the overbank regions. This could be of interest in correcting or avoiding scour problems.

# SUMMARY

The distributions of flow for both the FESWMS-2DH model used herein and the WSPRO model used by the USGS were presented in the tables above. While the values in one of the relief bridges (Bridge 1) were quite different, the main-channel bridge carried about the same portion of the total flow for both models. Therefore, this study was not conclusive in the finding that FESWMS-2DH is always necessary for multiple opening bridges. It may, however, be useful in trying to determine whether a relief structure is actually needed or if more than one is needed. For example, the table above shows that Bridge 1 for SKC carries less than 1 percent of the total flow. Bridge 2, for that matter, doesn’t carry very much of the total flow. Consequently, either one or both of the relief bridges may be unnecessary. Additional testing would be required to make this conclusion, however.

A model such as FESWMS-2DH may be of use in situations where scour countermeasures are being considered. The model would allow one to test various features such as spur dikes as to their effect on velocity magnitudes and, particularly, angles of attack on bridge piers. Three programs were developed as pre- and postprocessors for FESWMS-2DH that allow a WSPRO input file to be used to generate the input files for FESWMS-2DH. The pre-processor programs PREFES and WSPROFES essentially create a finite element grid from the bridge and cross sectional data from the WSPRO file. The POSTFES post-processor program extracts the pertinent scour and bridge flow data from the immense FESWMS-2DH output file. These programs are described in detail in the KDOT report K-TRAN: KU-94-5.

Typical 1-dimensional models use the energy equation with friction and empirical relationships to determine water surface elevations. Lateral velocity distributions can be estimated using local conveyance distribution. However, since they are 1-dimensional models, they offer no information regarding velocity vectors and therefore angle of attack on piers. Gross estimates can be made using the WSPRO streamtube alignments. A true two-dimensional model like FESWMS-2DH solves the equations of motion. Consequently, inertial effects as well as friction forces are taken into account. These models are therefore superior in situations where inertial forces may dominate the flow field. This situation exists in strong channel bends and in complicated transitions such as multiple bridge openings through roadways that are fairly close together. The 1-dimensional models are nearly useless for the complicated transitions. An example of such a transition could be two roads meeting at near right angles with each road having multiple openings near the intersection. Neither WSPRO nor HEC-RAS would be of much use in the analysis of such a flow field where inertial forces rather than friction clearly dominate the flow field. A two-dimensional model (either mathematical or physical) would be required if any kind of reliable analysis were desired.

***For regular backwater calculations, it is doubtful that the two-D models are worth the effort.*** In fact, during the course of this study doubt developed as to how well the two-dimensional model accounted for friction. It seems that the 1-D models may be more appropriate for typical backwater situations where friction dominates between bridges since Manning's n estimates typically used are based on 1-D models. Analysis of an important bridge system might therefore involve one-dimensional modeling upstream and downstream from regions with complicated one-dimensional flow characteristics and the application of a two-dimensional model in the complicated flow region. The results of the one-dimensional model would provide the necessary boundary conditions for the two-dimensional modeling.

For situations in which it would be desirable to model the flow with FESWMS-2DH, the program can be used to automatically create the finite element network if a digital contour map is available. This would greatly reduce the level of work that was required to develop the input data files for the model described herein where only a hard copy of the contour information was available. Consequently, if digital contour information were available, one would be more likely to consider applying a two-dimensional model. A model such as Surfacewater Modeling System (SMS), available through Boss International, should be used if KDOT decides to perform FESWMS-2DH applications. It allows the engineering to apply the FESWMS-2DH model fairly easily if digital elevation maps are available. We tested SMS here and found it impressive.

# FIGURES

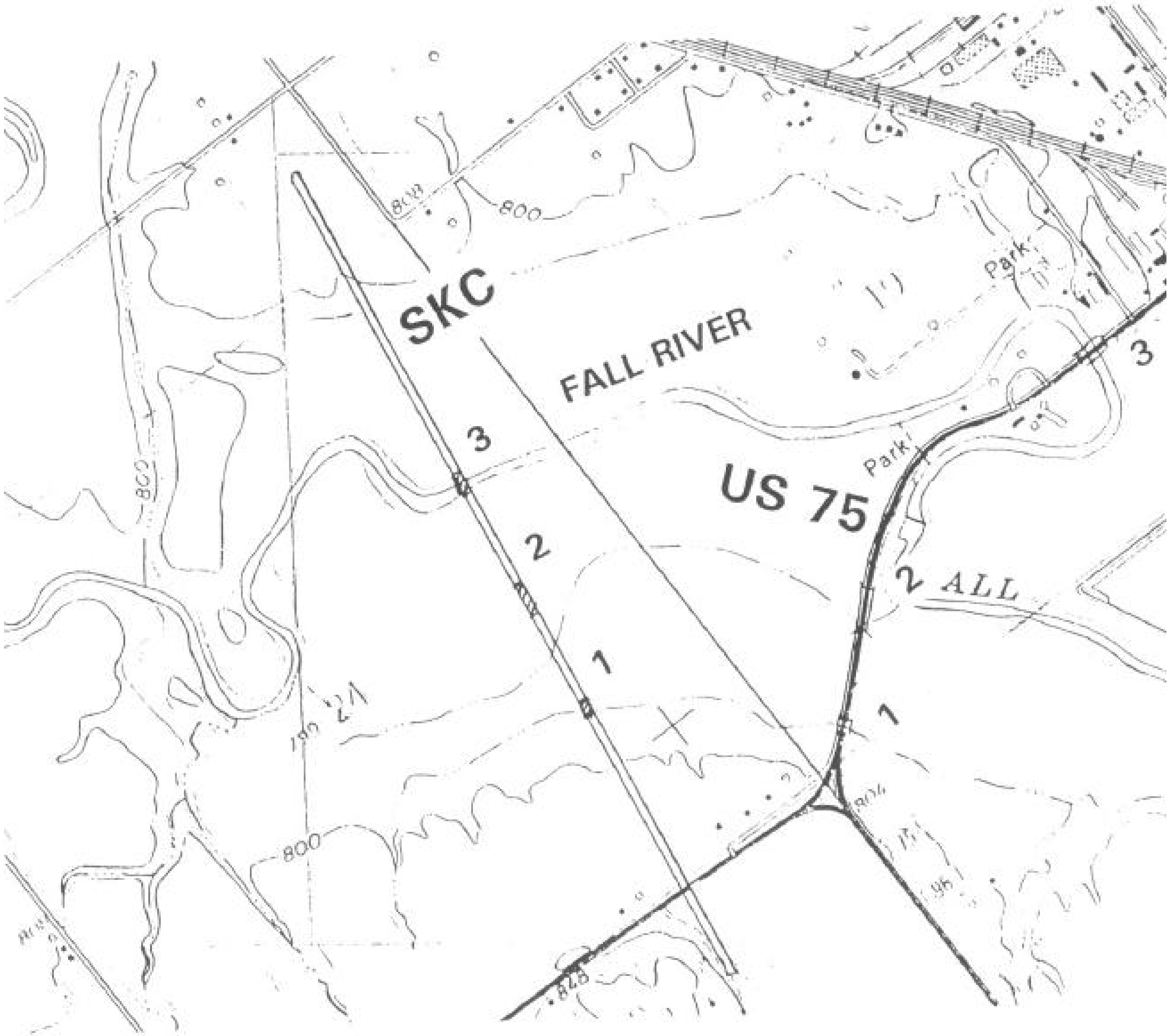
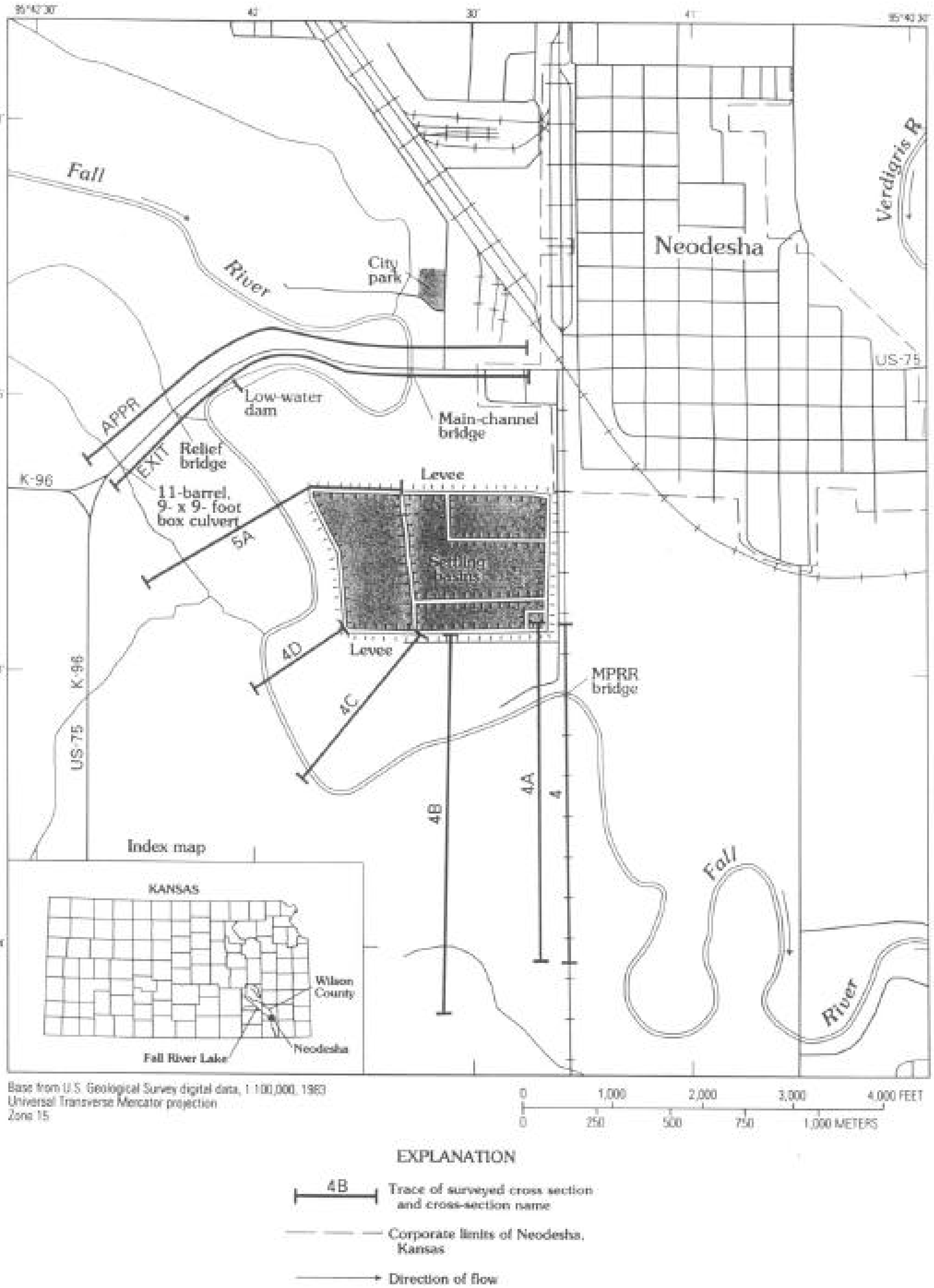
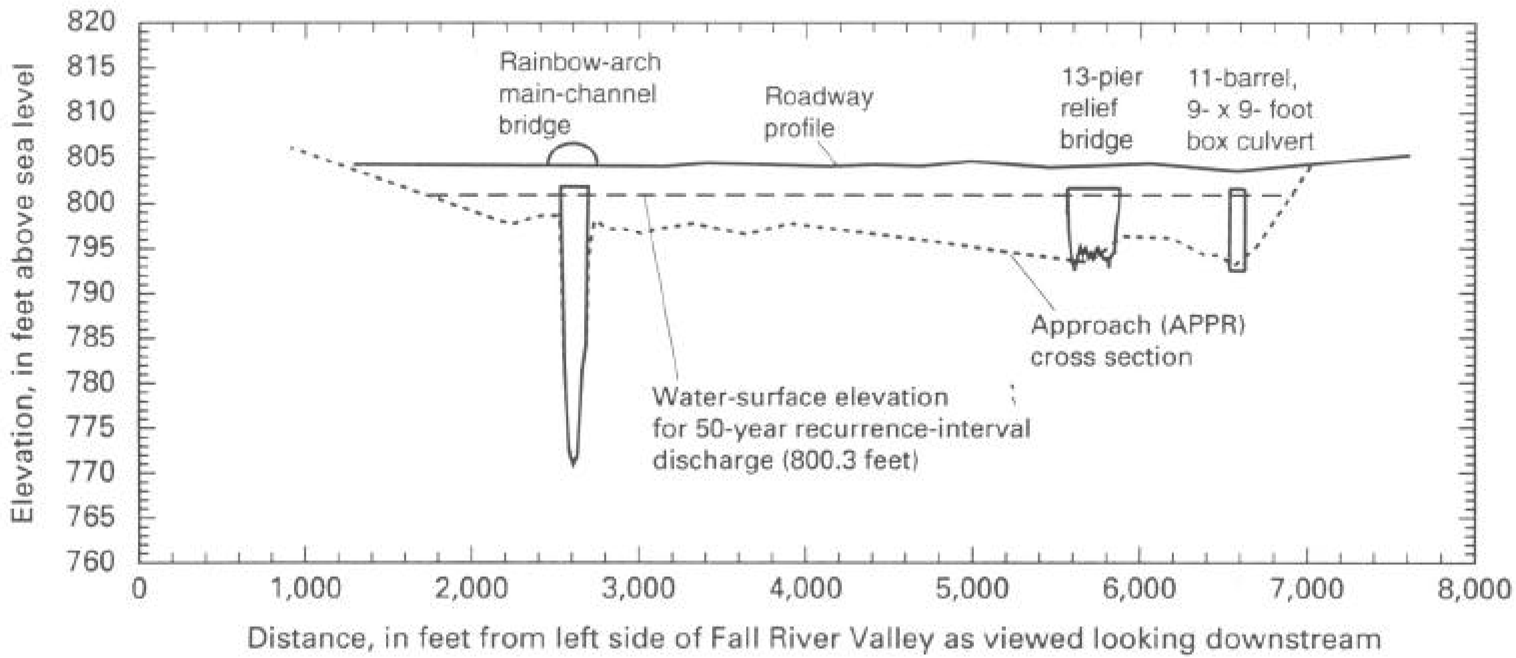



Figure 1. Study Area of the Fall River near Neodesha




Vicinity of Neodesha, southeast Kansas, and location of surveyed cross sections.

**Figure 2. USGS Study Area for WSPRO Modeling**
***(Figure 1 in USGS Open-File Report 97-13)***




Cross section APPR and roadway profile across the Fall River near Neodesha, Kansas, and flow-structure openings with water-surface elevation for 50-year recurrence-interval discharge.

**Figure 3. Cross Section Showing Multiple Openings for US 75**
***(Figure 6 in USGS Open-File Report 97-13)***

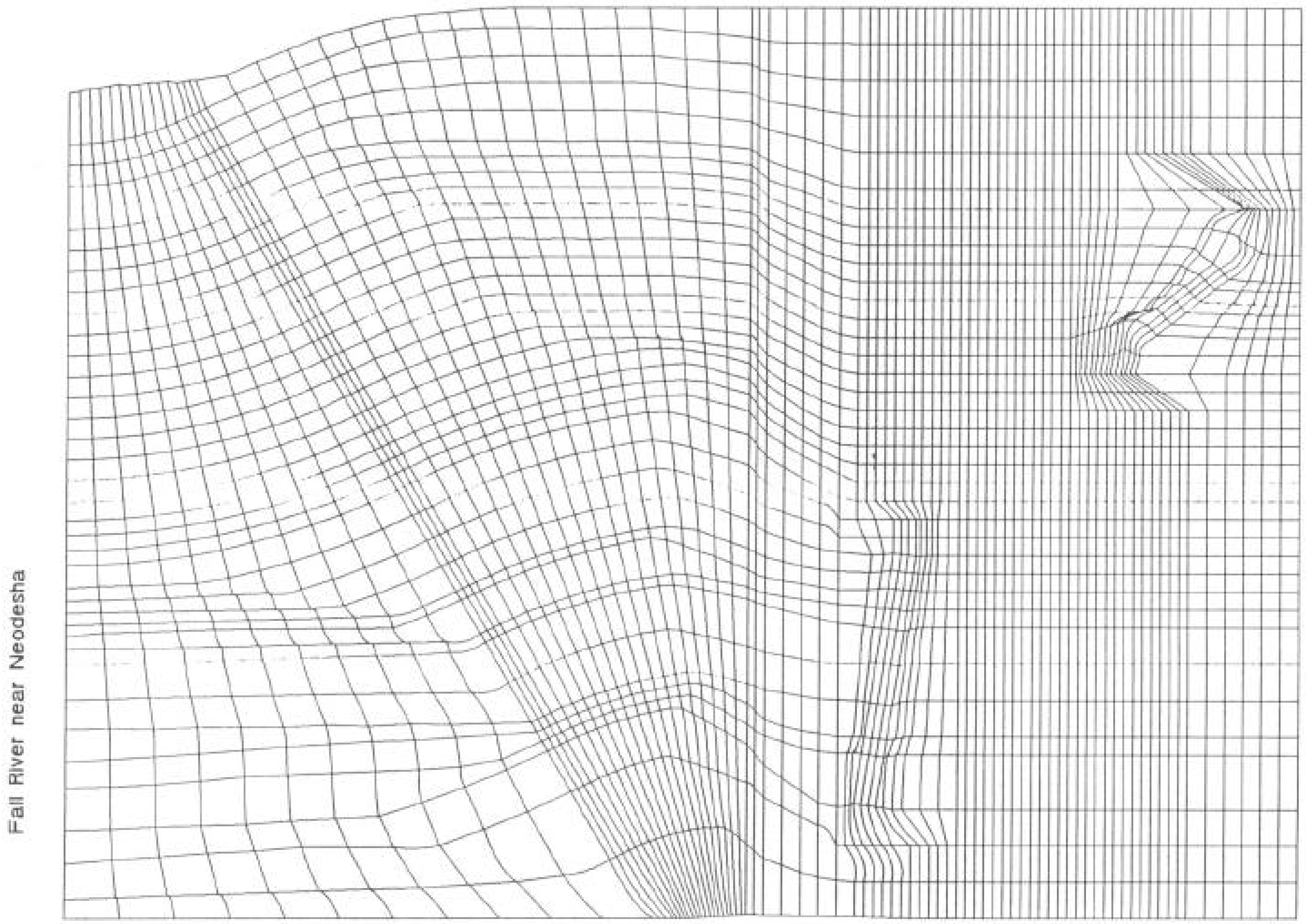



Figure 4. Finite Element Grid for Site

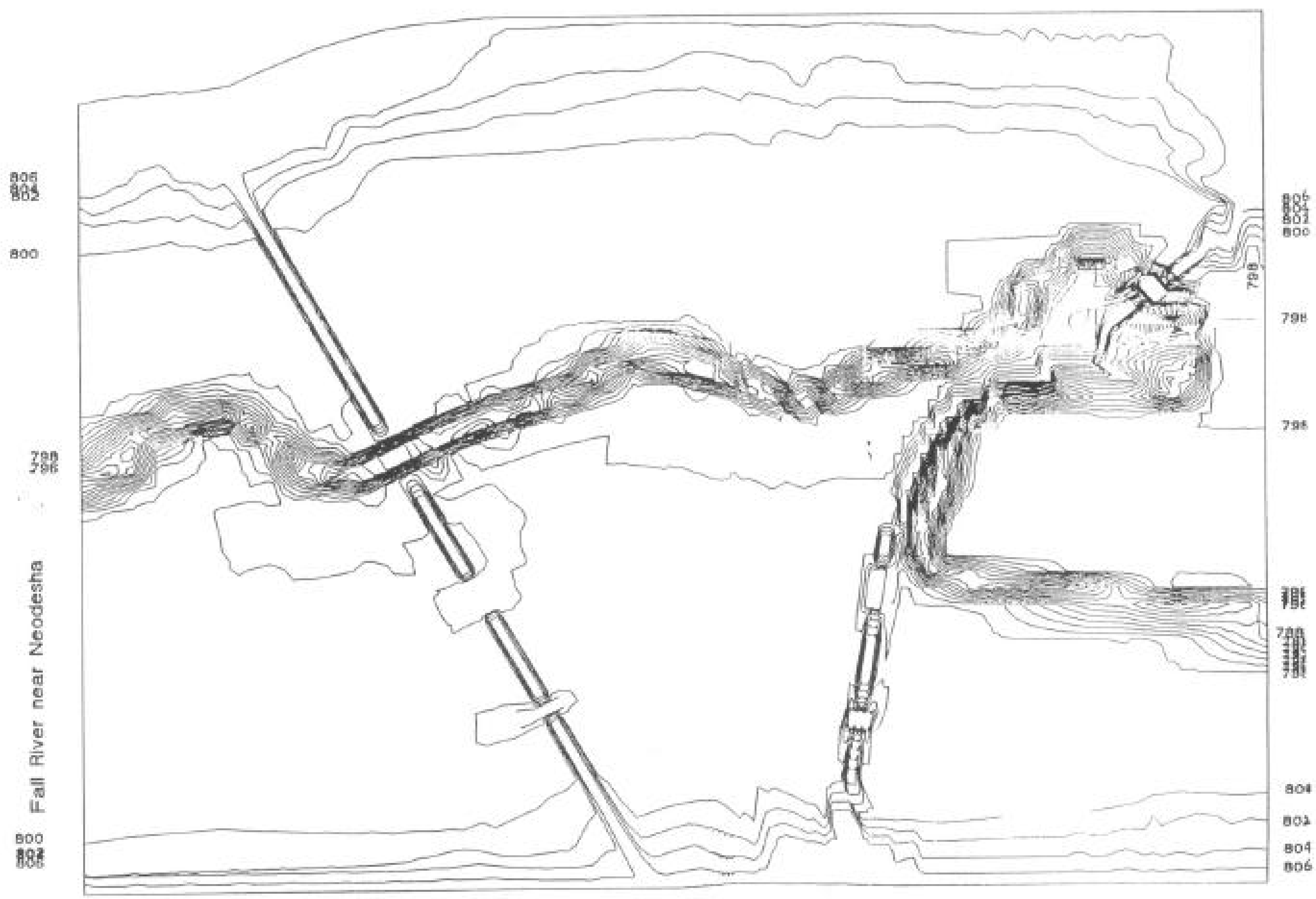



Figure 5. Ground Elevation Contour Map Created by FESWMS-2DH

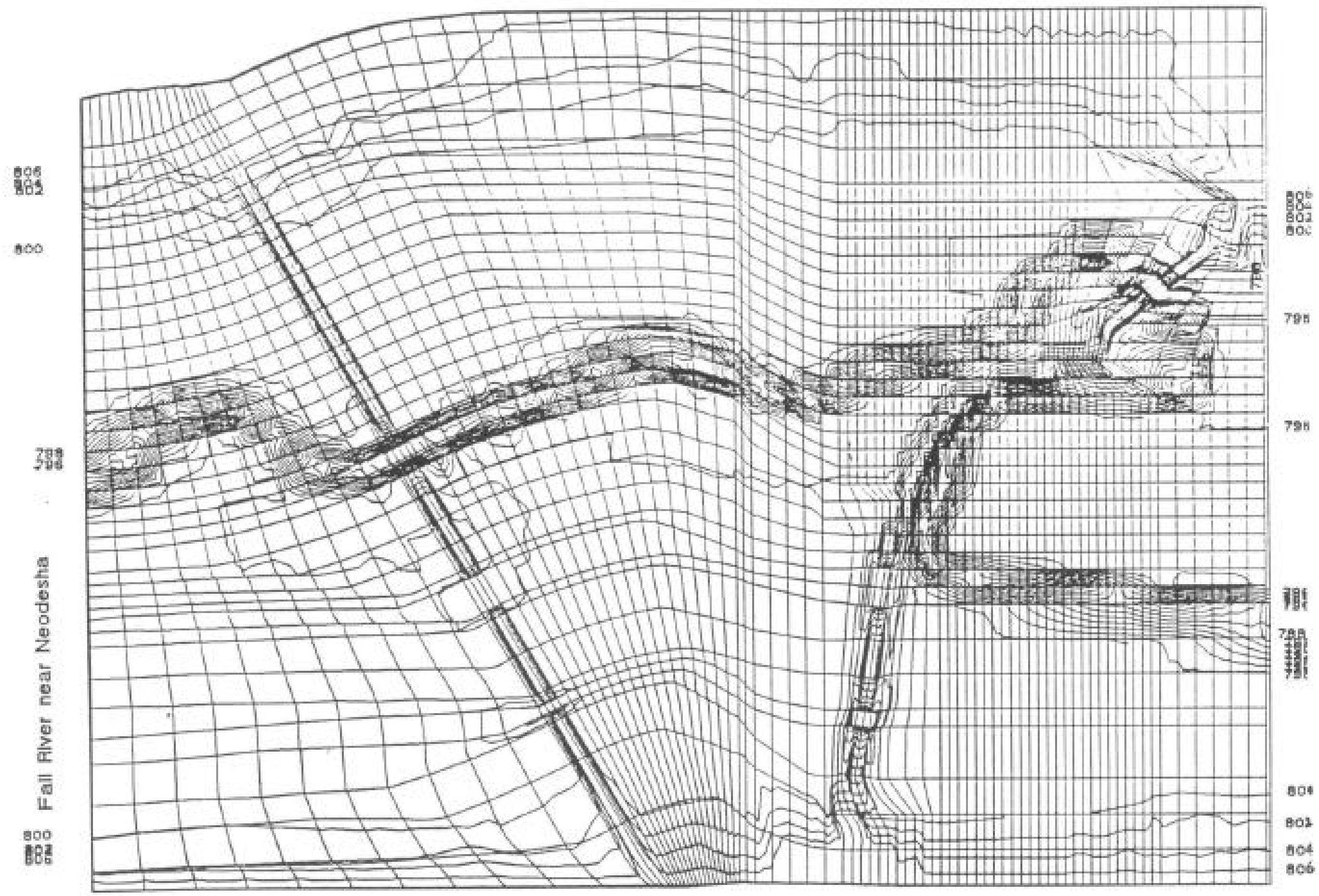



Figure 6. Ground Elevation Contour Map Created by FESWMS-2DH with Finite Element Grid Superimposed

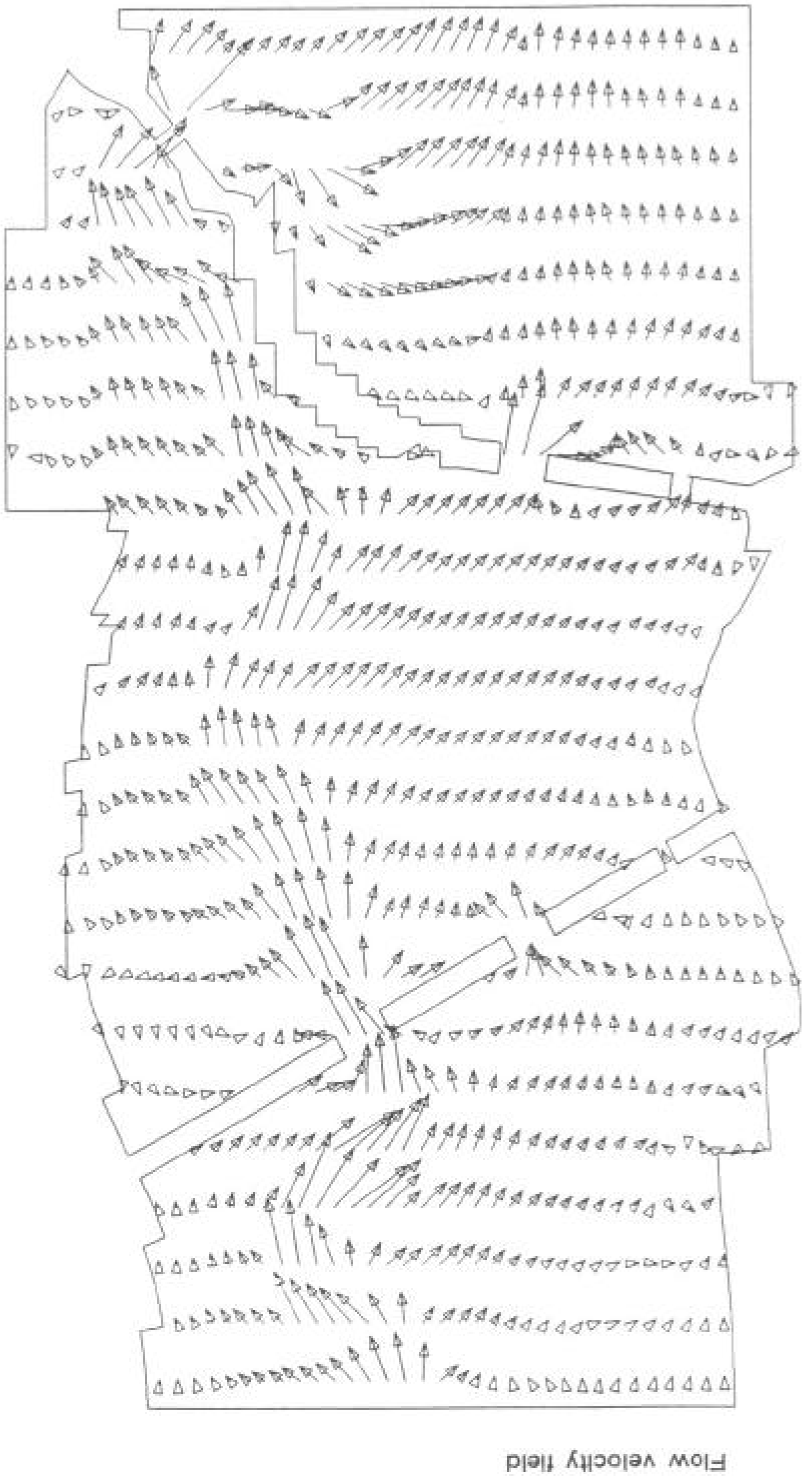



**Figure 7. Velocity Vector Plot Created by FESWMS-2DH**

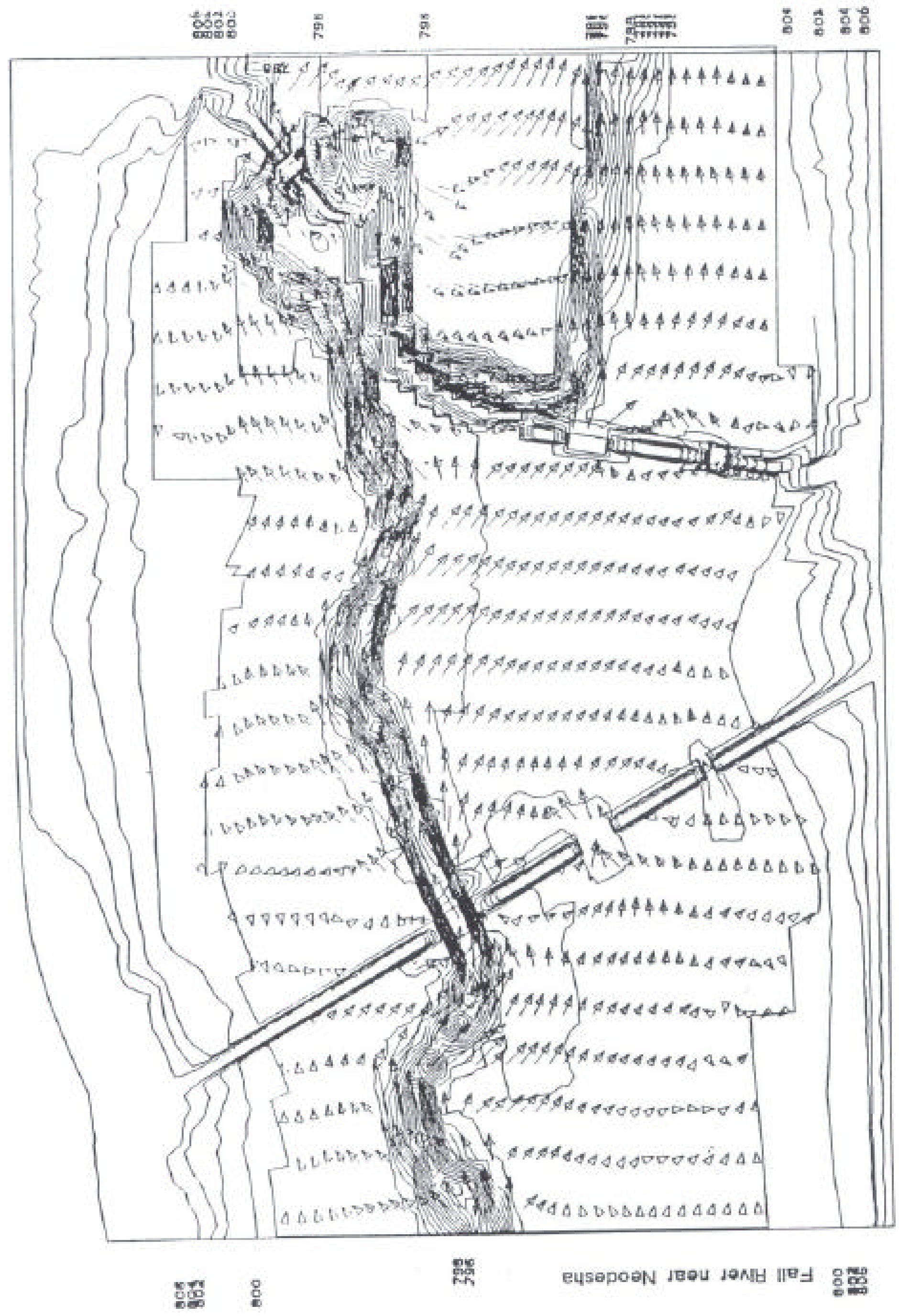



**Figure 8. Velocity Vector Plot Created by FESWMS-2DH with Contour Map Superimposed**

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Clement, R.W. and C.A. Perry “Hydraulic Analysis of U.S. Highway 75 Crossing of the Fall River at Neodesha, Southeast Kansas,” U.S. Geological Survey Open-File Report 97-13, 1997.

# APPENDIX

## *FESWMS-2DH INPUT FILES*

# FLOMOD.DAT

```
SWMS              1         1
       Fall River near Neodesha withoout Contraction Scour
    0    3    0    0    0    0    0    0    1    0    1
    1    0    1    1    0    0   98   99
         1         0         0        10      .000      .000      .000      .670
   799.250      .000

PROP
         1      .045     5.000      .035     8.000                   1     .6000
         2      .055     4.000      .045     7.000                   1     .6000
         3      .065     3.000      .055     6.000                   1     .6000

QSEC
         1  34000.00
    1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
   17   18   19   20   21   22   23   24   25   26   27   28   29   30   31   32
   33   34   35   36   37   38   39   40   41   42   43   44   45   46   47   48
   49   50   51   52   53   54   55   56   57   58   59   60   61   62   63   64
   65   66   67   68   69   70   71   72   73   74   75   -1

ZSEC
         1   799.250                   2
1200112002120031200412005120061200712008120091201012011120121201312014120151201 6
120171201812019120201202112022120231202412025120261202712028120291203012031120 32
12033120341203512036120371203812039120401204112042120431204412045120461204712048
12049120501205112052120531205412055120561205712058120591206012061120621206312064
120651206612067120681206912070120711207212073120741207 5   -1

FLUX
    1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16
   17   18   19   20   21   22   23   24   25   26   27   28   29   30   31   32
   33   34   35   36   37   38   39   40   41   42   43   44   45   46   47   48
   49   50   51   52   53   54   55   56   57   58   59   60   61   62   63   64
   65   66   67   68   69   70   71   72   73   74   75   -1
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12033120341203512036120371203812039120401204112042120431204412045120461204712048
12049120501205112052120531205412055120561205712058120591206012061120621206312064
12065120661206712068120691207012071120721207312074120 75   -1

LAST
```

# ANOMOD.DAT

```
SWMS              1         1                                     0
0
    0    1    1    0    0    0
VECT              0
0
             Flow velocity field
    1    0
        20         0         1            300.000    100.00
      .140      .070
     0.000     0.000      .000      .000   900.000   1100.00     0.000
ISOL              0
0
             Water surface contour
    1    2    1
         0    804.00       0.2
      .140      .070
     0.000     0.000      .000      .000   900.000   1100.00     0.000
ISOL              0
0
             Velocity contour
    1    3    1
         0     20.00       .50
      .140      .070
     0.000     0.000      .000      .000   900.000   1100.00     0.000
LAST
```

# DINMOD.DAT

```
SWMS              1         1
        FALL RIVER NEAR NEODESHA (Natural Channel without Contraction Scour)
    3    3    1    0    0    0    1    0
PLOT
        Fall River near Neodesha
    0    0
      0.14      0.07     0.105     0.105       2.0
     0.000     0.000      .000      .000   900.000  1100.000     0.000

LAST
```

# GRID.DAT
# (Partial Listing)

```
    12075      2960
    1   457.590   100.020   807.500      .000
    2   457.590   217.000   805.000      .000
    3   457.590   225.030   801.073      .000
    4   457.590   355.650   800.102      .000
                        •                                   •
                        •                                   •
                        •                                   •
  3198  3014.847  4179.144   798.625      .000
   3199  2995.790  4243.751   798.635      .000
   3200  2976.733  4302.359   798.635      .000
   3201  2957.677  4361.968   798.635      .000
                        •                                   •
                        •                                   •
                        •                                   •
  9998  6668.379  2330.043   797.575      .000
   9999  6668.379  2388.729   797.575      .000
  10000  6668.379  2447.414   797.575      .000
  10001  6668.379  2506.099   797.575      .000
                        •                                   •
                        •                                   •
                        •                                   •
  12073  7726.114  5733.793   807.505      .000
  12074  7726.114  5851.164   807.505      .000
  12075  7726.114  5968.535   807.753      .000
 1    1   76  151  152  153   78    3    2   77    3
 2    3   78  153  154  155   80    5    4   79    3
 3    5   80  155  156  157   82    7    6   81    3
                        •                                   •
                        •                                   •
                        •                                   •
 585 2309 2384 2459 2460 2461 2386 2311 2310 2385    3
 586 2311 2386 2461 2462 2463 2388 2313 2312 2387    3
 587 2313 2388 2463 2464 2465 2390 2315 2314 2389    3
 588 2315 2390 2465 2466 2467 2392 2317 2316 2391    3
                        •                                   •
                        •                                   •
                        •                                   •
2478 997110046101211012210123100048 9973 997210047    3
2479 997310048101231012410125100050 9975 997410049    3
24801005110126102011020210203101281005310052101 27    3
24811005310128102031020410205101301005510054101 29    3
                        •                                   •
                        •                                   •
                        •                                   •
295811919119941206912070120711199611921119201 1995    3
295911921119961207112072120731199811923119221 1997    3
296011923119981207312074120751200011925119241 1999    3
```