UPPER MISSISSIPPI RIVER SYSTEM FLOW FREQUENCY STUDY
APPENDIX A - Hydraulics

1. Introduction

1.1 Selection of the UNET Model. Following the Midwest Flood of 1993 Congress tasked the Corps of Engineers to conduct a comprehensive, system-wide study to assess flood control and floodplain management practices in the areas that were flooded. That study was known as the Floodplain Management Assessment study (FPMA) (USACE, 1995). It encompassed three Corps of Engineer Division boundaries and five District boundaries. Participating Districts included: St. Paul, Rock Island, and St. Louis on the Mississippi River, and Omaha and Kansas City on the Missouri River. To accomplish the study objectives, an unsteady flow model of the Upper Mississippi and Lower Missouri Rivers was developed. Each District developed independent models which produced results that were assimilated by neighboring Districts so that floodplain management alternatives could be evaluated systemically. The unsteady flow model was used to evaluate the potential impacts of various levee modification alternatives and upland watershed measures, such as reservoirs and land treatments, on the 1993 flood. The model selected for use in the FPMA study was UNET (HEC, 2001). It is a one-dimensional unsteady open channel flow simulation model UNET was subsequently employed as the kernel river hydraulics model for the development of a comprehensive real time flood forecasting system; the Mississippi Basin Modeling System (MBMS, HEC 1998). The UNET simulation model was further applied for the Upper Mississippi Flood Frequency study to associate stage frequency with flow frequency by continuous unsteady flow simulation of historic periods of record.

2. The UNET Modeling System

2.1 Description. UNET (HEC, 2001) was the primary hydraulic analysis tool used in the FPMA and MBMS studies. It simulates one-dimensional unsteady flow through a network of open channels. One element of open channel flow in networks is the split of flow into two or more channels. For subcritical flow, the division of flow depends upon the capacities of the receiving channels. Those capacities are functions of downstream channel geometries and backwater effects. A second element of a network is the combination of flow; termed the dendritic problem. This is considered to be a simpler problem than the flow split because flow from each tributary is dependent only on the stage in the receiving stream. A flow network that includes single channels, dendritic systems, flow splits, and loops such as flow around islands, is the most general problem. UNET has the capability to simulate such a system.

Another capability of UNET is the simulation of storage areas; e.g., lake-like regions that can either provide water to, or divert water from, a channel. This is commonly called a split flow problem. In this situation, the storage area water surface elevation will control the volume of water diverted. That volume, in turn, affects the shape and timing of downstream hydrographs. Storage areas can be the upstream or downstream boundaries for a river reach. In addition, the river can overflow laterally into storage areas over a gated spillway, weir, levee, through a culvert, or via a pumped diversion.

In addition to solving the one-dimensional unsteady flow equations in a network system, UNET provides the user with the ability to apply many external and internal boundary conditions including flow and stage hydrographs, gated and uncontrolled spillways, bridges, culverts, and levee systems.

To facilitate model application, cross sections are encoded in a modified HEC-2 (HEC, 1990) forewater (upstream to downstream) format. Many river systems have been modeled using HEC-2, and those existing data files can be readily adapted to UNET format. Boundary conditions (flow hydrographs, stage hydrographs, etc.) for UNET can be input from any existing HEC-DSS (HEC, 1995) data base. For most simulations, particularly those with large numbers of hydrographs and hydrograph ordinates, HEC-DSS is advantageous because it eliminates the manual input of hydrographs and creates an input file which can be easily adapted to a large number of scenarios. Hydrographs and profiles which are computed by UNET are output to HEC-DSS for graphical display and for comparisons with observed data. Guidance for numerical modeling of river hydraulics is given in the Corps of Engineers Engineer Manual on *River Hydraulics* (USACE, 1993).

2.2 UNET Versions. UNET version 3.1 was released by HEC for general use at the end of FY 1996. That release contained substantial changes from the prior (ver. 3.0) release of UNET. Some added features included greater use of DSS for graphical displays, additional simple spillway connections, tunnel simulation, embankment breach simulation, more types of boundary conditions, etc. Documentation of those changes is available from HEC. Near the end of FY 1997 version 3.2 was released for general use. That version corrected some errors in ver. 3.1 relative to DSS reads/writes and embankment breaches. The HEC-UNET user's manual was substantially improved in its correspondence with the software.

A special version of UNET was developed during the Mississippi Basin forecasting project. HEC included appropriate features of the MBMS version of UNET in HEC-UNET public release 4.0 (HEC, 2001).

Customized versions of UNET were developed as necessary via contracts with Dr. Barkau by several District offices involved in the Flow Frequency Study; see individual District Appendices for details.

2.3 Developments to UNET for the MBMS Project.

2.3.1 Levee Algorithms. The leeved areas along the Mississippi-Missouri River systems are substantial. Breaching of levees, as shown in Fig. 1, results directly in flooding of areas meant to be protected by the levees. The water that floods those areas is stored for later return to the river. The modeling of this exchange and storage of water resulting from levee breaches is an important aspect of UNET. This feature is included in HEC-UNET Ver. 4.0.

Figure 1. Levee Breach (North Central Division, 1994)

The UNET approach to simulation of the impact of levee overtopping and/or breaching on flood characteristics prior to the 1993 flood event considered the area behind the levee to be a storage area. That is, it fills and empties through a levee breach or overtopped area, but does not convey water in the downstream direction. This concept of storage areas is used to approximate a blend of one-dimensional and two-dimensional approaches to river modeling. For most confined locations and for overbank floods lesser than that of 1993, this has been an adequate assumption.

A simple reservoir routing algorithm is used in the existing UNET model to compute the flow through the levee breach; the routing coefficient can be fitted to observed data (hindcasting). Application of the UNET system to forecasting, however, should use coefficients and parameters derived as much as possible from field measurable information, rather than calibrated to past events. The routing coefficient that needs to be selected is the *k* in the equation:

$$Q_s = k\Delta V$$

where V is the volume of storage, Q_s is the flow of water to or from a storage cell (i.e., between cells or between the river and cell), ΔV is the volume to be filled or emptied, and *k* is a linear routing factor with the units of $time^{-1}$. In the UNET model, *k* can vary among storage cells, but does not change with time nor with breach parameters such as width.

The above description of levee breaches and the associated hydraulics is simplified. As a part of the MBMS development, research was performed to develop a physical interpretation of the linear routing coefficients (Shen and Zhao, 1995). This research involved comparing results using the storage area (linear routing) technique with those obtained using a fully two-dimensional hydrodynamic model. It was concluded that the routing coefficient required for the storage cell technique could only be accurately determined from past events and not from physical (e.g., topographic) data.

As a result of the 1993 flood on the Missouri River, a new capability for simulating the effects of levee breaches was added to UNET. During 1993 virtually all of the agricultural levees along the Missouri were overtopped, resulting in significant overbank conveyance. This situation poses a peculiar modeling problem. For flows below a certain transition discharge, the levee interior acts as a storage cell which communicates with the river through a breach, or breaches, in the embankment. When flow exceeds the transition discharge the area behind the levee no longer acts as a storage cell but becomes part of the river, conveying flow. Therefore, there are two situations that must be modeled; a storage cell and a flowing river. An algorithm was developed that allows the overbank storage areas to change to conveyance areas (and back) based upon a triggering river flow or stage. Consequently, the conveyance and storage of the levee cells is described by traditional cross section data rather than with a lumped routing coefficient. A detailed description of this technique, known as the "Kansas City Levee Algorithm", is given in the Kansas City District (NWK) Appendix and has been incorporated into HEC-UNET Ver. 4.0.

Note, however, that these techniques do not directly predict the location, size, or timing of a levee breach. Once these parameters are known or estimated, however, the impacts of the levee breach on upstream and downstream flows and stages can be computed. Operationally, from forecasted stages, the forecaster may be able to hypothesize the locations and times of potential levee breaches and use the MBMS to rapidly evaluate impacts of various scenarios. Such an application would require that the possible levee overtopping and/or breaching parameters be built into the geometric data.

2.3.2 Levee Breach Assumptions. Implementation of the UNET levee breach algorithms developed for the MBMS and related studies requires specification of a water surface elevation in the river at which the levee begins to breach. Historic observations, levee design parameters and geotechnical research indicate that levees may withstand some degree of overtopping prior to initiation of substantial breach development. Initiation of breaches with water surfaces lower than the levee crest is also possible due to wind waves, vegetation, local subsidence, etc. Selection of a consistent breaching criterion was addressed in the formulation of study parameters - "*A consensus* (being) *reached where federal levees would be modeled to fail when the water surface elevation exceeds the top of levee…*" (Attachment A).

2.3.3 Navigation Dam Algorithms. A major effort was undertaken to provide the ability to simulate lock and dam operations (as shown in Fig. 2) with the UNET system (Barkau, 1996). The capability to use operating rule curves at navigation dams as internal boundary conditions was developed and implemented. Preparation of the input data necessary to describe these rule curves was accomplished by the District offices.

Figure 2. Melvin Price Lock and Dam

Two types of navigation dam operation can be simulated with UNET:

Control point within the navigation pool. For this type of operation, the navigation pool is adjusted to maintain a constant elevation at a control point in the navigation pool. This procedure is also called hinge pool operation because the pool conceptually tilts about the control point. The hinge pool operation was devised to minimize the amount of flooded land that had to be purchased by the Government in the upper reaches of the pool. The operation of a hinge pool is defined by an operating curve (essentially a rating curve) at the dam. The operating curve is usually derived from experience. Operating curves are a set of functions which relate control point elevation to pool elevation at constant flow. An example of the operation criteria that can be prescribed by input data for a hinge pool is shown on Figure 3. Figure 3 portrays a hinge pool operation as used by the St. Louis District. In this case, the instruction to the lockmaster is to maintain a target pool elevation.

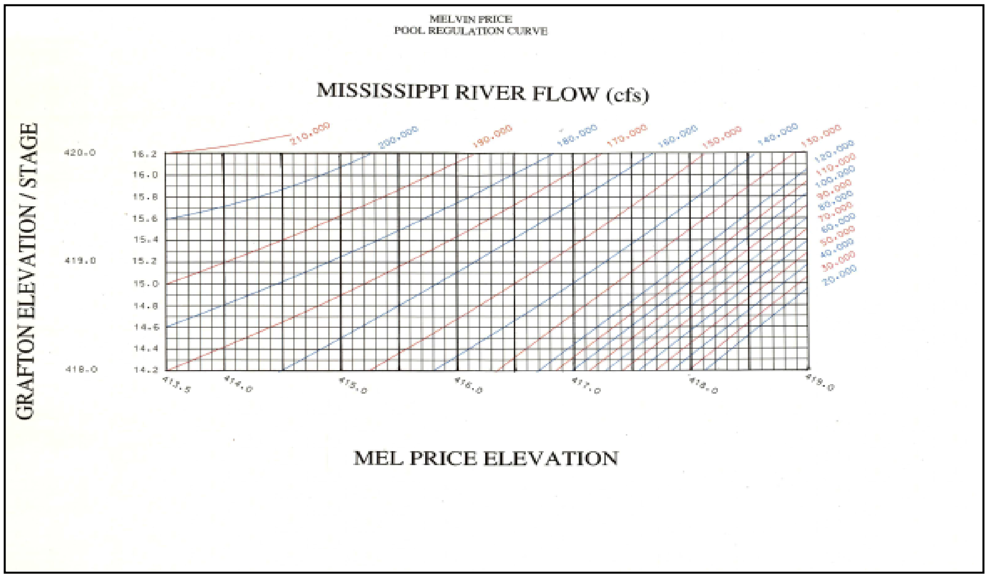

Figure 3. Melvin Price L&D Hinge Pool Operation

Control point at the dam. This is the simplest regulation procedure for a navigation dam. The navigation pool is maintained at a target elevation at the dam. When the tailwater elevation plus the swellhead through the structure exceeds the target elevation, the pool is no longer controlled by the dam and the dam is in open river condition. The target elevation can change with the seasons. Figure 4 reflects a general operation as performed by the St. Paul District. For high flows tailwater controls (open river condition) and the difference between the pool and tailwater is the loss at the structure (swellhead). For lesser flows, gates are set to maintain a constant pool elevation. For low flows, the pool level is increased to maintain an upstream navigation depth. In this case, the lockmaster is given gate settings. Flexibility must be provided to allow for seasonal variations (ice, wind, etc.) and local requirements.

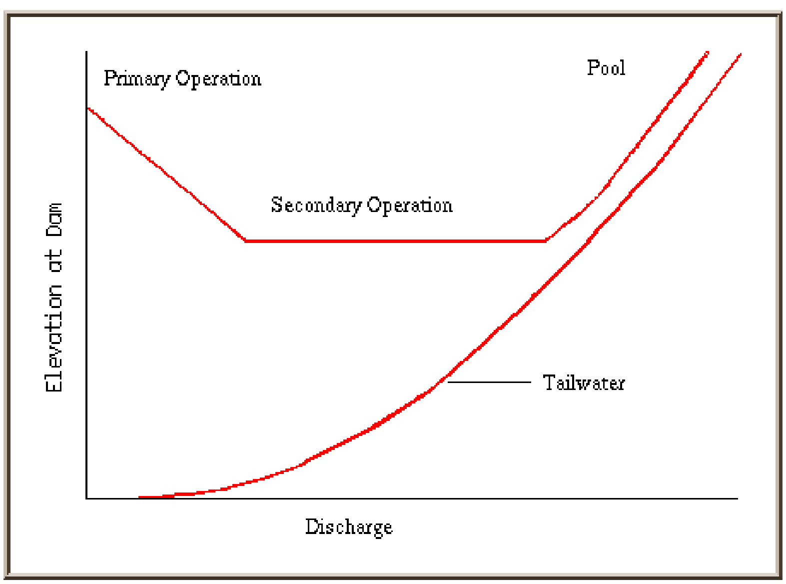

Figure 4. St. Paul Dist. L & D Operation

The UNET navigation dam algorithm functions for two modes of application - simulation application and forecast application.

3. Calibration of UNET

3.1 Procedure. The primary parameter that is adjusted during UNET calibration is the channel conveyance. Adjustment of channel conveyance is considered to be the equivalent of adjusting Manning's *n* (assuming that gross channel geometric properties do not change through scour, deposition, or avulsion). The general steps used to achieve calibration are:

1. Adjust conveyance to match simulated flows and USGS gaged flows (base calibration).
2. Estimate ungaged inflows/outflows using the UNET null internal boundary condition (Barkau, 1995; HEC, 2001).
3. Calibrate stages to intermediate gages.
4. Estimate, for locks and dams, the ungaged inflow between gages.
5. Calibrate to secondary gages.
6. Fine tune by adjusting to the individual event using the discharge-conveyance change factors.

Descriptions of the data, methodology and adjustments for calibration of UNET are described in the District Office H&H Appendices.

3.1.1 Definition of Data. It is useful to categorize "data" into three types:

1. <u>Input</u> (or <u>run</u>) data: The data necessary to operate a numerical model such as UNET. Topographic information (cross sections) and flows entering/leaving the modeled reaches fall into this category.

2. <u>Calibration</u> data: Field data (measurements) used to evaluate the performance of a numerical model and adjust model parameters as necessary to obtain a better match with the measurements. Typically, observed flows and/or stages within the modeled reach are used for the MBMS calibration. Note, these observations may be anecdotal in nature (e.g., "This flood was higher than the flood of 1882.").

3. <u>Verification</u> data (also known as <u>confirmation</u> or <u>circumstantiation</u> data): Additional field data, not used in calibration, that are used to verify that the model performs adequately under conditions other than those for which it was calibrated. It is rare, when dealing with a complex river system such as the Mississippi-Missouri, that verification data will be available. It is incumbent upon the modeler to demonstrate that the results are credible and reliable.

3.1.2 Data Requirements. In addition to the categories of data described above, the quality and reliability of the data are of interest. It is important to note that all field data contains some degree of measurement error. A continuing area of concern that arose many times during the course of this study is the quantification of the relationship between higher accuracy topographic data and increased accuracy and reliability of the results computed from those data. This has been studied and documented for the use of HEC-2, a one-dimensional steady flow model (HEC, 1986). That study determined that the primary source of uncertainty in computed results was the estimation of energy loss coefficients, not topographic data accuracy using normal surveying standards at that time. Experience with one-dimensional unsteady flow models, such as UNET, has confirmed and expanded that conclusion.

It is important, in the application of an unsteady flow model, that storage as well as conveyance be properly represented. This requires accurate definition of the conveyance and the flow-controlling elevations and locations (e.g., levees, weirs, etc.). Ground elevations in storage areas such as overbanks and leveed areas are not as critical, if the volumetric capacity of those areas is correct. Information based on topographic maps with 1.5m (5 ft.) contours is usually adequate for overbank areas for systems with broad floodplains. When applying a two-dimensional flow model, however, the ground topography becomes more important, particularly in areas of little vertical relief. It was decided that 0.5m (2 ft.) vertical resolution was needed in the cross-over area between the Missouri and Mississippi Rivers for reliable two-dimensional modeling. This requirement depends on the relationship between water depth and bed elevation changes. When applying any of these hydraulic modeling approaches, one must be aware that there is substantial uncertainty in past inflows to the system as well as the forecasted inflows, all of which will influence the reliability of the computed results. Note however, that for the purposes of mapping and producing inundation displays, more detailed overbank topography may be useful.

3.2 Null Internal Boundary Condition. The "null internal boundary condition" (NIBC) is a modification to the UNET system created by Dr. Barkau to estimate residual (incremental) flows between gages where hydrologic models were not available (Barkau, 1995; HEC, 2001). These may be thought of as ungaged lateral inflows or outflows. The NIBC is inserted between two identical cross sections that overlay each other. The NIBC assumes that the flow and stage at the two cross sections are the same. For any reach of river of substantial length, the NIBC is applied at the principal gage locations where the stage records are the most accurate. This procedure requires two executions of UNET. The first assumes stage continuity at gages, with each gage location being an internal boundary condition. This results in computed flows both upstream and downstream of the gage, which will most likely differ. DSSMATH (an HEC-DSS utility) is then used to compute the flow difference between gages to achieve flow continuity at the gages. The flow difference is then distributed throughout the upstream reach (usually uniformly) and lagged in time as deemed appropriate. The second execution uses these flows as (uniform) lateral inflow hydrographs and removes the internal boundary conditions, resulting in an open river condition at the gages. This technique assumes that the model is well calibrated. This feature is available in HEC-UNET Ver. 4.0.

4. Geographic Coverage. The area modeled using UNET is extensive - from Anoka, MN to Thebes on the Mississippi River, from Gavins Point Dam on the Missouri River to St. Louis (confluence with the Mississippi) and from Lockport Lock & Dam to Grafton on the Illinois River. Portions of numerous smaller tributaries in the Basin are also modeled as unsteady flow routing reaches. A schematic representation of the system showing key locations that are referred to later in this report is shown on Figure 5.

The main channel coverage by the Corps of Engineers District offices is as follows: St. Paul District (MVP), Mississippi R. from Anoka MN to Dubuque IA (289 river miles); Rock Island District (MVR), Mississippi R. from Guttenberg IA to Grafton IL (314 river miles) and the Illinois R. from Lockport L&D to Grafton IL (220 river miles); Omaha District (NWO), Missouri R. from Gavins Point Dam to St. Joseph MO (313 river miles); Kansas City District, Missouri R. from Rulo NE to St. Charles MO (498 river miles); St. Louis District (MVS), Mississippi R. from Lock & Dam 22 tailwater at Saverton MO to Birds Point MS (299 river miles) and the Illinois R. from Meredosia IL to Grafton IL (71 river miles).

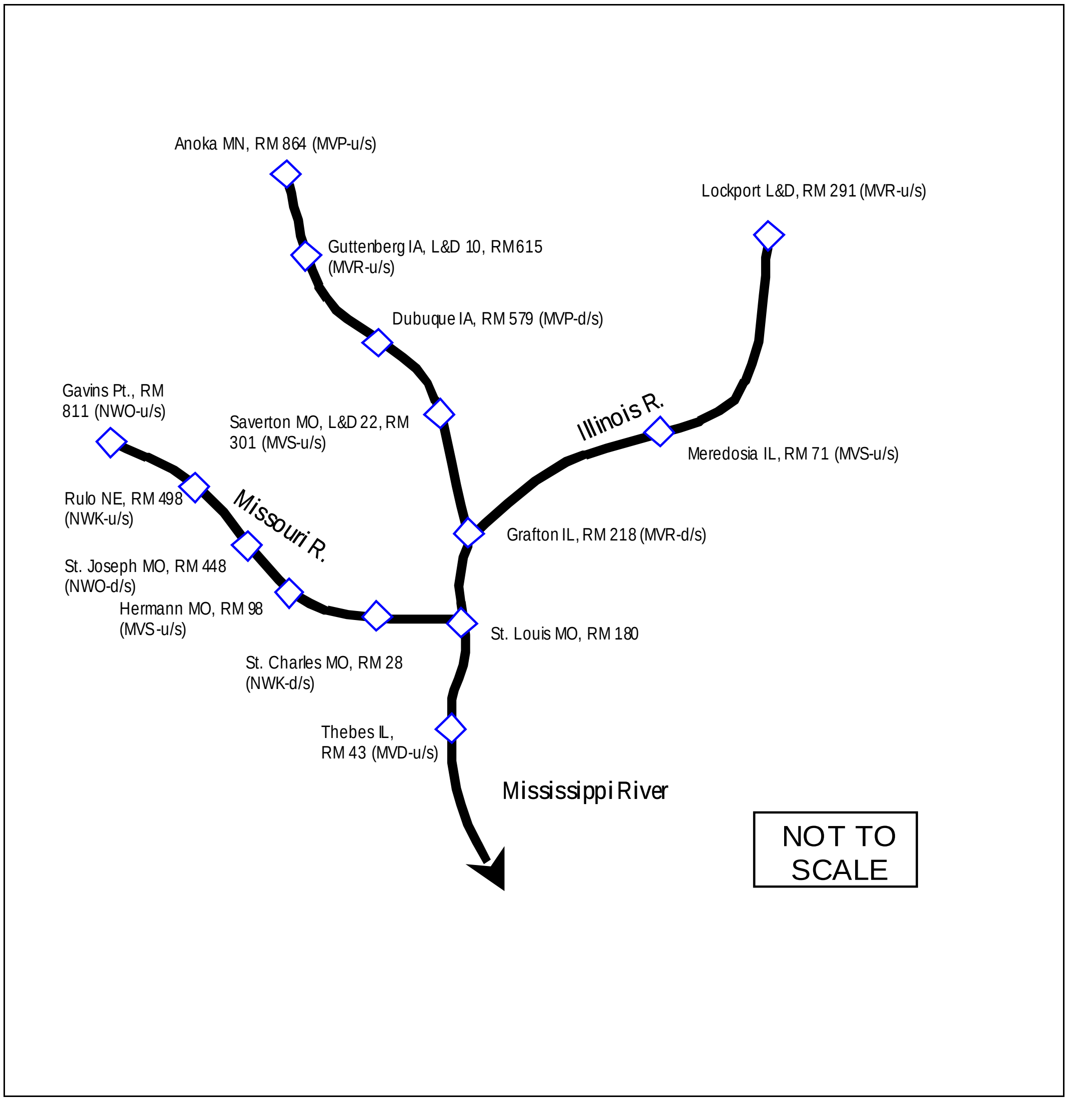

Figure 5. Schematic Diagram of UNET Geographic Extent. (u/s = upstream location of UNET boundary condition, d/s = downstream location of UNET boundary condition.)

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Attachment A

Memorandum for Record

Subject: Upper Mississippi Basin Flood Frequency Study, development of floodway and flood inundation mapping for FEMA, meeting 1/20/99

1. Introduction

The purpose of the meeting was to discuss the possibility of determining floodways and flood inundation mapping needed to satisfy FEMA=s flood insurance mapping objectives for the Upper Mississippi Basin. A Corps of Engineers (COE) only meeting was held in the morning to discuss the technical and funding requirements necessary to use the results of the current Upper Mississippi Basin Flow Frequency Study to satisfy the FEMA objectives. The COE presented these technical and funding requirements to FEMA representatives in the afternoon meeting.

2. COE only meeting (attendees: Earl Eiker, Ming Tseng, Ken Zwickl, Al Branch, S.K. Nanda, Bob Occhipinti, Dan Pridal and David Goldman)

2.1 Technical Issues

The technical issues discussed involved: 1) the end product of the Upper Mississippi study; 2) floodway determination; 3) criteria for modeling levee failure; 4) application of risk and uncertainty analysis.

2.1.1 Upper Mississippi Flood Frequency Study Products

The current study will result in estimates of flow and stage frequency curves useful for evaluating project performance and plan formulation. Stage frequency curves will be published as the median estimates of profiles for a particular exceedance frequency (e.g., the 1% chance exceedance frequency profile). Note: median estimate refers to the traditional FEMA estimate of the frequency curve or what is commonly referred to as the Acomputed@ frequency curve.

2.1.2 Floodway Determination and Flood Inundation Mapping

Floodway determination, as well as the production of flood inundation maps, will require an extensive effort beyond that envisioned for the current Upper Mississippi Study. The COE districts need to establish a strategy for identifying the base flood condition and analyzing encroachments. The technical issues involve the acceptability of the UNET model, the potential need for a steady flow model such as HEC-RAS for future applications, and the investigation of interior flooding problems.

<u>UNET application</u>

Typically a steady flow model, such as HEC-RAS or HEC-2, is used to determine floodways. However, the UNET unsteady flow model is capable of determining the flood profiles for the base condition and changes in the profiled due to any new encroachments or proposed modifications of the existing levee system. Potential disadvantages to using UNET are obtaining FEMA=s acceptance for its application; and the difficulty of determining allowable encroachments if deviations from the base condition are planned.

Currently, FEMA is examining the application of UNET to the Illinois River, and may find its application acceptable. However, the UNET application in this instance is for a new floodway determination. Re-examination of an existing floodway will be required in the Upper Mississippi which may prove to be more controversial.

Application of UNET to floodway determination may be inconvenient if new encroachments need be evaluated. UNET does not have algorithms for automatically determining allowable encroachments. Standard approaches to the distribution of floodway conveyance may not be easily addressed within the model. Establishing the encroachments may not be a tremendously difficult problem for most of the study area in that the floodway is already determined by the existing levee system. However, an existing levee may not provide sufficient level of protection, and floodway determination will be more difficult in this case.

HEC-RAS Alternative

The development of an HEC-RAS model was proposed as an alternative to using the UNET model. The HEC-RAS model would be calibrated to reproduce the flood profiles established using the UNET model. HEC-RAS has the potential advantage of being readily accepted by FEMA and more easily used by private contractors in future studies. The disadvantage of using a steady flow model such as HEC-RAS is that it does not directly address the volume related dynamics of the flood problem which are important to both levee failure analysis and flood inundation mapping. Furthermore, development of the HEC-RAS model will require additional funding.

Interior Flooding Problems

Flood inundation maps will require at least the investigation of interior flooding due to failure of flank or cutoff levees. The current Upper Mississippi Study does not consider any aspect of this problem. Consequently, this analysis problems needs to be considered carefully in assessing the funding requirements for developing flood inundation maps.

2.1.2 Modeling Levee Failure

Previously, the COE districts participating in the Upper Mississippi Study, had agreed on criteria for modeling levee failure in the UNET model. The failure criteria depended on whether the levee was federal or non-federal. Federal levees would be assumed to fail when the simulated water surface reaches an elevation somewhere between the design water surface elevation and the top of levee. Non-federal levees would fail at an elevation determined by COE district experience. No credit will be given to flood fighting.

Some controversy arose with regard to these criteria in that levees have survived water surface elevation that exceed the top of levee. Consequently, some argument for raising the levee criteria might be entertained.

However, geotechnical considerations and experience in general advise against a criteria that would allow the levee to survive overtopping. Limited levee overtopping at a specific location may not always cause levee failure. However, if the overtopping had occurred at a different location which had a minor defect then failure is likely. A consensus was reached where federal levees would be modeled to fail when the water surface elevation exceeds the top of levee (note here that levees will not fail at a design water surface elevation less than top of levee). For modeling purposes, it is safe to assume that levee reliability does not degrade with time due to successive events given that maintenance is performed.

The criteria previously considered by the COE will be maintained for non-federal levees. The sensitivity of study results to assumed non-federal levee failure elevation should be investigated.

2.1.3 Risk and Uncertainy Analysis

The information needed for application of risk and uncertainty (R&U) analysis to plan formulation should be developed to the extent possible during the Upper Mississippi Basin Study. This information will not be published as part of a study product. Rather the information will exist for future district use in plan formulation studies.

R&U analysis, will at a minimum, requires an estimate of uncertainty in the flow frequency and rating curves used to establish stage frequency. Uncertainty in the flow frequency curve is easily established for the period of record. The suggestion was made that uncertainty in the rating curve be established as part of the UNET model calibration process. Variation of UNET model parameters, most likely Manning n values, are logical candidates for establishing the uncertainty in rating curves.

One caveat about this approach is that the sensitivity analysis may cause different levee failure scenarios causing significant variations in discharge and stage. Perhaps, this variation can be considered primarily as uncertainty in the rating curve. Clearly, the overall aspect of performing the uncertainty analysis with the UNET model will require careful coordination among the districts so that reasonable estimates of uncertainty in the stage frequency curve are obtained.

2.2 Funding Requirements

The COE districts were canvassed for proposed funding requirements to determine floodways for FEMA. The cost varied between districts, but, the preliminary estimates totaled to 6-7 million dollars. The costs do not include geotechnical investigations that would be necessary for levee certification. A meeting between Corps Districts will be scheduled to develop better estimates of the funding requirements.

3. FEMA Meeting (COE attendees: Earl Eiker, Ming Tseng, Ken Zwickl, S.K. Nanda, Bob Occhipinti, Dan Pridal and David Goldman. FEMA attendees: Mike Buckley, Matthew Miller and Mike Grimm)

3.1 Description of Upper Mississippi Study Products

The products of the study were described as flood profile information that would be useful for COE studies. FEMA wanted to know if these profiles would involve a full evaluation of the levee system. COE indicated that some analysis would be performed, but not to the extent that would be required for levee certification.

3.2 Funding requirements for Floodway Determination

Six to seven million dollars is a preliminary estimate for performing the floodway determination. This figure does not include the cost for performing geotechnical investigations needed for levee certification.

3.3 FEMA Requirements/Problems

The COE study has created the expectation of new flood insurance mapping from FEMA. The problem is that the COE study will not provide these products. At this time FEMA does not have the funding to provide these products.

3.4 FEMA Proposal

FEMA would like the Corps to determine floodways and flood inundation maps. They have good experience in working with the Corps and prefer this to contracting with Private A/E firms.

FEMA would like the Corps to attempt to gain funding for the study through a request for a line item appropriation. They would endeavor to provide whatever support possible.

3.5 COE Response to FEMA Proposal

The COE does not want to request line item funding for floodway determination because the funds would likely be taken from general investigations money. Rather, the COE viewpoint was that FEMA needs to fund this type of flood insurance investigation. Given the different viewpoints on funding, the suggestion was made that FEMA make a proposal to the COE liason with FEMA as a basis for future discussions.