

Review Guidance

Full Equations (FEQ) Model for the Solution of Full, Dynamic Equations of Motion for One-Dimensional Unsteady Flow in Open Channels and Through Control Structures

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1.0 Introduction

The Full Equations (FEQ) model is a computer program used for the solution of full, dynamic equations of motion for one-dimensional unsteady flow in open channels. The hydraulic characteristics of the floodplain, including the channel, overbanks, and all control structures affecting the movement of flow, are computed by its companion program, Full Equations Utilities Model (FEQUTL). Both models are published by the U.S. Geological Survey (USGS).

The review guidance summarized in this report has been developed for facilitating reviews of FEQ (and FEQUTL) analyses of floodplains submitted to the Federal Emergency Management Agency (FEMA) in support of floodplain mapping and revisions of Flood Insurance Studies (FISs) and Flood Insurance Rate Maps (FIRMs) published under the auspices of the National Flood Insurance Program (NFIP). This review guidance complements the information available in the following publications:

- USGS Water Resources Investigations (WRI) report 96-4240 “Full Equations (FEQ) Model for the Solution of the Full, Dynamic Equations of Motion for One-Dimensional Unsteady Flow in Open Channels and Through Control Structures,” 1997;
- USGS WRI 97-4037 “Full Equations Utilities Model (FEQUTL) for the Approximation of Hydraulic Characteristics of Open Channels and Control Structures During Unsteady Flow,” 1997;
- USGS Draft Open-File Report “Application Guide for the Full Equations (FEQ) Model of One-Dimensional, Unsteady, Open-Channel Flow”; and
- The database at the USGS Web site under “Diagnosing Computational Problems in FEQ.”

This review guidance is prepared as a tool for FEMA and its contractors to increase the efficiency of processing requests for map revisions based on FEQ analyses and to provide consistent and accurate reviews of the submitted analyses.

This review guidance discusses issues related to determining the appropriateness of the chosen hydraulic components and parameters to model the floodplain and the level of accuracy of the flood hazard parameters computed by the analysis. However, methods for resolving computational difficulties and diagnosing their causes are not discussed in this document. The reader is referred to the FEQ home page maintained by the USGS at il.usgs.gov/proj/feq for guidance on methods to resolve computational difficulties associated with an FEQ or FEQUTL model.

1.1 Use of FEQ in the NFIP

Many versions of FEQ and FEQUTL are in use. However, FEQ version 8.92 and FEQUTL version 4.68 are currently supported by the USGS and accepted by FEMA for use in the NFIP. The current version can be found at the USGS Web site water.usgs.gov/software/feq.html, and updated documentation is linked through the page. FEQ analyses prepared using other unofficial versions (not available from USGS) must be rerun using the accepted versions of FEQ and FEQUTL before being utilized in the NFIP. These models are included in the list published by FEMA titled “Numerical Models Accepted by FEMA for NFIP Usage” (known as the accepted models list) available at the FEMA Web site www.fema.gov/mit/tsd/en_modl.htm. This Web site will have information on any future updates to the FEQ and FEQUTL models by the USGS.

1.2 Limitations

FEMA has identified two limitations with FEQ analyses and has listed them in the accepted models list. The limitations identified are for the analysis of culvert flow (Type 5 in the USGS culvert flow classification) and modeling a floodway based on the equal conveyance reduction concept.

Type 5 culvert flow is a complex hydraulic phenomenon. The assumptions used by the FEQUTL analysis of Type 5 flow are different than those used by the other hydraulic models accepted for use in the NFIP. The Type 5 culvert flow computations developed with FEQUTL Version 4.68 (currently available from the USGS) require verification with results obtained using methodology or models accepted for use in the NFIP.

FEQ and FEQUTL do not have the capability to compute the optimum floodway that satisfies the equal conveyance reduction concept and the maximum surcharge criterion simultaneously. The USGS FLDWY program, or a similar program with floodway modeling capability, may be used to assist the determination of the initial floodway configuration for an FEQ analysis.

FIS preparation frequently involves the analysis of many miles of river floodplains. It is cost-effective to create and extract FIS data with ease. However, FEQ and FEQUTL do not have summary output tables where the hydraulic parameters necessary to prepare FISs and FIRMs can be conveniently extracted.

These limitations are included in the list published by FEMA titled “Numerical Models Accepted by FEMA for NFIP Usage” (known as the accepted models list) available at the FEMA Web site www.fema.gov/mit/tsd/en_modl.htm. This Web site will have information on any future updates to the FEQ and FEQUTL models by the USGS.

1.3 Organization of This Document

The issues covered in this review guidance document are the data submittal requirements and a summary of available guidance useful in the review of an FEQ analysis. Chapter 2 discusses data requirements for the review of an FEQ analysis submittal. Chapter 3 discusses the general outline of FEQ and FEQUTL input data. Chapter 4 briefly outlines the hydrologic analysis review, which is a prerequisite for the review of an FEQ analysis. Issues relevant to the calibration of an FEQ analysis are summarized in Chapter 5. The review guidance of FEQ and FEQUTL analyses is

documented in Chapter 6. Guidance useful in the review of FEQ models representing complex flow situations is summarized in Chapter 7. Chapter 8 provides a summary of pre- and post-processing programs and documents the technical resources available for FEQ.

2.0 FEQ Submittal, Acknowledgment/Additional Data Request Letters

The first step in reviewing an FEQ analysis is to ensure that the submittal has all the necessary data. FEQ is a hydraulic model with the capability to analyze unsteady flows through open channels and control structures. However, unlike other unsteady flow models, FEQ has a companion program, FEQUTL, that creates the rating tables used by the FEQ program. Therefore, an FEQ submittal will contain input/output files of FEQ and FEQUTL analyses. A complete FEQ submittal requires a large amount of disk space to store all the data and is generally submitted on a CD-ROM.

2.1 FEQ Input Data and Output Data

The FEQ input file defines the magnitude of flood runoff carried by the stream network, the hydraulic properties of the floodplain (cross sections) and structures, the connectivity of the stream network, the external boundary conditions, and the level of output required. Figure 2.1 illustrates a schematic diagram and the corresponding physical features of a hypothetical stream network system. The schematic diagram represents the connectivity of the physical features of the stream network using branches, bridges, and other appropriate structures. Cross sections are used to represent the topography of the branches and structures.

FEQ reads the hydraulic properties of the cross sections and structures as one-dimensional, two-dimensional, or three-dimensional tables. Some of these tables are created by the FEQ companion program, FEQUTL. Others are created by manual entry of parameters computed by other means. A general understanding of the different tables used by FEQ is necessary to review the accuracy of an FEQ analysis. A detailed discussion of FEQ tables is given in Chapter 11, "Function Table Description" (page 132), of the FEQ manual (USGS WRI 96-4240). The variables used in the tables are also explained in Chapter 11. In addition, Section 1.2 of the FEQUTL manual (USGS WRI

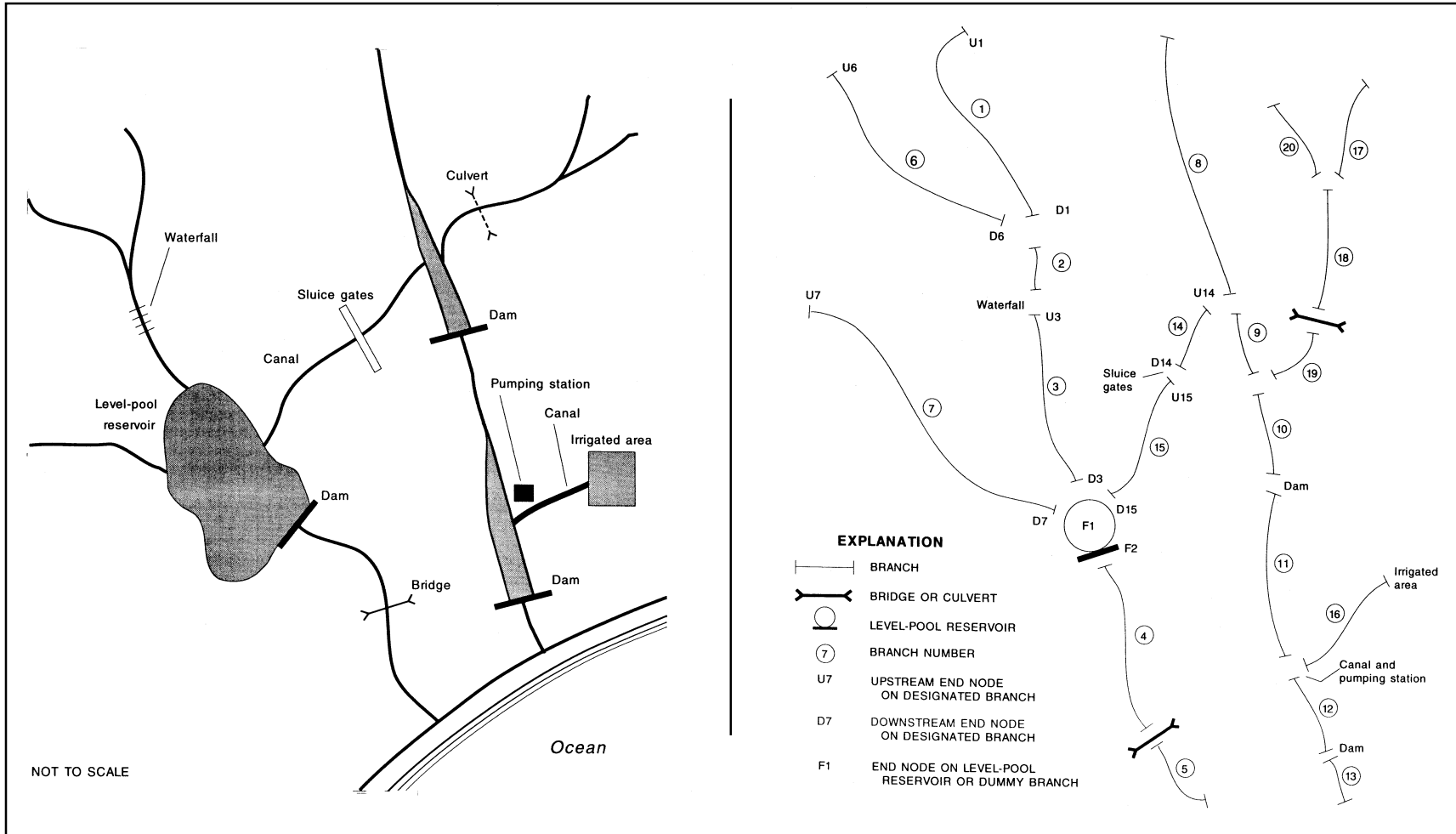


Figure 2.1 - Schematic Diagram of a Stream Network

97-4037) describes the table types created by FEQUTL. A brief discussion of the tables used by FEQ is given in Section 2.1.1 of this report.

Generally, an FEQ input file contains the following data:

- Control parameters that define the:
 - basic equations involved,
 - accuracy of the results, and
 - the level of detail required in the output.
- The magnitude of the flood carried by the stream system (a hydrograph, or the unit area runoff intensities).
- Tables containing the hydraulic properties of the floodplain (cross sections) and structures. These tables are generally created by the FEQ companion program, FEQUTL. FEQUTL is capable of conducting steady state analyses of flow through various hydraulic structures and cross sections.
- The connectivity of the stream system (cross sections and structures). The connectivity is also illustrated in a schematic diagram and a topographic map of the project area.
- External boundary conditions.
- Initial conditions data to start the simulation.
- Nodes where detailed hydrographs or flood elevations are stored.

FEQ creates more than one output data file. A general output file is created where the input data are echoed, the initial internal starting water-surface elevations (backwater analysis results) are printed, and the maximum discharges and flood elevations computed for the stream network are printed. Warning messages and error messages are printed in this file. The name of this output file is specified at the time of execution. If requested, FEQ can also create a second special output file where time-varying flow or the water-surface elevation computed for a node is written. The special output files and the nodes where the output is requested are defined in the FEQ input file. Appendix B of the USGS draft User's Guide gives a glossary of terms used in the FEQ output data. This glossary is also available at http://il.water.usgs.gov/proj/feq/appendix_b/gloss.html

FEQ also provides online messages regarding the status of the program execution. However, these messages are generally not submitted for review.

FEQ output files will generally contain the following information:

- General output file:
 - version of FEQ used,
 - echo of the input data,
 - starting water-surface elevations determined using backwater analysis,
 - branch and stream network ponding volume (for storm sewer analysis only),
 - flow, flow depth, and water-surface elevations at all exterior nodes,
 - summary of extreme elevations and flows for all nodes in the stream network, and
 - warning and error messages.
- Special output file:
 - node number,
 - flow or elevation, and
 - corresponding time.

2.1.1 Hydraulic Property Table Types Used by FEQ

FEQ reads the hydraulic properties of the cross sections and structures as one-dimensional, two-dimensional, or three-dimensional tables. The one-dimensional table has one argument (independent variable), the two-dimensional table has two arguments, and the three-dimensional table has three arguments. The hydraulic properties of a floodplain cross section can be represented using a one-dimensional table where the depth of water in the cross section is the independent variable. Hydraulic properties of a submerged flow through a culvert can be represented using a two-dimensional table where the upstream head and tail water level are the two independent variables controlling the flow through the culvert. The submerged flow through an underflow gate (with variable gate settings) can be represented using a

three-dimensional table where the upstream head, tail water level, and gate settings are the three independent variables.

FEQ version 8.92, which is the version accepted for use in the NFIP, uses 17 types of tables: 13 of these tables are one-dimensional tables, 3 are two-dimensional tables, and 1 is a one-dimensional table. However, a later version of FEQ (FEQ version 9.19), not yet available on the USGS Web site, but used in some of the FEQ training classes, uses 18 types of tables. Table type 10, a new two-dimensional table type, is available in this new version. Table 2.1 summarizes the different table types used by FEQ and independent variables used, along with the hydraulic parameters computed for these independent variables.

Table 2.1 - Hydraulic Property Table Types Used by FEQ

Table Number	Type	Independent Variables			Number of Hydraulic Properties	Remarks
		One	Two	Three		
2	1-D	user defined	none	none	1 (function)	
3	1-D	user defined	none	none	2 (function and derivative)	
4	1-D	user defined	none	none	2 (function and derivative)	
6	2-D	head	head	none	1 (flow)	
7	1-D	time	none	none	1 (function)	year, month, date, hour
8	1-D	time	none	none	2 (function and derivative)	
9	1-D	time	none	none	2 (function and derivative)	

Table 2.1 (cont.) - Hydraulic Property Table Types Used by FEQ

Table Number	Type	Independent Variables			Number of hydraulic properties	Remarks
		One	Two	Three		
10	2-D	user defined	user defined	none	2 (function and derivative)	Available in FEQ Version 9.19 only
11	1-D	time	none	none	2 (wind speed and direction)	
13	2-D	time	time	none	2 (flow and derivative)	
14	2-D	head	flow	none	2 (head and derivative)	
15	1-D	gate setting			2 (2-D table numbers)	3-D relationship
20	1-D	depth	none	none	4 (cross section properties)	T, A, \sqrt{K} , β
21	1-D	depth	none	none	5 (cross section properties)	T, A, \sqrt{K} , β , J
22	1-D	depth	none	none	7 (cross section properties)	T, A, \sqrt{K} , β , J, α , Qc
23	1-D	depth	none	none	6 (cross section properties)	T, A, \sqrt{K} , β , Ma, Mq
24	1-D	depth	none	none	7 (cross section properties)	T, A, \sqrt{K} , β , J, Ma, Mb
25	1-D	depth	none	none	8 (cross section properties)	T, A, \sqrt{K} , β , J, α , Qc, Ma, Mq

The notations used in Table 2.1 are explained in Section 2.1.2 of the FEQUTL manual (USGS WRI 97-4037) and Table 6 in Chapter 11 of the FEQ manual (USGS WRI 96-4240). They are reproduced below:

<u>Notation</u>	<u>Explanation</u>
1-D	one-dimensional table
2-D	two-dimensional table

<u>Notation</u>	<u>Explanation</u>
T	top width of the water surface
A	cross sectional flow area
\sqrt{K}	square root of conveyance
J	first moment of area taken from the water surface
β	momentum flux correction coefficient
α	energy flux correction coefficient
Qc	critical flow rate
Ma	weighting factor that converts area to volume per unit length of channel
Mq	weighting factor that converts flow rate to momentum per unit length of channel

2.2 FEQUTL Input Data and Output Data

The hydraulic properties of the cross sections and the control structures are computed by the steady state analyses performed by FEQUTL and are stored as rating tables. More than one FEQUTL analysis is generally necessary to analyze the hydraulic properties of the structures and cross sections in a floodplain. The topography of the cross sections and the control structures are defined in FEQUTL input data files. These rating tables are identified by numbers and stored in files. The path for the files is defined in the FEQ input data file.

A typical FEQUTL input data file generally contains the following information:

- standard header;
- command blocks to compute the hydraulic characteristics of the open channel cross sections and the structures in the floodplain;
- number of the table where the computed hydraulic properties (by each of the command blocks) are stored;
- tables where discharge relationships are stored (for structures only); and
- a set of water-surface elevations for which the hydraulic properties are computed (for structures only).

Different command blocks are necessary to compute the hydraulic properties of the open channel cross sections and the structures. Topographic data of the floodplain and structures, Manning's roughness coefficients, discharge coefficients, and loss coefficients are generally included in the command blocks.

FEQUTL creates two output files: a general output file, and a file where the computed hydraulic properties are stored. The general output file includes an echo of the input data, the hydraulic properties computed by each of the command blocks, warning messages, and error messages. The hydraulic properties file contains the table number, the type of table, and a table with hydraulic properties.

The FEQUTL output file generally includes the following information:

- General output file:
 - version of FEQUTL,
 - echo of the input data,
 - command block,
 - table computed by the command block,
 - hydraulic properties of the cross sections (for structures),
 - hydraulic properties computed for the cross section or structure,
 - flow type (for culverts),
 - warning and error messages.
- Hydraulic properties file:
 - table number,
 - table type,
 - hydraulic properties for cross section,
 - datum.

2.3 Data Submittal Checklist

The basic data necessary to review an FEQ analysis include the following:

- All of the FEQ input and output data files used to define the flood hazard parameters of the 10%, 2%, 1%, and 0.2% annual chance floodplains. Please note the multiple analysis option is not available in the FEQ program, and each frequency floodplain will have its own FEQ input data set.
- All of the FEQUTL input data files used to generate the rating tables used in the FEQ models and the rating tables.
- If hydrographs used in the FEQ analysis are not previously accepted for use in an effective FIS, it is necessary to review hydrologic data used in the FEQ model. This review should be done prior to the review of the FEQ/FEQUTL analysis.
- MT-2 certification forms and an annotated FIRM, as necessary, for the type of revision request.
- A report with the following information:
 1. A summary of the analysis including a layout map indicating the location and extent of the floodplain modeled in the submitted FEQ/FEQUTL analyses.
 2. A summary of the computer programs used to model the hydrologic and hydraulic processes of the floodplain.
 3. List of assumptions used in the FEQ/FEQUTL models and the general description of the data sources.
 4. Schematic diagram illustrating the stream system.
 5. FEQ floodway models along with a description of the methodology used to determine the initial floodway configuration to satisfy the equal conveyance reduction criterion.

6. Topographic map of the floodplain illustrating the locations of the cross sections and other physical features considered in the analysis.
7. Certified topographic data to support the FEQUTL models of the cross sections, storage areas, and control structures.
8. Ground photographs and computations to support the selection of Manning's roughness coefficients.
9. Alternate analyses to support rating curves used for culverts with Type 5 flow situations.
10. Calibration models, if historic information is available for the subject watershed (stream gage data and high-water marks, comparison of observed and computed results).
11. A table summarizing the identification of the cross sections, storage areas, and control structures and the corresponding hydraulic tables used in the FEQ analyses.
12. A table summarizing the channel invert, distance between cross sections, and computed flood elevations at all cross sections and at the structures within the floodplain.
13. A table summarizing the data necessary to prepare the floodway data table for the floodplain.

2.4 Acknowledgment/Additional Data Request Letters

The requester submitting an FEQ analysis will be notified that the request was received (type 316 letter). At that time, the requester will be informed of any additional data necessary for us to complete the review of the analysis.

3.0 General Outline of FEQ/FEQUTL Input Data

FEQ input data are broken into blocks. The data are assembled in these blocks to achieve specific functions necessary in the FEQ solution process. Blocks used in FEQ are summarized in Table 3.1. The run control block, branch description block, network-matrix block, function table block, and backwater block are the minimum required data to execute an FEQ model of a floodplain.

Table 3.1 - Summary of Input Blocks for an FEQ Input File

Block Name (Shaded rows indicate the minimum required FEQ input)	Function of the Block	Page reference, WRI 96-4240 (1996)
Run control	Definitions of constants and general hydraulic properties of the FEQ model of the floodplain	Section 13.1 Page 145
Branch description	Description of the nodes on each branch	Section 13.2 Page 159
Tributary area	Drainage area of each land use type that contribute flow to a computational element	Section 13.3 Page 164
Branch exterior node	Relationship between branches and the flow path end nodes	Section 13.4 Page 168
Near-zero depth	Controlling value for depths and interpolation rules, generally used when modeling shallow flows	Section 13.5 Page 168
Network-matrix control	Definition of the stream network, and the governing equations necessary to find the solution	Section 13.6 Page 169
Point flows	Point inflows and outflows to or from a branch	Section 13.7 Page 181
Wind information	Wind speed and direction, and air properties	Section 13.8 Page 181

Table 3.1 (cont.) - Summary of Input Blocks for an FEQ Input File

Block Name (Shaded rows indicate the minimum required FEQ input)	Function of the Block	Page reference, WRI 96-4240 (1996)
Special output locations	Specification of nodes where output information is written to a specific file	Section 13.9 Page 184
Input files	Information describing files used to input flow or water-surface elevation at a node	Section 13.10 Page 185
Block Name (Shaded rows indicate the minimum required FEQ input)	Function of the Block	Page reference, WRI 96-4240
Output files	Information describing files used to write output information of flow or water-surface elevation at a node	Section 13.11 Page 186
Operation control structures	Operational rules of any dynamically operated control structure	Section 13.12 Page 187
Function tables	Specification of all tables of hydraulic properties in a user-selected order; the specification can be the table itself, or the path definition necessary to find the table	Section 13.13 Page 191
Free-node initial conditions	Elevations, sign indicating whether the flow is into or out of the system, and initial value for all the free nodes of the FEQ model	Section 13.14 Page 202
Backwater analysis	Initial flows and starting depths necessary to compute initial conditions at all nodes	Section 13.15 Page 203

Note: Relevant information can also be found using the search engine available at the USGS Web site il.usgs.gov/proj/feq

FEQUTL input consists of a standard header block followed by one or more command blocks to do the analysis of flow through specific hydraulic features. A command block will have the name of the command followed by information necessary for that command. The commands available in FEQUTL are listed in Table 3.2. The standard

header block remains the same in all FEQUTL input data files. In the FEQUTL input data file, these commands can appear in any order.

Table 3.2 - Summary of Commands in an FEQUTL Input

Command	Hydraulic Feature	Function of the Command	Page reference WRI 97-4037
BRIDGE	Bridge flow	Bridge flow analyzed using Bureau of Public Roads Procedure. This command is replaced by WSPROT14	Section 5.1, page 78
CHANNEL	Channel curvilinearity	Sinuosity is computed for a series of flow lines to compute correction coefficients	Section 5.2, Page 80
CHANRAT	Channel rating	Flows are computed for short, prismatic bypass channels	Section 5.3, Page 87
CRITQ	Critical flow	Critical flow is computed	Section 5.4, Page 89
CULVERT	Culvert flow	Flow through culverts and over the roadway is computed	Section 5.5, Page 91
EMBANKQ	Embankment and weir flow	Flows over embankments, weirs, and other weir-like structures are computed	Section 5.6, Page 106
EXPCON	Flow expansion and contraction	Flow undergoing expansion or contraction is analyzed	Section 5.7, Page 111
FEQX	Flow through a cross section	Hydraulic properties of a cross section are computed	Section 5.8, Page 116
FEQXEXT	Flow through a cross section	Cross sections are extended with a frictionless vertical wall	Section 5.9, Page 118
FEQXLST	Flow through a cross section	Hydraulic properties are computed from data in list format	Section 5.10, Page 122
FINISH	Finish	FEQUTL computation is closed	Section 5.12, Page 122
FLOODWAY	Floodway	Floodway stations are used with FEQX data to compute hydraulic properties of the floodway cross sections	Section 5.12, Page 122
FTABIN	Function table input	One or more tables in a format appropriate for FEQ are read	Section 5.13, Page 125
GRITTER	Dam-break flow	Generalized Ritter dam-break solution method	Section 5.14, Page 126

Table 3.2 (cont.) - Summary of Commands in an FEQUTL Input

Command	Hydraulic Feature	Function of the Command	Page reference WRI 97-4037
HEC2X	Cross section from HEC-2 file	CHANNEL or FEQX input is generated using HEC-2 input data	Section 5.15, Page 127
MULCON	Multiple conduits flow	Hydraulic properties of flow through one or more closed conduits are computed	Section 5.16, Page 129
MULPIPES	Circular pipe flow	Hydraulic properties of flow computed	Section 5.17, Page 133
QCLIMIT	Critical flow limit	A limit on critical flow rate in a closed conduit is set; generally used with EXPCON command	Section 5.18, Page 136
SEWER	Sewer pipe flow	Hydraulic properties for a single circular section are computed	Section 5.19, Page 137
UFGATE	Underflow gate	Flow through underflow, sluice, or tainter gates, with variable gate settings, is computed	Section 5.20, Page 139
WSPROQZ	Bridge flow	Input lines for WSPRO bridge analysis are prepared to analyze the flow	Section 5.21, Page 146
WSPROT14	Bridge flow	A table is prepared using the WSPRO analysis results	Section 5.22, Page 148
WXPROX	Cross sections from WSPRO file	CHANNEL or FEQX input is generated using data from a WSPRO input data file	Section 5.23, Page 149
XSINTERP	Cross section interpolation	Cross sections are interpolated using data from two cross sections	Section 5.24, Page 151

Note: A search engine is available at the USGS Web site www-il.usgs.gov/proj/feq

4.0 Review of Hydrologic Analysis

The amount of water carried by the stream network will be determined by an independent hydrologic analysis of the contributing watershed. The flood runoff is input data read by the FEQ model in one of the following formats:

- Hydrograph:
 - from a file,
 - from a HEC-DSS data file, or
 - from the FEQ input-data file;
- Point discharge at a node, steady-state discharge;
- Discharge distributed uniformly or linearly along a branch (generally used to model the flow in urban storm sewer networks); or
- Unit runoff and corresponding rain gage and land use matrix for branch nodes.

4.1 Review Guidance

A review of the hydrologic analysis is warranted if the flood runoff values used in the FEQ model are not the same as those used in the effective FIS of the subject flooding source. If the FEQ analysis is submitted in support of defining flood hazard parameters for a floodplain previously unstudied for a FIS, the submitted hydrologic analysis of the watershed should be reviewed. The review should also ensure that the flood runoff parameters computed in the hydrologic analysis are correctly applied in the FEQ model of the floodplain.

4.2 HEC-DSS: Integration of FEQ Results Into Watershed Analyses

FEQ has the capacity to model flows through complicated flood control systems where flows are diverted to offline reservoirs and pumped back into the main stream network after the flood peak has been conveyed. FEQ can be used to route the flow through such flood control systems. The FEQ capacity to read and write data in the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center Data Storage System

(HEC-DSS) format is used to integrate FEQ analyses with watershed analyses. The HEC-DSS stores hydrologic data in a format convenient for inventory, retrieval, archiving, and computer model use.

4.3 Locating the Flood Runoff Data in the FEQ Input Data File

The flood runoff data for FEQ are specified at one of the following locations of the FEQ input data file:

- FEQ network-matrix control block, or
- FEQ tributary area block.

The hydrograph, or constant steady-state discharges, are defined at the network-matrix block. FEQ-Code 6 is used to define these data. FEQ has the ability to read hydrographs stored as HEC-DSS data files (or ASCII flat files).

The location of the unit runoff data and drainage areas are defined in the tributary area block. The data defined in the tributary area block are used to compute the runoff hydrograph.

A list of hydraulic features is given in Table 4.1. These features, when reflected in an FEQ model, may affect the discharge of the stream network.

Table 4.1 - Hydraulic Features That May Affect the Stream Discharge

Modeled Hydraulic Feature	FEQ input file
Level pool reservoir	Code 7 in the network-matrix block
Inflow/outflow at right angles to main stream	Code 13 in the network-matrix block
Side weir	Code 14 in the network-matrix block
Dummy branch	Code 15 in the network-matrix block
Inflow/outflow along a branch	Line 1 in branch-description block

5.0 Hydraulic Model Calibration and the Preparation of the Existing Conditions Model

Whenever an FEQ model of a floodplain is calibrated to historic events, the FEQ analysis submittal will consist of calibration models and existing conditions models. During the review, the calibration models will be reviewed in addition to the existing conditions models. If the topography of the floodplain changed between the time of occurrence of the historic flood and present (such as changes caused by the construction of a new highway bridge), the calibration model will be different than the existing conditions model. The existing conditions model will be based on the calibration model; however, it will reflect the present day topographic conditions of the floodplain.

Generally, calibrations are considered good if there is less than a 10% difference between the computed and observed peak discharges and the computed flood elevations match within 0.5 foot of the observed high-water marks.

6.0 Review of an FEQ Analysis

An FEQ analysis is reviewed to determine the following to find specific areas of concern:

1. Representation of the flow path, topography, and hydraulic structures. Is the topography of the channel, floodplain, and hydraulic structures accurately reflected in the existing conditions and calibration models?
2. Modeling methods. Are the physical processes that affect the transmission of water in the floodplain modeled using acceptable methods?
3. Calibration. Is the performance of the floodplain model calibrated to and verified against available past historic data?
4. Discharges. Are the 10%, 2%, 1%, and 0.2% annual chance floodplain data computed using appropriate hydrologic data?
5. Flood hazard parameters. Is all the information necessary to prepare the FIS report, flood profiles, and FIRM available in the output data?

The following discussion provides useful guidance to conduct the review of the five specific areas presented above.

6.1 Representation of the Topography, Flow Path, and Hydraulic Structures

An FEQ analysis defines the stream network using branches, nodes, and control structures. Each branch will have at least two nodes located at its ends. A branch can have many interior nodes. Cross sections are used to define the hydraulic properties of the floodplain represented by the branch. The number of branches used in the FEQ model is specified in the run control block. The NBRA parameter (read at line 1 of the run control block) specifies the number of branches used in the FEQ model.

The stream network is defined in the FEQ input data network-matrix control block. The network matrix that reflects the connectivity of the stream network is defined using 13

FEQ codes (code 1 to code 15, where code 9 and code 10 are not used). The codes relate the branches, nodes, and hydraulic structures necessary to model the floodplain. Codes 4, 5, and 6 consist of any of a total of 15 types of flow. Familiarity with the different FEQ codes and flow types is essential in establishing the relationships between the floodplain, schematic diagram, and the FEQ representation of the floodplain. These issues are discussed in Section 13.6 of the FEQ manual (WRI 96-4240). A brief summary of the FEQ codes and flow types are presented in Table 6.1 and Table 6.2. Table 6.1, "FEQ Codes and Types Used in the Network-Matrix Control Block," presents the FEQ codes, 15 flow types, the function of the codes and flow types, and a reference page from FEQ manual WRI 96-4240, where additional information can be found.

Table 6.1 - FEQ Codes and Types Used in the Network-Matrix Control Block

Code	Type	Description	Page from WRI 96-4240
1	-	Branch	171
2*	-	Number of branches in a junction	171
3	-	Equality of water-surface elevations between nodes	171
4		One-node head-discharge relationship	171
	1	Flow over a weir	171
	2	Stage-discharge relationship	171
	3	Channel control of flow	171
	4	Structure capacity as function of time	171-172
	5	Structure capacity varied dynamically	172
	6	Pump with capacity limited by tail water	172
5		Two-node head discharge relationship	172
	1	Expansion or contraction with critical flow	172

* Number of exterior nodes in a junction

**Table 6.1 (cont.) - FEQ Codes and Types Used in the
Network-Matrix Control Block**

Code	Type	Description	Page from WRI 96-4240
5	2	Bi-directional flow tables and pumping	173
	3	Variable speed, variable head pump	174
	4	Bridge with flow over roadway	175
	5	Abrupt expansion with inflow or outflow	175-176
	6	Two-dimensional tables for flow in both directions	176
	7	Variable height weir	176
	8	Sluice gates (not for general use)**	176
	9	Underflow gate tables	177-178
6	-	Node with known elevation or flow relationship	178
7	-	Level pool reservoir	178
8	-	Critical depth	178
9	-	Not in use	-
10	-	Not in use	-
11	-	Momentum balance option	179
12	-	Match average elevations at two nodes	179
13	-	Conservation of momentum or energy	179
14	-	Side weir	179
15	-	Dummy branch	180

**Applicable only to base sluice gates at Stratton Dam on Fox river at McHenry, Illinois

Note: Level-pool reservoirs, dummy branches, and branches will have at least one end in a junction (except for a single-branch model). Therefore, the common item involved in code 2 is one exterior node.

Table 6.2, "FEQ Codes, Types, and Hydraulic Parameters Defined in the Network-Matrix Block," summarizes the various hydraulic properties at the different fields for the FEQ codes and flow types. In the first column under the title of 'subject,' the flow type represented by the FEQ code and flow type is listed. The second column denotes the page number of the FEQ manual where a detailed discussion of that particular FEQ code or flow type is found. Each row of the third column names the parameter associated with a particular FEQ code and the corresponding flow type (for codes 4, 5, and 6).

Table 6.2 - FEQ Codes, Types, and Hydraulic Parameters Defined in the Network-Matrix Block

Subject	Page FEQ Manual	Code	N(1) A 6-9	N(2) B 10-13	N(3) C 14-17	N(4) D 15-21	N(5) E 22-25	N(6) F 26-29	N(7) G 30-33	N(8) H 34-37	N(9) I 38-41	N(10) J 42-45	F(1) 46-52	F(2) 53-59	F(3) 60-66	F(4) 67-73	F(5) 74-80	Remark
Data found at→ Branch equation	171	1	Branch no.															Branch
Junction $\Sigma Q = 0$	171	2	Nodes at junction	Junction node	Junction node	Junction node	Junction node	Junction node	Junction node	Junction node	Junction node	Junction node						Junction
Equal water level at nodes	171	3	First flow path end node	Second flow path end node														Used at junctions
Flow over weir	171	4	Type 1	Number of nodes where head is specified	Number of nodes where flow is specified	+1, flow is into the system -1, flow is out of system	Table number						Datum for head	Weir length				Generally used to define boundary conditions
Head-discharge	171		Type 2				Datum for head											
Channel control	171		Type 3				Channel slope											
Structure capacity given as fn. of time	171-172		Type 4				Datum for head											
Structure capacity computed by FEQ	172		Type 5				Datum for head											
Pump	172		Type 6				Q-H table number >0Q-H table <0,read unit	Q limit table								Datum for head		
Expansion contraction with critical flow	172	5	Type 1	Upstream (u/s) node	Downstream (d/s) Node	Discharge (Q) specified u/s or d/s <i>Notations used: Operation block (oper.blk) Open (opn) Weir (Wr.) Contraction (Cont.) Coefficient (coef.) Positive (+, or +ve) Negative (-, or -ve) Maximum (max) Submergence (subm.) Bridge (br.)</i>	+1, expansion -1, contra.	Cross section table number					Loss coef. u/s to d/s	Loss coef. d/s to u/s	Datum for head			Define variable losses
Bi-directional flow including pump	173		Type 2				Table flow u/s to d/s	Table submerged data	Table flow d/s to u/s	Table submerge data	0 or 1 pump	Node pump	Datum for head	Flow distance	Pump rate	Pump inlet	Pump cutoff	Pump
Variable speed/head pump	174		Type 3				1, u/s to d/s -1, d/s to u/s	Performance curve	Table/entrance loss	Table/exit loss	Table/coef.	Table speed	Pump name	Outlet pipe elevation	Area/outlet	Inlet pipe elevation	Coef. velocity head	Pump
Bridge with weir flow	175		Type 4				Table/loss coefficient	Table/loss coefficient - flow	Table/bridge area	Table/ +ve weir. flow	Table/ -ve wr. flow	Table/ submergence	Max. br area	Br high elevation	Subm. coef.	Datum for head	Bridge name	Bridge modeling
Abrupt expansion with inflow/outflow	175-176		Type 5				Table/ cr. flow											Abrupt expansion with critical flow
Flow in both directions (u/s to d/s-d/s to u/s)	176		Type 6				Table u/s to d/s	Table d/s to u/s	Factor to multiply values in N(5) or N(6)	Table/ with alternate elevations		Indicate continuation of data	Datum for head					Bidirectional flow through a structure
Variable height weir	176		Type 7				+oper.blk - table/opn	Table weir elevation	Table u/s weir coefficient	Table d/s weir coefficient	Table subm.	Weir name	Weir length	Factor velocity head				Weir heights varies with time
Sluice gate at Stratton Dam, McHenry, IL	177		Type 8				+ oper.blk - table/opn						Sill elevation	Max opening	Width factor			Specific to one sluice gate on Fox river, IL.
Underflow gates	177-178		Type 9				+ oper.blk - table/opn	Gate name	Table 15 u/s to d/s flow	Table 15 d/s to u/s flow			Sill elevation	Max opening				Under flow gate detailed o/p available

Depending on the FEQ code and flow type, up to 15 parameters are read in the network-matrix control block. FEQ reads data in the fixed format available in the FORTRAN programming language. The FEQ manual refers to the first ten parameters as N(1), N(2), ..N(10). The next five parameters are referred to as F(1), F(2), .., F(5). The title row of Table 6.2 gives all 15 parameters N(1) to F(5) and their corresponding fields in the FEQ network-matrix input data. The last column is reserved for remarks.

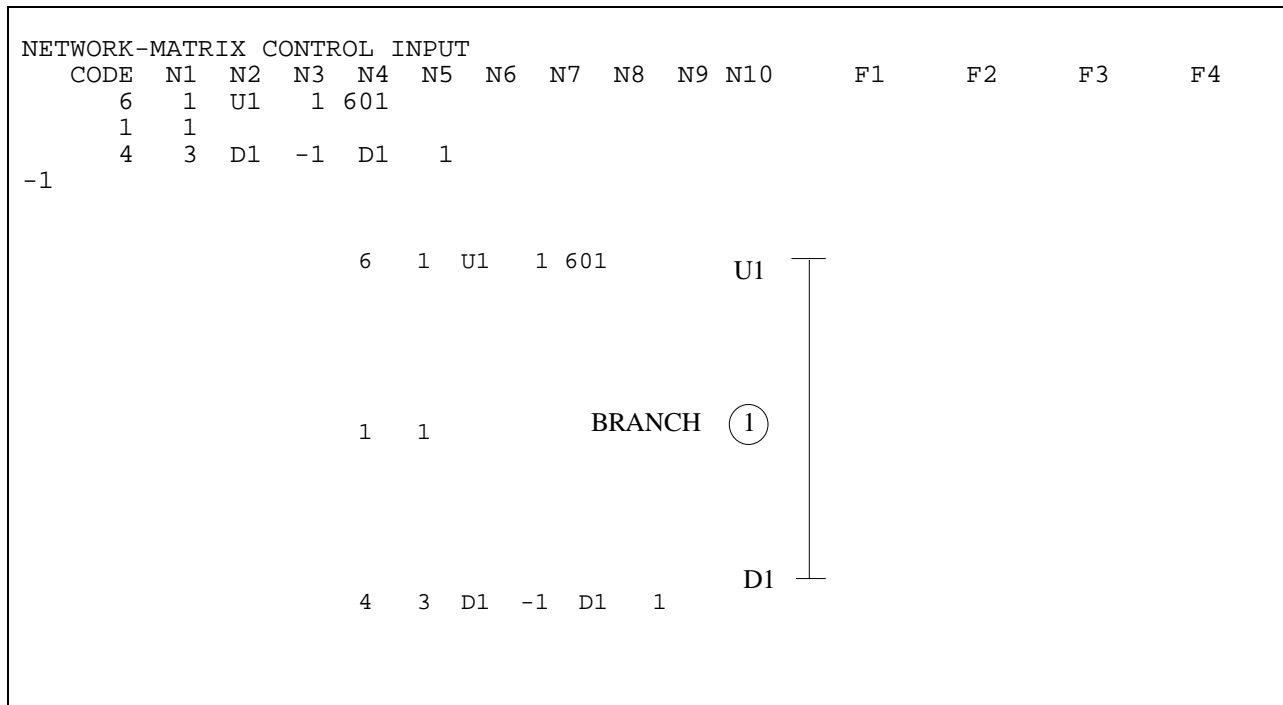
The following example demonstrates how Table 6.2 can be utilized to understand the stream network formulation.

Example: Network-matrix input data (taken from USGS Draft Open-File Report, “Application Guide for the Full Equations (FEQ) Model of One-Dimensional, Unsteady, Open-Channel Flow”).

The description of the stream system network for the FEQ code is specified in the NETWORK-MATRIX CONTROL BLOCK (see Franz and Melching, 1996a, Section 13.6, “Network-Matrix Control Block—Network-Matrix Table,” for detailed input description). A simple example of the FEQ input for a conceptual stream schematization is presented below.

For the first simulation of the prototype model, the network will be represented as just one branch. Figure 6.1 shows the input to FEQ followed by the schematic and expanded input to represent this situation.

Figure 6.1. FEQ Input and Network Schematization for a Single Branch



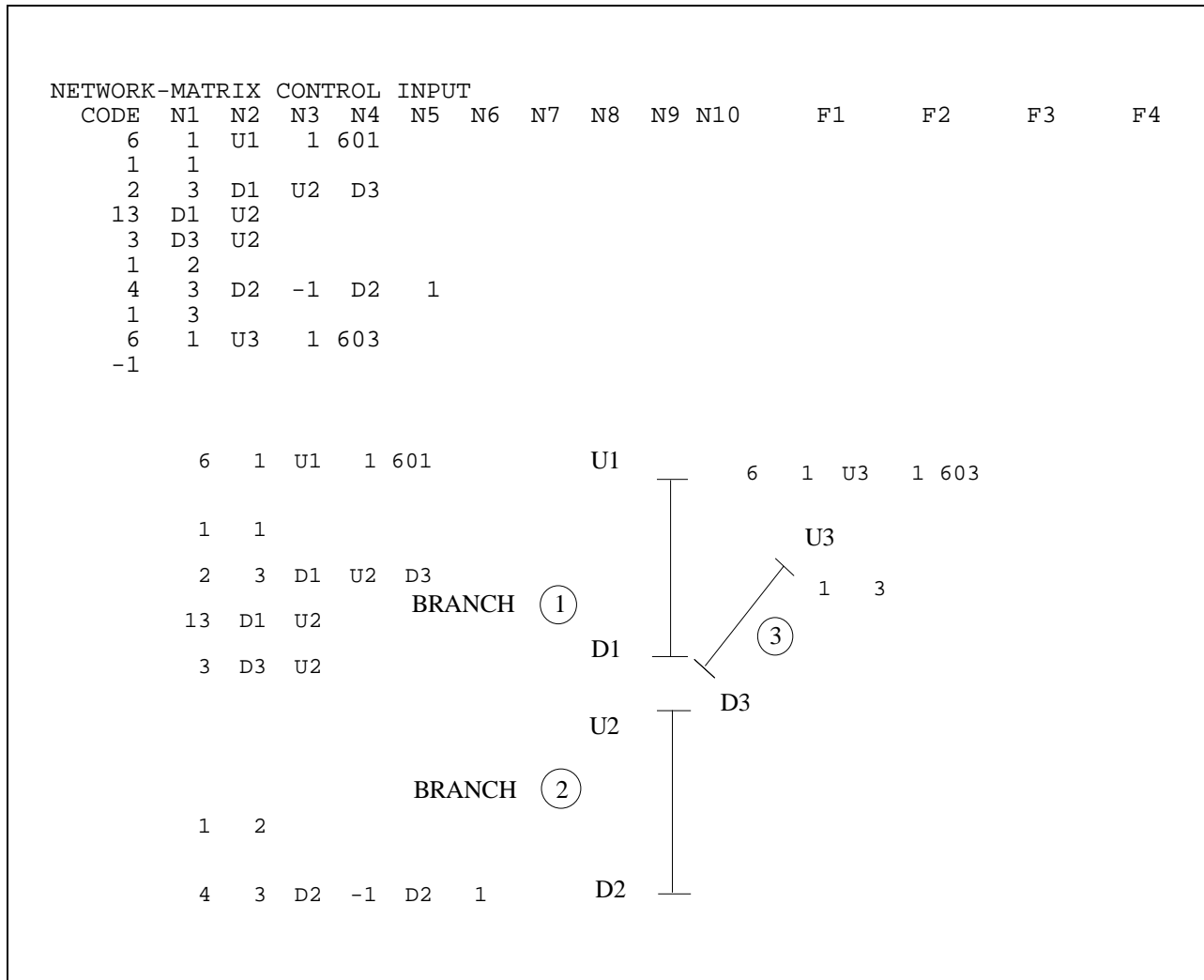
The Code 6 in the first line of input indicates that a time series file is to be the input to node U1 (upstream end of branch 1). The 1 indicates that the type of time series data is discharge. Table 601 is the table containing the data. The positive 1 in location N3 indicates that flow is into the node. Flow into an upstream node is positive.

The Code 1 in the next line of input indicates that there is a branch. The 1 in the next field indicates that the branch is numbered 1.

The third line of input is a Code 4, indicating a one-node control, which is a unique relation between discharge and elevation. The type 3 indicates that a channel control slope rating is to be calculated at node D1 (downstream end of branch 1). The -1 indicates that the slope to be used is the bottom slope of the channel. The second reference to node D1 indicates the node from which the elevation is taken.

The next stage in the model development is to add a tributary to the model. Figure 6.2 shows the FEQ representation followed by the network schematic.

Figure 6.2. FEQ Input and Network Schematization for a Three-Branch System With Tributary



Until familiarity with FEQ codes and flow types is obtained, Table 6.2 can be used as a tool to assist the reviewer in understanding the stream network formulation used in the FEQ analysis.

The first step in reviewing an FEQ analysis involves the review of the stream network. This can be achieved by studying the topographic map of the floodplain, the schematic diagram, and the network-matrix control block of the FEQ input data file. The topographic data of the different elements used in the FEQ model will be stored in the

corresponding hydraulic tables, generally created by an FEQUTL model of the element. The hydraulic property table numbers are defined in the network-matrix control block.

The FEQUTL model of each element (branches, bridges, long pipes, level pool reservoir) will have the cross sections, Manning's roughness coefficients, expansion and contraction coefficients, and other pertinent data necessary to model the flow. The locations of the cross sections are generally defined in the FEQ branch description block. For the hydraulic structures reflected in the FEQ model, the distances between the cross sections are defined in the FEQUTL model input data.

The topographic data of the cross sections and the hydraulic features of the floodplain used in the FEQ/FEQUTL analysis should be certified by a Professional Engineer or Licensed Surveyor. However, topographic information submitted by a Federal agency is accepted without this certification.

6.2 Modeling Methods

A review of the modeling method will involve determining whether the physical processes affecting the transmission of water through the stream network are modeled correctly. Specifically, the governing equations, boundary conditions, and the methods and parameters used to model the flow through the floodplain will be checked. The following discussion highlights issues relevant to the review.

6.2.1 Governing Equations Used in the Analysis

The default option of the FEQ program will use the full dynamic equations for the analysis. The governing equations are altered through the 'inertia' parameter defined in line 1 of the branch description block. The different choices are given below:

Full dynamic equation	inertia = 1.0, the default value
Partial or non-inertia approximation	inertia < 1.0

By assigning a very small value, such as 0.01, to inertia, the non-inertia approximation of the governing equation can be used in the analysis. When non-inertial approximation of the governing equation is used, the momentum components of the dynamic equation are excluded. In some cases, this approximation can be used to overcome convergence problems. Convergence problems can be caused by errors in modeling, and faulty results can be obtained if non-inertial approximations are used inappropriately to overcome these problems. Generally, FEQ models should use the default option and solve the full dynamic equations.

Partial inertia, with a factor of 0.1 or less, can also be used to allow computation with supercritical flow in storm sewers and other lined channels on steep slopes. Additional losses associated with hydraulic jumps are modeled using non-zero values of KA and KD.

6.2.2 External Boundary Conditions of the Floodplain Model

External boundary conditions are given at end nodes of every flow path connected to the internal members of the stream network. Three types of boundary conditions can be defined for these nodes: head-discharge relationship, discharge as a function of time, and head as a function of time. These conditions are defined in the network-matrix block of the FEQ input file. Codes 4, 6, and 8 cover these boundary conditions. External boundary conditions are further explained in Section 8.2 of the FEQ manual

(USGS WRI 96-4240). The review will identify the external boundary nodes and determine the appropriateness of the applied boundary condition.

6.2.3 Methods of Modeling a Floodplain Unobstructed by Structures

A floodplain unobstructed by structures is modeled using one or many branches, depending on reach hydraulic properties. The FEQUTL FEQX command computes the hydraulic parameters of the cross sections. The review will ensure that the cross sections are properly coded into the FEQUTL model, Manning's roughness coefficients are assigned to match the existing channel and overbank conditions, and the distances between the cross sections are reflected correctly for computational convergence. The FEQ program has the capability to interpolate intermediate cross sections. This feature is often used in FEQ analyses. When the distances between adjacent cross sections are small, FEQ models generally do not use expansion and contraction coefficients to account for energy losses, except when there is a sudden change in the hydraulic characteristics, such as roughness, slope, width, etc. The following guidelines apply to the different aspects of the FEQ analysis of a floodplain unobstructed by structures.

Manning's roughness coefficients

The FEQUTL model input and output results for the cross sections should be reviewed to verify the appropriate assignment of Manning's roughness coefficients. The selection of the Manning's roughness coefficients should be justified with ground photographs and/or calibration to high-water marks.

Distance between cross sections

The distance between cross sections is defined in the branch description block.

Expansion and contraction losses

These losses, often called eddy losses, may be needed in a branch with irregular geometry. Canals and generally prismatic channels probably do not require these additional losses. In general, the published Manning's roughness coefficients are selected to represent the frictional energy losses occurring in a reach. Gradual changes in cross section geometry are generally accounted for in the friction loss expressed by Manning's roughness coefficients. In the FEQ program, these energy losses are represented by using the parameters KA and KD in the branch-description block.

If the change in geometry of the channel is sufficiently rapid, it may be necessary to insert a junction and use the EXPCON command in FEQUTL to compute a 2-D table describing the flow through the change in geometry. This is required if the change in geometry causes critical flow conditions.

Supercritical flow

Storm sewers of modest slopes (0.5%) and steep channels can cause supercritical flow conditions to occur. FEQ can simulate supercritical flows in channels by using a partial inertia approximation. However, the user is required to identify supercritical flow reaches. Additional energy losses occur when hydraulic jumps are formed where supercritical flows meet subcritical flows. These additional losses can be modeled using non-zero values of KA and KD of the branch description block.

6.2.4 Methods of Modeling Flow Through Culverts

The review should determine whether the culvert flow is modeled according to FEQUTL guidelines and provides reasonable results. The FEQUTL CULVERT analysis solves the governing equations to determine the hydraulic properties of flow through culverts.

As discussed in Section 2.2, FEQUTL can provide two output files. One is a general output file with the results of the culvert analysis and any associated error messages. The other is a table of the hydraulic properties of the culvert flow read by the FEQ analysis. The general output FEQUTL file also identifies the type of flow through the culvert. The review of a culvert analysis should be accomplished by reviewing the FEQUTL input and the general output file.

Losses at culverts are included in the coefficients assigned in the CULVERT command in FEQUTL. The user is provided the geometric description of the entrance geometry and the approach cross section size. For partially full entrance flows in culverts, the Federal Highway Administration recommends entrance loss coefficients for different types of culverts. These coefficients are published in Table 12 of the September 1985 report, FHWA-IP-85-15, titled "Hydraulic Design of Highway Culverts."

The CULVERT command computes the energy losses at an exit section using momentum balance principles.

The discharge coefficients used by the CULVERT command to compute flow through a culvert barrel are taken from Chapter A3, "Measurement of Peak Discharge at Culverts by Indirect Methods," of the USGS publication, "Techniques of Water-Resources Investigations of the United States Geological Survey," Book 3.

Flow over roadways (weir flow) is analyzed by FEQUTL using discharge coefficients. These coefficients are taken from Chapter A5, "Measurement of Peak Discharges at Dams by Indirect Methods," and also from the USGS publication, "Techniques of Water-Resources Investigations of the United States Geological Survey," Book 3. User-defined discharge coefficients can also be used by FEQUTL to model weir flows.

The reviewer should verify that appropriate discharge coefficients are used in the submitted analysis to analyze the weir flow being modeled.

FEQ computations for Type 5 flow through the culvert should be verified using the results of other models in FEMA's accepted models list.

The "Handbook of Hydraulics For the Solution of Hydraulic Engineering Problems," Sixth Edition, by Barter and King (1976, McGraw-Hill Publishing Company), is widely used in the United States as a reliable source to check the discharge coefficients of weirs and orifices.

Error messages printed by the FEQUTL analysis should be reviewed to determine whether the culvert flow has been modeled correctly.

6.2.5 Methods of Modeling Flow Through Bridges

FEQUTL uses the USGS WSPRO computer program to conduct bridge flow analyses. The review should be conducted using the guidelines available for a WSPRO bridge analysis. The review should determine whether the topography of the bridge, as well as the floodplain in the vicinity of bridge, are reflected correctly. In addition, the energy losses associated with the flow contraction (upstream of the bridge) and the flow expansion (downstream of the bridge) are modeled using coefficients recommended in the WSPRO manual. If weir flow is modeled, the discharge coefficients used should be checked against nationally accepted values. The aforementioned "Handbook of Hydraulics" is widely used in the United States as a reliable source to check the discharge coefficients of weirs. For a given range of discharges, FEQUTL can compute water-surface elevations upstream of a bridge (flow rating relationship). The FEQUTL analysis is conducted for free flow conditions as well as submerged flow conditions. The general output file printed by the FEQUTL program will contain the flow rating relationship computed for the bridge. In addition, error and warning messages are printed by FEQUTL on the general output file. The warning and error messages indicate potential problems of the analysis and should be reviewed.

6.2.6 Methods of Modeling Flow Through Long Pipes

The practice of containing portions of streams in a closed conduit to permit development of the land above often creates long pipe flows. General guidelines are not available for the classification of closed conduit flow into culvert flow and long pipe flows. Generally, flows in short closed conduits are modeled as culverts. Flows in longer closed conduits with a portion of flow unaffected by the entrance and exit turbulence may be more appropriately modeled as long pipes.

A long pipe is treated like a branch in FEQ. The cross section of the long pipe can be described using one of the following FEQUTL commands:

- SEWER
- MULPIPES
- MULCON

For the range specified by the user, the SEWER, MULPIPES, and MULCON commands have the capability to generate the hydraulic properties relationship for the long pipe.

The energy losses at the entrance and exit (contraction and expansion losses) of a long conduit are generally computed by the EXPCON command available in FEQUTL. These losses are stored in a 2-dimensional table. In some cases, the expansion and contraction losses at each end of the long pipe can be computed using the CULVERT command. If the CULVERT command is used to model expansion and contraction losses, it is necessary to select the approach and departure sections to represent the flow conditions at each end of the pipe.

The review should check that the entrance and exit losses are in a reasonable range and that the conduit shape, roughness, and profile is properly represented.

If the long pipe collects storm runoff through inlets (making it a storm sewer), the value of CFRATE and YC should represent the effective flow capacity at the inlets. The CFRATE defines the effective inflow area per unit length of the conduit. The following example further explains the use of CFRATE and YC to model long pipe flows.

Example: Estimation of the parameter CFRATE for storm sewers with inlets

A storm sewer has inlets that are 150 feet apart. The inlets are of circular shape with a diameter of 1 foot. The stationing unit used in the FEQ analysis is 1 mile.

The effective flow area for this long pipe is computed as follows:

Area of inlet = $\pi/4 \times 1 \times 1$ square feet

Assuming a discharge coefficient of 0.6, and 'g' as the gravitational acceleration,

Flow through one inlet into the storm sewer

$$= 0.6 \times \text{Area of inlet} \times \sqrt{(2g \times \text{water head})}$$

Flow/unit length of the storm sewer = $5280/150 \times$ inlet flow

$$= 5280/150 \times 0.6 \times \text{Area of inlet} \times \sqrt{(2g \times \text{water head})}$$

$$= \text{CFRATE (in square feet)} \times \sqrt{(2g \times \text{water head})}$$

$$= 17 \text{ square feet} \times \sqrt{(2g \times \text{water head})}$$

CFRATE for the storm sewer = 17 square feet

Generally, the estimate for the parameter CFRATE is approximate. For the example above, a reasonable estimate for CFRATE may lie anywhere between 10 and 25.

Unrealistically small CFRATE values will compute more surface ponding, and the flood peak will be attenuated by the ponding. When the parameter assigned for CFRATE is larger than necessary to reflect existing conditions, the analysis will produce unrealistic hydraulic gradelines as large amounts of flow are forced into the long pipe.

Unrealistically large CFRATE values typically may cause FEQ to fail to complete the desired calculations. Review should ensure that this situation is not encountered in the FEQ analysis.

Very small CFRATE values may result in the computation of excessive ponding. The ponding volumes are printed in the FEQ output file (branch data). Review should ensure that ponding volumes computed by FEQ are appropriate for the floodplain modeled.

6.2.7 Methods of Modeling Flow Through a Level Pool Reservoir

A level pool reservoir is assumed to have a horizontal water surface and the capacity to store water as well as convey it. A level pool reservoir is hydraulically represented by a relationship between different reservoir levels and the corresponding storage and outflows (stage-storage-discharge relationship). Level pool reservoir analysis has many potential applications in unsteady flow modeling. The most common application is to model the flow through lakes and ponds in the floodplain. Level pool reservoirs can also be used to reflect flows through wide, flat floodplains. In this case, roadways, levees, or dikes generally form the boundaries of the reservoir.

In schematic diagrams of the stream network, a level pool reservoir is usually shown using a circle and a short line and dummy branches (Figure 2.1). FEQ code 7 is used to model the stage-storage relationship of the level pool reservoir. The stage-storage relationship is usually stored in FEQ Type 3 tables. Section 8.6 of the FEQ user's manual provides a detailed discussion on FEQ analysis of level pool reservoir flows.

Review should proceed by checking the stage-storage relationship with the supporting computations and drainage area maps submitted. The discharge structure input and output files as well as error messages should be reviewed before determining the accuracy of the model.

6.2.8 Methods of Modeling Flow Junctions

Flow junctions are defined in the FEQ network-matrix block. Equality of water-surface elevation or momentum balance can be chosen as the criterion to analyze the flow at the junction. The review should verify whether the topographic information supports the schematization of the flow junction and whether the criteria selected to model the junction (equality of water-surface or momentum) reflect the flow conditions at the junction.

6.2.9 Methods of Modeling Flow Through Weirs, Spillways, and Underflow Gates

FEQ code 5 is used to model flow through weirs, spillways, and underflow gates. Flow type 7 of FEQ code 5 in the network-matrix data has the capability to model weirs, including those where height varies with time. The discharge coefficient, weir length, weir elevation, and submergence data are read in the FEQ network-matrix input data block.

The FEQUTL UFGATE analysis is generally used to analyze flow through gates. The FEQUTL EMBANKQ analysis analyzes flow over an embankment-shaped weir, such as flow over a typical roadway.

The review of these analyses will include checking whether the dimensions of the weirs, gates and spillways in the FEQ model correlate with the physical structures in the floodplain. This is achieved by consulting the topographic maps of the floodplain and other certified data related to the structures submitted with the analysis. In addition, the review should verify that the discharge coefficients used in the analysis are taken from nationally accepted sources. The aforementioned "Handbook of Hydraulics" is widely used in the United States as a reliable source to check the discharge coefficients of weirs.

6.2.10 Computation of a Floodway

A floodway is computed by reducing the conveyance equally from the existing conditions model of the floodplain on either side of the stream such that the difference between the floodway elevation and the natural water-surface elevation (surcharge) is lower than the maximum allowable limit. The maximum allowable surcharge in the NFIP is 1.0 foot; some communities and/or States specify lower surcharges. This is known as computing the floodway based on equal conveyance reduction criterion. FEQ does not have the capability to automatically define floodway stations based on this criterion. FEQUTL offers a FLOODWAY analysis where conveyance is reduced equally from both sides of the floodplain. However, to obtain the final floodway configuration, many combinations of conveyance reductions have to be analyzed using the FEQUTL and FEQ programs.

In the past, FEQ analyses have used the steady state USGS FLDWAY model to define the initial set of floodway stations based on equal conveyance reduction criterion. The peak-flow discharge and computed water-surface elevations and the cross section geometry is fed into the FLDWAY model to obtain the corresponding floodway stations. These stations can be the basis to define the floodway for floodplains studied using the FEQ program. In this method, the floodway stations are incorporated into FEQUTL input files for the corresponding cross sections. Subsequently, the FEQ floodway model is created using the hydraulic properties computed by FEQUTL for the floodway cross sections (and hydraulic features). The floodway surcharge values associated with the floodway configuration are computed manually using the 1% annual chance water-surface elevations of the natural floodplain model and the corresponding floodway model.

During the review, data from two FEQ analyses (natural floodplain model and the floodway) will be checked. The review should determine the following:

- Equal conveyance reduction criterion was used to determine the floodway stations.
- Surcharges and flood elevations were determined correctly using the natural floodplain model and the floodway model.
- The same discharges were used in the natural floodplain and floodway models.

6.2.11 Flood Hazard Parameters

The floodplain delineation on the FIRM and the flood profile and floodway data table in the FIS are prepared using the hydraulic parameters defined in the FEQ analysis. The following data are necessary to prepare or revise a FIS and FIRM:

- Cross section locations (distance from upstream and downstream cross sections). These are defined in the branch description block of the FEQ input data.
- Water-surface elevations. These are obtained from the summary output tables of the FEQ general output file.
- Channel invert locations and elevations. These are defined in the branch description block of the FEQ input data as well as in the FEQUTL input and output files for the cross sections.
- Location and geometry of the bridges, culverts, and similar structures. These data are found in the FEQ branch description block (locations) as well as in the input and output files of the corresponding FEQUTL analyses (geometry).

- Average velocity of flow. These data are obtained from the summary output of the FEQ general output file. Because the average velocity of flow of the floodway is necessary, the FEQ floodway model should be used.
- Floodway stations. These data are found in the FEQUTL analyses of the floodway cross sections and structures.
- Floodway water-surface elevations. These elevations are obtained from the summary output of the FEQ (floodway analysis) general output file.
- Floodway surcharge. This will be manually computed using the flood elevations computed by the FEQ analysis of the 1% annual chance natural floodplain and the floodway.
- Flow area. This information is obtained from the hydraulics properties table computed by FEQUTL.
- Top widths. This information is obtained from the hydraulic properties table computed by FEQUTL.
- Channel and overbank Manning's roughness coefficients. These data can be found in the FEQUTL input data file.

These data will generally be summarized in the report submitted with the FEQ analysis. However, review should verify that the data provided in the report are generated by the FEQ and FEQUTL analyses.

7.0 Complex Flow Situations

Frequently, an FEQ analysis is prepared to analyze flow situations that cannot be accurately analyzed using steady-state backwater models such as the USACE HEC-RAS model. These complex flow situations include flow diversion, flow reversal, urban storm sewer flow, and levee overtopping.

The review of these analyses includes checking whether the dimensions of the structures or pumps used in the FEQ model correlate with the actual physical structures in the floodplain. This is achieved by consulting the topographic maps of the floodplain and other certified data related to the structures submitted with the analysis. In addition, the reviewer should verify that the discharge coefficients used in the analysis are taken from nationally accepted sources. The aforementioned "Handbook of Hydraulics" is widely used in the United States as a reliable source to check the discharge coefficients of weirs. Following is a summary of the FEQ features that can be used to model these complex flows:

Flow Diversions

Flow diversions are generally modeled as side weirs using dummy branches. In addition, a flow evacuation pump can divert flow. The FEQUTL EMBANKQ analysis is used to model flow over embankment-shaped weirs. FEQ code 14 is used to model flows over side weirs. The selection of the side weir coefficient is crucial in modeling the flow diverted by side weirs. Flows affected by pumps are modeled using Code 5, Types 2 or 3 of the network-matrix control block (Please refer to Table 6.2). Similarly, the flow junctions are generally modeled using codes 2 and 3 of the network-matrix block.

Flow Reversal

FEQUTL can create a hydraulic properties table for bi-directional flows through hydraulic features (in upstream to downstream and downstream to upstream directions). These properties will be used by the FEQ analysis to model flow reversals.

Urban Storm Sewer Flow

Surcharged flows and low flows in storm sewer networks can be modeled using the FEQ and FEQUTL analyses. The surcharged flow is modeled in the branch description block using CFRATE and YC in line 1 of the branch description block. The maximum effective flow area (in square feet) available per unit length of a branch is represented by the parameter CFRATE. The parameter YC represents the depth of water at a storm sewer inlet at the beginning of ponding. The FEQ program computes the maximum rate at which water can enter or exit a storm sewer using CFRATE in conjunction with YC. If the rate of inflow is less than the maximum rate computed, the entire inflow is assumed to enter the storm sewer; otherwise, only the maximum rate is allowed to enter. The FEQ program assumes that the excess water is stored and allowed to enter into the storm sewer at a later time when the inflow capacity is available. However, additional modeling is necessary to compute the depth of ponding caused by surcharged storm sewer flows.

Generally, the ADDNOD option available in the same line is used to add additional nodes in a storm sewer modeled as one branch.

8.0 Program Execution

Review of FEQ and FEQUTL analyses sometimes requires the execution of these models. The submitted FEQ and FEQUTL analyses are executed to establish the sensitivity of the hydraulic parameters.

8.1 Pre- and Post-Processing Programs

FEQ does not have its own pre-processing program or data editor to create the data file. The input and output files can be created/read by any convenient editors. Some proprietary programs exist to plot the schematic diagram used in an FEQ model (e.g., DuPage County, Illinois; and Illinois Department of Natural Resources). However, these models are not available for general, public use.

The recently released USGS program GENSCN provides some post-processing graphical capabilities for FEQ. Water-surface elevation, top width, flow area, and other data can be plotted as time series at any node, or as a profile of one or more branches. The water-surface elevations and cross section and channel invert data can be manually entered into the FEMA RASLOT program to create flood profiles.

8.2 Running the FEQ and FEQUTL Programs

The FEQ and FEQUTL programs will be executed by typing the following commands at the monitor prompt:

FEQ: FEQ input file, output file

FEQUTL: FEQUTL input file, general output file, hydraulic table file

(where “input file”, “general output file”, and “hydraulic table file” refer to file names)

File names have to be limited to eight alphanumeric characters, starting with an alphabetical character, and the extensions consist of three alphanumeric characters. The file names must be entered with their extensions.

8.3 Useful Technical Resources

The USGS in Urbana, Illinois, maintains some useful Web sites to provide technical support to the users of the FEQ and FEQ programs. They are listed below:

<http://water.usgs.gov/software/feq.html>

<http://il.water.usgs.gov/proj/feq/>

The latest approved version of FEQ is listed in the accepted models list posted at the FEMA Web site www.fema.gov/mit/tsd/EN_modl.htm.

The following publications are posted at the USGS Web site and have information related to FEQ and FEQUTL analyses.

Bodhaine, G.L., 1968, "Measurements of peak discharges at culverts by indirect methods: U.S. Geological Survey Techniques," U.S. Geological Survey, Water-Resources Investigations, Book 3, Chapter A3, p.60.

Brater, E.F. and King, H.W., 1976, Handbook of Hydraulics, 6th ed.: New York, variable pagination.

Bradley, A.A.; P.J. Cooper; K.W. Potter; and T. Price, 1996, "Floodplain mapping using continuous hydrologic and hydraulic simulation models," American Society of Civil Engineers, *Journal of Hydrologic Engineering*, Vol. 1, No. 2, pp. 63-68.

Cooper, Paula, and H. Sherrie Chang, 1998, "Applications of the FEQ Unsteady Flow Model in DuPage County and Beyond," American Society of Civil Engineers, Water Resources Planning and Management Division, *Water Resources and the Urban Environment*, pp. 141-146.

Franz, D.D., 1982, "Tabular representation of cross-sectional elements," American Society of Civil Engineers, *Journal of the Hydraulics*, Vol. 108, No. 10, pp. 1070-1081.

Franz, D.D., and C.S. Melching, 1997, *Full Equations (FEQ) model for the solution of the full, dynamic equations of motion for one-dimensional unsteady flow in open channels and through control structures*, U.S. Geological Survey, Water-Resources Investigations Report 96-4240, p. 258.

Franz, D.D., and C.S. Melching, 1997, *Approximating the hydraulic properties of open channels and control structures during unsteady flow using the Full Equations Utility (FEQUTL) program*, U.S. Geological Survey, Water-Resources Investigations Report 97-4037, p. 205.

Husling, H., 1967, "Measurement of peak discharge at dams by indirect methods," U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A5, p.29.

Ishii, A.L.; T.J. Charlton, T.W. Tortel, and C.C. Vonnahme, 1998, "Modeling system for near real-time flood simulation for Salt Creek in Du Page County, Illinois," Subcommittee on Hydrology of the Interagency Advisory Committee on Water Data, Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, pp. 8.51-8.58.

Ishii, A.L.; T.J. Charlton; T.W. Tortel; and C.C. Vonnahme, 1998, "Operational Modeling with Dynamic-Wave Routing," American Society of Civil Engineers, Water Resources Planning and Management Division, *Water Resources and the Urban Environment*, pp. 147-152.

Ishii, A.L., and J.E. Wilder, 1993, "Effect of boundary condition selection on unsteady-flow model calibration," Proceedings of the XXV Congress of International Association for Hydraulic Research, Tokyo, pp. 193-200.

Ishii, A.L., and M.J. Turner, 1997, *Verification of a one dimensional, unsteady flow model for the Fox River in Illinois*, U.S. Geological Survey, Water-Supply Paper 2477, p. 65.

Knapp, H.V., and T.W. Ortel, 1992, "Effect of Stratton Dam operation on flood control along the Fox River and Fox Chain of Lakes," Illinois State Water Survey Contract Report 533, p. 79.

Lan, Y.; S. Rogers; J. Sikora; P. Cooper; and C. Klepp, 1996, "Unsteady flow hydraulic modeling for flood plain mapping along the West Branch Du Page River, Du Page County, Illinois," International Water Resources Association Rivertech96 Proceedings of the 1st International Conference on New/Emerging Concepts for Rivers, Chicago, pp. 204-211.

Moore, W.P., 1996, "Peaking operation study for the Markland Hydroelectric Project," International Water Resources Association Rivertech96 Proceedings of the 1st International Conference on New/Emerging Concepts for Rivers, Chicago, pp. 246-253.

Turner, M.J., 1994, *Data-collection methods and data summary for verification of a one-dimensional, unsteady-flow model of the Fox River in Illinois*, U.S. Geological Survey, Open-File Report 93-483, p. 40.

Turner, M.J.; A.P. Pulokas; and A.L. Ishii, 1996, *Implementation and verification of a one-dimensional, unsteady-flow model for Spring Brook near Warrenville, Illinois, U.S.* Geological Survey, Water-Supply Paper 2455, p. 35.