Chapter 3
Formulating Hydraulic Studies

3-1. Initial Considerations

When assigned a hydrologic engineering study, the tendency of many hydraulic engineers is to immediately begin the technical analysis. However, the entire study components must be planned first, recognizing the hydrologic/hydraulic information needs of other study team members. For most hydrology and hydraulics (H&H) studies, the engineer's initial effort should be spent on scoping and evaluating as many aspects of the entire study as can be identified. Besides individual experience, the hydraulic engineer should utilize the experience of others for advice and guidance in the technical aspects of the study. Frequent communications with the study manager, the economist, and other team members are necessary to ensure that their requirements are met. Other Corps personnel, the local project sponsor, and higher level reviewers will also have useful suggestions and information that will be valuable in establishing the overall scope and procedures for the hydraulic analysis. All of this information should be summarized in a written document, called a HEMP (Hydrologic Engineering Management Plan) which guides the hydraulic engineer through the course of the analysis. The HEMP is a detailed work outline covering the complete technical study. It should be the first significant item of work completed by the hydraulic engineer and should be updated during the study process as new insights are gained. The purpose of this chapter is to present the ingredients needed to develop this document. Additional information about a hydraulic work plan is given in Appendix C.

a. Project objectives. The objectives of a proposed project are usually broad. For the majority of Corps' work, these objectives are to provide flood control, and/or navigation to a specific reach of stream or an entire river basin. Other objectives often include hydropower, river stabilization, water supply and conservation, ground water management, permits, recreation, and environmental and water quality enhancement. For a project involving many of these objectives, the hydraulic engineer may require consultation with outside experts. Personnel from HEC, WES, the Hydrology Committee, various centers of expertise in Corps Districts, state agencies, universities, or private consultants can provide assistance in developing the hydraulic study scheme and in making decisions regarding selection of appropriate hydraulic analysis tools.

b. Study objectives. Once the project objectives are established, specific elements of the hydraulic analysis can be addressed. Development of the study plan requires establishment of appropriate levels of detail commensurate with the particular study phase. The appropriate level of hydraulic analysis detail is a key issue in most studies affecting, perhaps drastically, both the time and cost of the effort. This issue is often a major matter that should be resolved between the hydraulic engineer and the study or project manager early in the study.

(1) The hydraulic engineer must be knowledgeable of the planning process and design the analysis to meet the requirements of any particular reporting stage of the study (reconnaissance versus feasibility versus design). The engineer must be prepared to explain why a certain level of detail is needed, and why short-cut/less costly methods (or more expensive methods) would not (or would) be necessary and appropriate at particular stages of a study. Frequent and clear communications with the study team and development of a HEMP will facilitate specification of the appropriate levels of study detail. A justifiable H&H study cost estimate cannot be made without first developing an H&H work plan.

(2) Level of detail for the feasibility stage should be determined during the reconnaissance phase. Assuming Federal interest is found during the reconnaissance study, the most important work done in the reconnaissance report is to itemize all perceived problems and data needs and document how the study team proposes to address them in the later reporting stages. The reconnaissance report is the instrument used to define the level of detail required for the feasibility report stage. Table 3-1 overviews the objectives and level of detail typically required in the Corps' reporting process; particular circumstances may require a different blend of requirements and objectives.

3-2. Overview of Techniques for Conducting River Hydraulics Studies

A general overview is given below; the following chapters discuss various technical approaches in detail.

a. Field data. Field (prototype) data collection and analysis serves both as an important aspect of the application of other methods and as an independent method. It is an indispensable element in the operation, calibration, and verification of numerical and physical models. Also, to a limited extent, field data can be used to

Table 3-1
Hydraulic Study Objectives

Type	Stage	Objective/Considerations
Pre-Authorization	Reconnaissance	Qualitative analysis: one year± time frame, primarily use existing data, with and without project analysis to determine if economic justification is likely, establish required data collection program.
	Feasibility	Quantitative analysis: 2-3 year time frame, with and without project H&H, economics, and plan formulation finalized, qualitative evaluation of mobile boundary problems, hydraulic design sized, continue/refine data collection program.
Post-Authorization	Re-Evaluation Report	Quantitative analysis: are the feasibility report findings still applicable? Update economics and hydraulics to current conditions, initiate quantitative investigation of movable boundary problems (usually).
	General Design	Quantitative analysis-detailed hydraulic analysis and design, detailed modeling and movable boundary analysis, finalize all hydraulics for simple projects.
	Feature Design	Quantitative analysis-detailed hydraulic analysis and design of one component or portion of a complex project, physical model testing, if necessary.
Continuing Authority	Reconnaissance Report	Qualitative analysis: usually similar to reconnaissance report portion of the feasibility report.
	Detailed Project Report	Quantitative analysis: a combined feasibility report and design.

estimate the river's response to different actions and river discharges using simple computations. Obtaining detailed temporal and spatial data coverage in the field, however, can be a formidable and difficult task.

b. Analytic solutions. Analytic solutions are those in which answers are obtained by use of mathematical expressions. Analytical models often lump complex phenomena into coefficients that are determined empirically. The usefulness of analytic solutions declines with increasing complexity of geometry and/or increasing detail of results desired.

c. Physical models. Analysis of complex river hydraulic problems may require the use of physical hydraulic models. The appearance and behavior of the model will be similar to the appearance and behavior of the prototype, only much smaller in scale. Physical scale models have been used for many years to solve complex hydraulics problems. Physical models of rivers can reproduce the flows, and three-dimensional variations in currents, scour potential, and approximate sediment transport characteristics. The advantage of a physical model is the capability to accurately reproduce complex multidimensional prototype flow conditions. Some disadvantages are the relatively high costs involved and the large amount of time it takes to construct a model and to change it to simulate project alternatives. Model calibration, selection of scaling and similitude relationships, construction costs, and the need for prototype data to adjust and verify physical models are discussed by the U.S. Department of the Interior (1980), Franco (1978), Petersen (1986), and ASCE (1942). Conflicts in similitude requirements for the various phenomena usually force the modeler to violate similitude of some phenomena in order to more accurately reproduce the more dominant processes.

d. Numerical models. Numerical models employ special computational methods such as iteration and approximation to solve mathematical expressions using a digital computer. In hydraulics, they are of two principal types finite difference and finite element. They are capable of simulating some processes that cannot be handled any other way. Numerical models provide much more detailed results than analytical methods and may be more accurate, but they do so with increased study effort. They are also constrained by the modeler's experience and ability to formulate and accurately solve the mathematical expressions and obtain the data that represent the important physical processes.

e. Hybrid modeling. The preceding paragraphs described the four principal solution methods and some of their advantages and disadvantages. Common practice has been to use two or more methods jointly, with each method being applied to that portion of the study for which it is best suited. For example, field data are usually used to define the most important processes and verify a model that predicts hydrodynamic or sedimentation conditions in the river. Combining physical modeling with numerical modeling is referred to as hybrid modeling. Combining them in a closely coupled fashion that permits feedback among the models which is referred to as an integrated hybrid solution. By devising means to integrate several methods, the modeler can include effects of many phenomena that otherwise would include effects of many phenomena that otherwise would be neglected or poorly modeled, thus improving the reliability and detail of the results. A hybrid modeling method for studying sedimentation processes in rivers, estuaries and coastal waters has been developed by the Waterways Experiment Station (WES) (McAnally et al., 1984a and 1984b; Johnson et al., 1991). The method uses a physical model, a numerical hydrodynamic model, and a numerical sediment transport model as its main constituents. Other optional components include a wind-wave model, a longshore current calculation, and a ship handling simulator.

f. Selection of procedure. Tables 3-2 and 3-3 give suggestions, based on experience, regarding usage of the various procedures in different phases of flood control and navigation studies. This information should be viewed as a starting point; it will change as computer resources and the Corps' planning process and missions evolve.

Table 3-2
Model Usage During Hydraulic Studies For Flood Control Projects

Stage	Existing Data & Criteria	GVSF	MB	GVUSF	Multi-D	Phys.*
Reconnaissance	X	X	?(1)			
Feasibility		X	X(1)	X(2)	?	?
Re-evaluation		X	X	X	?	?
General Design Memo.		X	X	X	X(3)	X(3)
Feature Design Memo.					X(3)	X(3)
Continuing Authority	X	X	X(1)	?	?	?

* Existing Data and Criteria = available reports, Corps criteria, regional relationships for depth-frequency, normal depth rating relationships, etc.; GVSF = gradually varied, steady flow [i.e. HEC-2, HEC (1990b)]; MB = mobile boundary analysis [i.e. HEC-6, HEC (1991a)]; GVUSF = gradually varied unsteady flow [i.e. UNET, HEC (1991b); not including hydrologic models like HEC-1, HEC (1990a)]; Multi-D = multidimensional analysis [i.e. TABS-2, Thomas and McAnally (1985)]; Phys. = physical models (by WES or similar agency).

? Possible, but very unusual - highly dependent on problem being analyzed.

(1) Sediment problems must be addressed, but the procedure at this stage may be qualitative or quantitative, depending on the type and magnitude of the project.

(2) Use is possible, but unlikely, on most flood control studies.

(3) Typically employed to evaluate design performance for a short reach of river or in the immediate vicinity of a specific project component, or to refine the hydraulic design of a project component.

Table 3-3
Model Usage During Hydraulic Studies For Navigation Projects

Stage	Existing Data & Criteria.	GVSF	MB	GVUSF	Multi-D	Phys.*
Reconnaissance	X	X				
Feasibility		X	X(1)	?	?	?
Re-evaluation		X	X	?	?	?
General Design Memo.			X	X	X	X
Feature Design Memo.					X	X
Continuing Authority	X	X	X(1)	(2)	(2)	?

* As defined in Table 3-2.

? As defined in Table 3-2.

(1) Sediment problems must be addressed at this stage, either quantitatively or qualitatively. Detailed movable boundary analysis with computer modeling is more likely at this stage for a navigation project than for a flood control project.

(2) Navigation projects for this stage are typically small boat harbor or off-channel mooring facilities of rather uncomplicated design. GVUSF or multidimensional modeling techniques are normally not utilized. A field survey during the reconnaissance and data gathering stages of a study by the responsible hydraulic engineer is essential.

3-3. Analysis of Hydraulic Components

Most problems that are studied have solutions that include hydraulic structures that are identified early in the reconnaissance phase. Different types of structures require different methods for proper evaluation. General guidance for method selection is given in Table 3-4 for flood control, navigation, and hydropower projects. The study objectives, along with the type of hydraulic component to be evaluated, should indicate the type of analysis required.

3-4. Data Requirements

There are three main categories of data needed for hydraulic studies: discharge, geometry, and sediment. Not all of these categories, or all of the data within each of these categories, will be needed for every study.

a. Discharge.

(1) A project is usually designed to perform a function at a specific discharge. It must also function safely for a wide range of possible flows. Flood control projects are usually designed for the discharge corresponding to a specific flood frequency, or design event, while navigation studies use a discharge for a specific low flow duration or frequency. The single discharge value for the hydraulic design should not be over-emphasized; rather, project performance must be evaluated for a range of flows, both greater than and less than the "design discharge." A levee may be designed to provide protection from the one-percent chance flood, but the levee design must also consider what happens when the 0.5- or 0.2-percent chance or larger flood occurs. A channel may be designed to contain the 10-percent chance flood, but the annual event may be the most dominant in terms of forming the channel geometry to carry the stream's water/sediment mixture. In some cases, the absence of a low flow channel to carry the everyday water and sediment flows has caused the 10-percent chance channel to be quickly silted up. Similarly, steady flow evaluations may be insufficient to adequately evaluate project performance. Full hydrographs or sequential routings for a period of record may be required to address the project's response to sediment changes or the occurrence of consecutive high or low flow periods. Velocities are important for water quality, riprap design, and other engineering studies. Velocity for the peak design flow

Table 3-4
General Guidelines for Typical Methods of Analysis for Various Hydraulic Components

Flood Control Component	Typical Analysis Procedures
Levees	GVSF normally; sediment analysis: often qualitative, but detailed movable boundary analysis may be necessary on flank levees.
Dams (height)	Normally hydrologic reservoir routing, or GVUSF.
Spillways	As above to establish crest elevation and width, general design criteria from existing sources to develop profile, specific physical model tests to refine profile.
Stilling Basins	General design criteria from existing sources to establish floor elevations, length and appurtenances, specific model tests to refine the design, movable boundary analysis to establish downstream degradation and tailwater design elevation.
Channel Modifications	GVSF normally, qualitative movable boundary analysis to establish magnitude of effects, quantitative analysis for long reaches of channel modifications and/or high sediment concentration streams, physical model tests for problem designs (typically supercritical flow channels).
Interior Flood	Integral part of a levee analysis - hydrologic routings normally for pump and gravity drain sizing, GVSF for ditching and channel design, physical model testing for approach channel and pump sump analysis.
Bypass/ Diversions	GVSF or GVUSF analysis, physical model testing, movable boundary analysis on sediment-laden streams.
Drop Structures	Similar to stilling basin design, although model tests often not required.
Confluences	GVSF usually, GVUSF for major confluences or tidal effects.
Overbank Flow	GVSF normally, GVUSF/Multi-D for very wide floodplains or alluvial fans.
FPMS Studies	GVSF normally.
Navigation	
Channel Modifications	Dikes - Movable boundary analysis (quantitative), multidimensional modeling, physical model tests.
	Cutoffs - GVSF or GVUSF, movable boundary analysis to establish the rate of erosion and channel shifting, physical modeling.
	Revetment - general design criteria from existing sources, GVSF, physical model tests.
Navigation Dams	Normally, GVSF to establish pool elevations, profiles and depths, multidimensional modeling to estimate current patterns, physical model testing, movable boundary analysis to establish downstream scour for stilling basin design.
Locks	General design criteria from existing sources, possible multidimensional modeling/physical modeling for approach and exit velocities and refinements of lock design and filling/emptying systems.
Other	
Hydropower	System simulation for optimal operation. Multidimensional analysis for flow patterns, physical model tests.

or velocities for specific time periods may be needed, depending on the study requirements.

(2) Discharge data include measured and/or synthesized flows along with frequency, velocity, duration, and depth information. Measured data at gages are the preferred source for this category; seldom, however, does sufficient measured data exist. A typical hydraulic analysis requires simulated data from hydrologic models as well as information on historical events, usually floods. This latter data is often obtained from extensive discussions with local residents living along the study stream and the review of newspaper accounts and/or Corps or other agency reports. A field survey during the reconnaissance and data gathering stages of a study by the responsible hydraulic engineer is essential.

b. Channel geometry.

(1) Channel geometry is required for any hydraulic study. Geometric data include channel and overbank topography, stream alignment, bridge and culvert data, roughness information, changes in stream cross section shape, and alignment over time. Extensive field and/or aerial surveys supply the bulk of these data; however, cost reductions can be achieved by locating and using available data. Most rivers and streams have been studied in the past. Floodplain or flood insurance reports are often available and can be valuable sources of geometric and other data. Bridge plans are usually available from state, county, or municipal highway departments. Navigable rivers have hydrographic surveys of the channel taken periodically. Aerial photos have been taken at regular intervals by the Soil Conservation Service since the mid-1950's providing data on stream channel changes. Even if it is decided that new surveys need to be obtained, the above sources provide valuable information on changes in channel alignment and geometry over time, indicating potential problems related to the stream's sediment regime. The keys to the usefulness of the data are the accuracy of the survey data and the locations of cross sections along the stream. Accuracy is discussed in section 3-4*e* and Appendix D. Additional information on the effects of survey data accuracy on computed water surface profiles can be found in "Accuracy of Computed Water Surface Profiles" (USACE 1986).

(2) The amount of survey data required depends on the study objective and type. For instance, more frequent surveys are needed for navigation projects than for flood control projects. Detailed contour mapping for urban studies should be obtained in the feasibility phase rather than in the design phase, whereas detailed mapping for agricultural damage reduction studies may often be postponed to the post-authorization stage. For movable bed studies repeat channel surveys are needed at the same locations, separated by significant time periods, to evaluate a model's performance in reproducing geometric changes. Thalweg profiles and/or repetitive hydrographic surveys are needed for analysis of bed forms and the movement of sand waves through rivers.

c. Sediment.

(1) The amount of sediment data needed is not always apparent at the beginning of a hydraulic study. The sediment impact assessment, as outlined in EM 1110-2-4000, is performed during the initial planning process. Sediment assessment studies are typically performed to determine if the project proposal is likely to create a sediment problem or aggravate an existing one. The results of this evaluation will dictate the need for additional data and quantitative studies during the feasibility and design phases. If a sediment problem presently exists, or is expected with a project in place, a sediment data collection program must be initiated so that the problem can be properly addressed in later stages of the analysis.

(2) Sediment data include channel bed and bank material samples, sediment gradation, total sediment load (water discharge versus sediment discharge), sediment yield, channel bed forms, and erosion-deposition tendencies. Long-term sediment measuring stations are few in number, and modern methods of sediment measurement can make older records questionable. Sediment data collected at a gaging site are usually short-term. Flood control or navigation studies must address sediment to determine if there is, or will be, a sediment problem if the study proposal is implemented. Often, the initial sediment analysis is performed in a rather qualitative fashion with a minimum amount of data. If there appears to be a sediment problem, a data collection program should be established, at least for a short period, to obtain calibration data. Chapter 7 and EM 1110-2-4000 should be reviewed for further guidance on sediment data.

(3) The type of project often dictates the amount and type of sediment data needed. For instance, reservoir and channelization proposals require that the entire suspended sediment load (clays, silts, sands, and gravels) be analyzed, whereas flood control channels or river stabilization projects primarily require analysis of the bed material load (mainly sands and gravels) because the finer materials (clays and silts) usually pass through the

reach. The latter type of projects may require less data than the former. For example, an evaluation of the bed material at and near the surface, through "grab samples" or collection with hand augers, may be adequate. If the material consists of fine sands, a detailed sediment study may be required, possibly in the feasibility phase.

d. Data availability. Data are usually available from the U.S. Geological Survey's (USGS) nationwide data collection system. Corps' water data measurements provide another source; in many parts of the United States state agencies and water conservancy districts also collect water data. If measured data are not available but are required for the study, a data collection system is necessary. Guidance on specifying and developing a gaging system is available from the USGS (1977) with additional information in ER 1110-2-1455. Definition of the need for certain data and budgeting for its collection should be included in the feasibility or reconnaissance report cost estimates.

e. Accuracy of data. Results from numerical models are routinely available to a precision of 0.01 foot, implying far more solution accuracy than that of the basic data. The hydraulic engineer should be aware of the impact of input data uncertainty relative to reliability of the computations. There are relatively few USGS discharge gages having records rated as "excellent." This rating carries an explanation that 95 percent of the daily discharge values are within 5 percent of the "true" discharge (thus 5 percent are outside of that limit). "Good" records have 90 percent of the daily discharges within 10 percent. If any specific discharge varies by 5 percent, the corresponding stage could vary significantly depending on the stream slope and geometry. Instantaneous peak discharges presumably would be less accurate. Thus, a potentially significant accuracy problem exists with the basic data.

(1) Geometric data are more accurate than flow data; however, some variation is still present, see U.S. Army Corps of Engineers (1989). If not located properly, cross sections obtained by any technique may not be "representative" of the channel and floodplain reach for which each section is used (see Appendix D). Significant errors in water surface profile computations have occurred when distances between cross sections were large. Closer cross section spacings will improve the accuracy of the profile computations (i.e. the solution of the equations), but will not necessarily result in a better simulation unless the sections are properly located to capture the conveyance and storage in the reach. A more detailed discussion of river geometry requirements is provided in Appendix D. The computer program "Preliminary Analysis System for Water Surface Profile Computations (PAS)" is designed to assist with data development for profile computations (U.S. Army Corps of Engineers 1988b).

(2) Sediment data have the most uncertainty, due both to the difficulties in obtaining the measurements and the incorporation of discharge and geometry measurements in the calculation of sediment load. Sediment load curves typically are the most important relationships in sediment studies. This water discharge/sediment discharge relationship should be sensitivity tested to evaluate the consequences of an over- or under-estimate.

(3) Absolute statements as to the accuracy of final hydraulic results should be tempered by an understanding of the field data accuracy. The more accurate the final hydraulics are required to be, the more accurate the data collection must be. Sensitivity tests to evaluate possible over- or under-estimates should be routinely made.

f. Hydraulic loss coefficients. Various energy loss coefficients are required for hydraulic studies. These energy loss coefficients include channel and overbank friction, expansion-contraction losses, bridge losses, and miscellaneous losses.

(1) Manning's *n*. For the majority of hydraulic studies, Manning's *n* is the most important of the hydraulic loss coefficients (U.S. Army Corps of Engineers 1986). The variation of water surface elevation along a stream is largely a function of the boundary roughness and the stream energy required to overcome friction losses. Unfortunately, Manning's *n* can seldom be calculated directly with a great deal of accuracy. Gage records offer the best source of information from which to calculate *n* for a reach of channel near a gage. These calculations may identify an appropriate value of *n* for the channel portion of the reach. Whether or not this value is appropriate for other reaches of the study stream is a decision for the hydraulic engineer. Determination of overbank *n* values requires a detailed field inspection, reference to observed flood profiles, use of appropriate technical references, consultation with other hydraulic engineers, and engineering judgment. For some streams, *n* varies with the time of year. Studies on the Missouri (U.S. Army Corps of Engineers 1969) and Mississippi Rivers have found that Manning's *n* is significantly less in the winter than in warm weather for the same discharge. If stages are to be predicted in the winter as well as the summer, temperature effects must be addressed. Similarly, many sand bed streams demonstrate a great

change in bed forms as discharge increases. A threshold level exists such that when discharge and velocity reach a certain range, the bed changes from dunes to a flat bed, thus dramatically decreasing *n*. A higher discharge can pass at a lower elevation than an earlier, lower, discharge due to this phenomena. This "discontinuous" rating curve is a characteristic of many streams. An example is shown in Figure 3-1. References by Chow (1959), French (1985), and Barnes (1967) may be used to assist in the estimation of *n* for a reach of stream. A more complete discussion of loss coefficients is provided in Appendix D.

(2) Equivalent roughness, *k*. An alternate method of defining Manning's *n* is by estimating an equivalent roughness coefficient *k*. This technique is described by

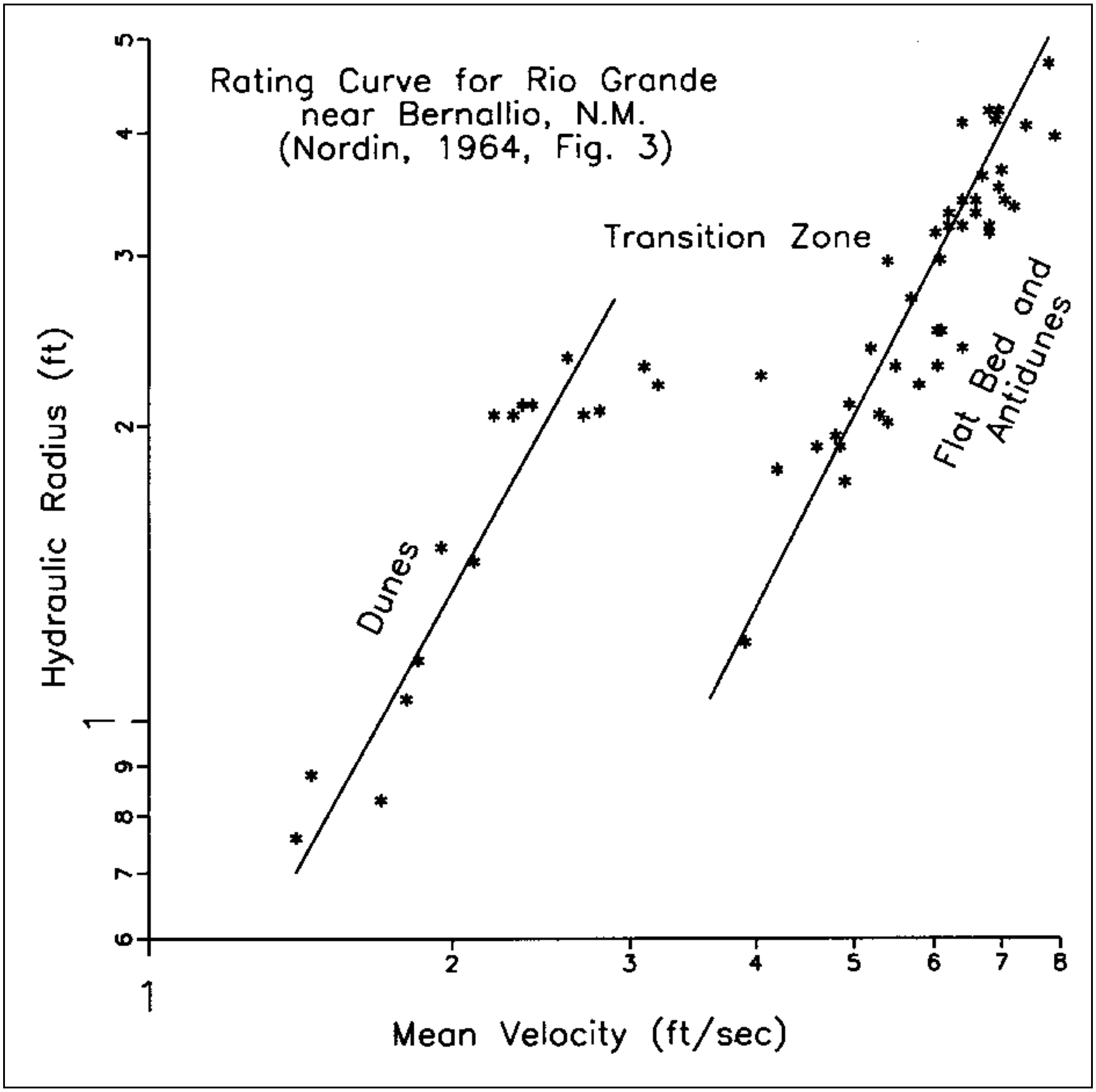

Figure 3-1. Discontinuous rating curve

Chow (1959) and in EM 1110-2-1601. It relates *n* to a function of *k* and the hydraulic radius (R). A *k* value is the equivalent diameter, in feet, of the predominant grain size in the channel or the average size of an overbank obstruction. Advantages to using *k* to calculate *n* include adjustments to *k* as depth changes are not required; *n* can be found directly from *k* and the R for the stage being evaluated, and errors in estimating *k* result in only small differences in the calculated value of *n*. The engineer must evaluate the significance of other factors influencing *n*, including bed form changes, channel alignment, cross-sectional area changes, and bank vegetation. Field inspection of the study stream at varying states of flow is imperative for attaining appropriate estimates of *n* for ranges of discharge. It is not beyond reason to expect the hydraulic engineer to walk or float the entire reach of stream to determine friction values.

(3) Expansion-contraction coefficients. Although water surface profiles are mostly influenced by friction forces, changes in the energy grade line, and the corresponding water surface elevations can result from significant changes in stream velocity between cross sections. This is most apparent in the vicinity of bridges which tend to force the discharge through an opening smaller than the upstream and downstream channels. Therefore, a contraction into and an expansion out of a bridge results in eddy energy losses. These losses are usually quantified with coefficients of expansion or contraction (when using a one-dimensional approach), based on the abruptness of the change. For most situations, the expansion/contraction energy losses are not great except in the vicinity of bridges and culverts. Using the appropriate coefficient at each streamflow obstruction is important, as well as adjusting the coefficient back to an appropriate value upstream of the obstruction. The references by Chow (1959) or U.S. Army Corps of Engineers (1988a, 1990b) provide typical values of expansion and contraction coefficients.

(4) Bridge losses. Bridges that cause relatively small changes in the energy grade and water surface profiles can be adequately modeled using appropriate values of Manning's *n* and expansion-contraction coefficients. Bridges that cause the profile to become rapidly varied near and within the bridge require other methods of analysis. Weir flow over the roadway, pressure flow through the opening, and open channel flow where critical depth in the bridge occurs are examples where detailed bridge analysis is required. To correctly model losses for these situations, bridge geometry becomes more important. The number, location, and shape of bridge piers must be obtained; a roadway profile and weir coefficient are needed for weir flow calculations; guardrails and/or bridge abutments which serve to partially or fully obstruct weir flow must be defined; the precise upstream and downstream road overtopping elevations must be identified (often through trial and error computations) and debris blockage estimated. Photographs and verbal descriptions of each bridge and field dictated to a hand-held tape recorder are most useful when modeling each bridge. References by U.S. Army Corps of Engineers (1975, 1988a, 1990b) should be consulted for additional information.

g. Study limits. The appropriate spatial scope for a hydraulic study is often incorrectly identified, particularly if all possible project effects are not envisioned. The study, or model, should not start and stop at the physical limits of the proposed project. Rather, the boundaries should extend far enough upstream and downstream from the project limits to completely encompass the full effects of the project on the basin. Reservoir, channelization, levee, and navigation projects may produce changes in stage, discharge, and sediment conditions that can affect reaches well removed from the physical location of the project. For example, major channelization, resulting in shortening of the stream, may generate upstream headcutting and downstream deposition that can continue for decades. Reservoirs can cause upstream deposition, thereby increasing water surface elevations over time, and may cause downstream degradation because of the relatively sediment-free waters that are released. The deposition and degradation can extend up tributaries also. Study limits must be established so that all effects of the project, both positive and negative, can be identified and evaluated. Figure 3-2 illustrates some considerations for establishment of study limits for a reservoir project and the type of data required at various locations within the study area.

h. Possible needs for additional data. Not all data needs can be foreseen at the start of a study. Consultations with experienced personnel early in the study are often useful in identifying data needs. Some common needs that often surface well into a study include stage and/or discharge duration data (especially where stage-frequency near a stream junction becomes important), surficial soils analysis to estimate sediment yield for ungaged areas (particularly where the amount of sand compared to the amount of fines is important), type and gradation of bed material present at different times for movable bed model calibration, measurement of velocity directions and magnitudes at various stages, times, and locations for use in multidimensional model calibration.

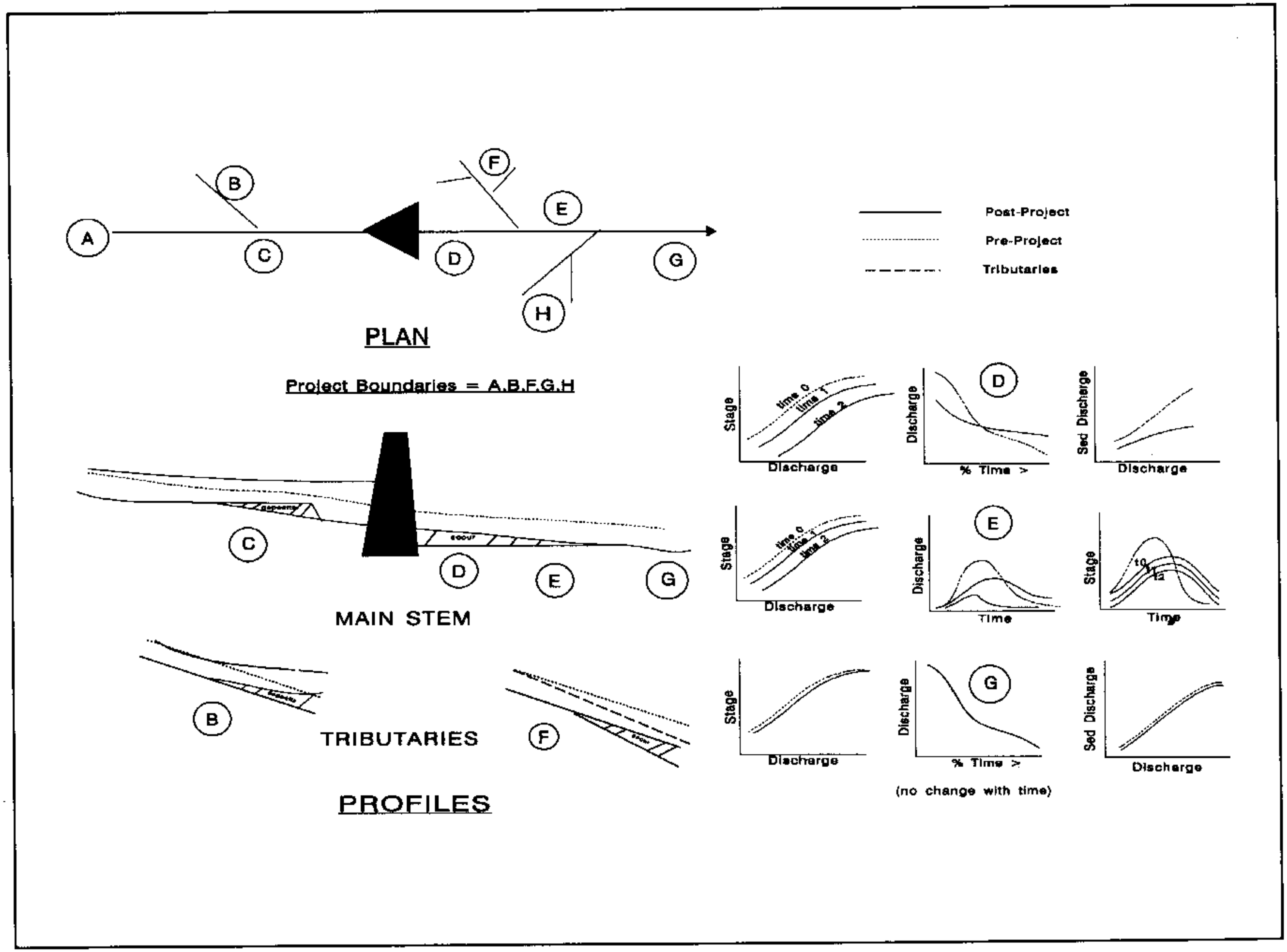

Figure 3-2. Example study limits and possible project impacts

i. Other factors. Ongoing or near-future, changes in the watershed should be considered in developing water surface elevations. Consideration of urbanization effects on future discharges has long been a requirement of Corps analysis. Other localized effects should also be considered. Local channel modifications and bridge replacements that are ongoing or scheduled to be completed prior to implementation of a Corps project should be incorporated into the hydraulic study. Bridge obstructions, particularly culverts under a high fill, can cause significant upstream ponding and induce damage to nearby structures. If the local community has no plans (or funds) to rectify a severe local flooding problem such as this, the Corps study team should include this obstruction in the future condition, without project, analysis. On several occasions, however, in the time between the Corps' feasibility report and the final design document, such obstructions have been replaced, greatly decreasing project benefits and affecting the authorized plan. Sensitivity tests on economic effects to the Corps' recommended plan of potential modifications to culverts or bridges are encouraged. The project manager should maintain continuous contact with the local community and highway department to obtain information on potential bridge replacements that may affect the project.

3-5. Calibration of Hydraulic Analysis Models

The reliability of the results of a hydraulic model study depends on the skills and experience of the hydraulic engineer performing the study, applicability of the model to the physical situation, and the quality of the data used to both model the study reach and calibrate the model. The overall calibration process incorporates three distinct steps: obtaining the necessary data and translating it into input for a numerical model, calibrating the model, and verifying the model. Additional guidance on calibration is given in Chapters 4 through 7 and Appendix D.

a. Purpose of calibration. The objective of the calibration process is to match the output of the model with observed data (usually water surface elevations). This process is performed by adjusting one or more parameters, such as Manning's *n*, until a satisfactory match of model results with known data is achieved. When a set of known conditions has been approximately matched by the model, one can apply the model to unknown conditions (the 1-percent chance flood, the Standard Project Flood, etc.) with more confidence that the model output is reasonably representative of the physical processes associated with that event. However, to be confident, the observed data for calibration should be obtained from an event that is near the scale of the events to be modeled.

b. Observed data. This includes data recorded at gages along with that obtained from field observations by Corps personnel, and from interviews with local residents. Recorded discharges, stages, and velocities are valuable for calibration purposes; however, it is rare that sufficient gage data are available for comprehensive calibration. The preponderance of calibration data usually comes from local observations during and after an event. The hydraulic engineer should plan for several days of field work to obtain highwater marks from local residents' observations or following an event that occurs during the study. The best data often come from people who have lived near the stream for many years. They can supply information concerning flood elevations, erosion or deposition tendencies, local channel modifications (when and where), tendencies for debris to obstruct bridge openings, how often the stream gets out of banks, and possible flow transfers between watersheds during floods. As much information as possible should be obtained from local residents for use in the calibration process. While all information is useful, the hydraulic engineer should recall that the further back in time, often the hazier the memory of the individual is for exact flood heights. The exact water level of the flood may not be accurately recalled. The engineer should not expect that model results will match every highwater mark exactly.

c. Calibration process. The calibration process normally focuses on matching stage and discharge data at gaging sites with highwater marks used to calibrate the model at ungaged sites. This section addresses only the stage or highwater mark calibration.

(1) The first step in the process does not begin until the study reach data have been assembled and entered into an input file, several discharges have been simulated, and the data file corrected as necessary. Effective flow area transitions between adjacent cross sections should be reasonable; profiles through bridges should be closely inspected to ensure that faulty modeling procedures are not leading to incorrect head losses and computed water surface profiles; and all warnings or messages from a numerical model should be reviewed and corrected if necessary. The hydraulic engineer should ensure that the model is performing reasonably well before "fine tuning" is initiated to match model results to field data.

(2) For subcritical flow, one-dimensional steady flow water surface profile computations begin

downstream from the study reach, preferably at a reliable boundary condition. If starting conditions are not known, the engineer must ensure that profile computations begin sufficiently far downstream that any errors in estimating starting water surface elevation will be eliminated by profile convergence to the correct elevation downstream of the study reach. This distance is mainly a function of the stream slope. Additional guidance on selecting the correct distance downstream of the study reach is given in "Accuracy of Computed Water Surface Profiles" (U.S. Army Corps of Engineers 1986).

(3) The channel *n* value can be calibrated for various flows if stage-discharge data are available (e.g. at a gage). Once a match of computed and actual stages at a gage site for in-bank flows is obtained, the channel *n* may be held constant and the overbank *n* calibrated for different historic floods. For one or more known discharges, the computed profile should be plotted and compared with measured stages and highwater marks. It should not be expected that the two will exactly coincide. A successful calibration occurs when the computed profile is close to the majority of highwater marks, with some scatter allowed. Means to achieve a calibration include changes to Manning's *n*, adjustments to expansion/contraction coefficients where warranted, modifications to effective flow boundaries, or to bridge geometry descriptions. Typically, most of the adjustments are to Manning's *n*.

(4) Considerable uncertainty exists in the estimation of *n*, with estimates by experienced hydraulic engineers commonly differing by ±20 percent at the same stream section (U.S. Army Corps of Engineers 1986). Thus, one can reasonably justify an increase or decrease of this magnitude to calibrate a model. The hydraulic engineer should be cautious if an "unreasonable" adjustment to *n* is required for calibration. Rigorous guidance on acceptable calibration errors cannot be given. The judgment and experience of the responsible hydraulic engineer and reviewers is foremost. Rules of thumb of ± 1 foot are often used, but this criterion may not be acceptable for all situations, particularly for steep streams. Some general considerations for the calibration process are given in Table 3-5. Figure 3-3 shows an example of satisfactory water surface elevation calibration for a stream reach. The process and rationale for calibration should be documented in the study reports.

(5) Additional calibration data are necessary for the application of two-dimensional, unsteady flow, and sediment transport models. Each chapter on the application of the various methods provides information on model calibration and verification.

d. Verification. The last step in the calibration process is verification of the model. This operation is most desirable, but is not always possible, often requiring more data than is available. The verification process is

Table 3-5
Data Gathering/Calibration Considerations

- Obtain as many highwater marks (HWM) as possible after any significant flooding, no matter how close together and how inconsistent with nearby HWM's. Physically describe each HWM location so that surveys may be obtained at a later date.
- Obtain highwater marks upstream and downstream of bridges if possible, so that the effects caused by these obstructions can be estimated and so that bridge modeling procedures may be confirmed.
- Check on bridge/culvert debris blockages with local residents. For urban streams, check with residents and newspaper files on occurrences of bridge opening blockages by automobiles or debris.
- For historical flooding, check on land use changes, both basin wide and local, since the flood(s) occurred.
- What has been happening to the stream since the last flood? Erosion or deposition that may have occurred since historic floods, if significant, will render calibration with today's channel configuration invalid.
- If HWM's are taken from debris lines, remember that wave wash can result in the debris line being higher than the HWM, particularly for pools.
- Is the observer giving the HWM biased? A homeowner may give an exaggerated HWM if the owner thinks it might benefit a project; the owner with a house for sale may give a low estimate or indicate no flooding occurs if he/she thinks it will affect the sale.

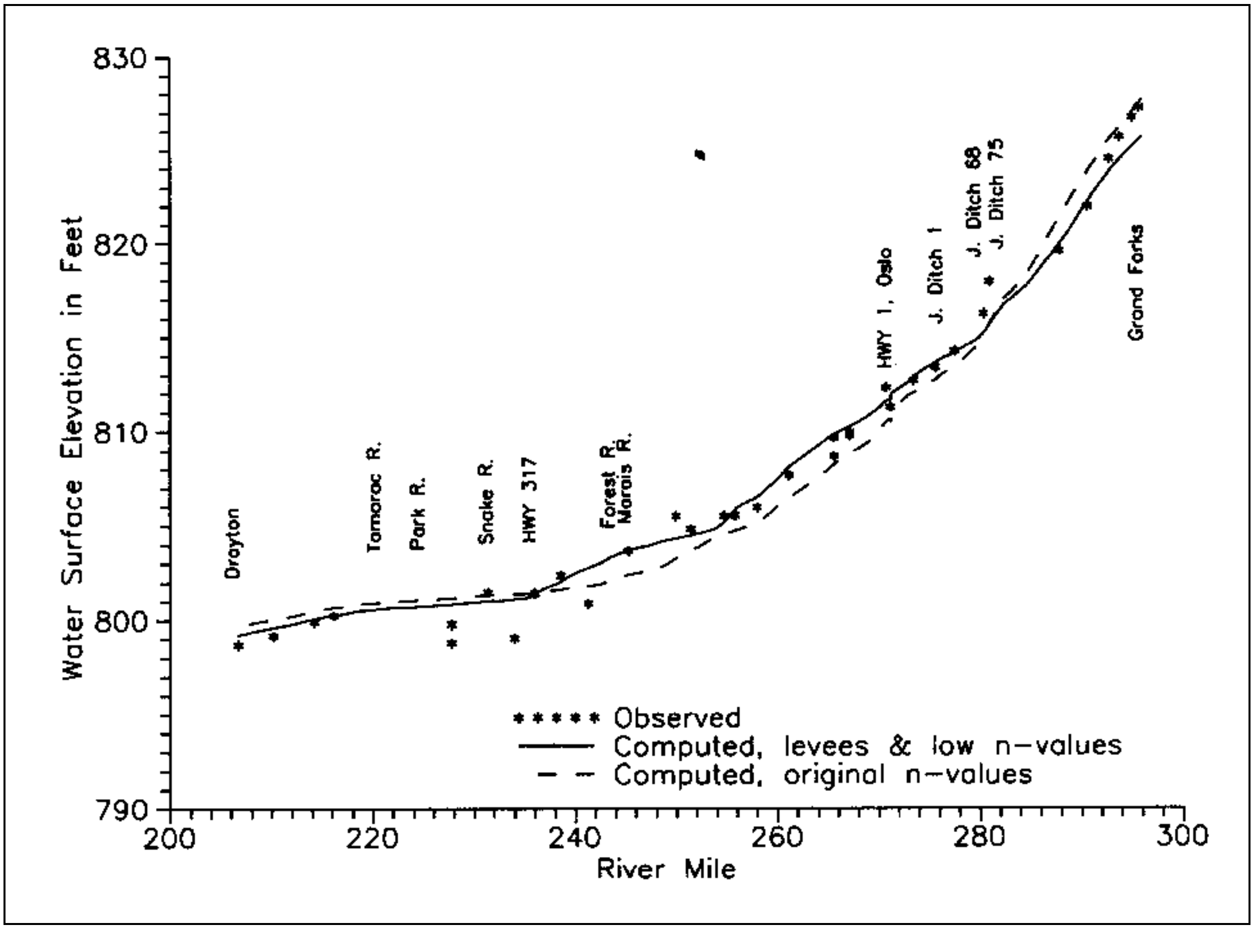

Figure 3-3. Profile calibration to high water marks

similar to the "split sample" testing procedure of frequency analysis. The calibrated model is used to compute elevations from additional flood events that were not used during the calibration process. The objective of this test is to confirm that the calibrated model can be used with confidence for other events. If only one or two floods have data, insufficient information may exist for the verification process; however, the verification step should be part of the overall calibration process. In the absence of data for verification, additional sensitivity analyses should be performed to evaluate the potential range of results due to uncertainty in input data.

3-6. Guidelines for Analytical Model Selection

The choice of appropriate analytical methods to use during a river hydraulics study is predicated on many factors including (1) the overall project objective, (2) the particular study objective for the project (level of detail being called for), (3) the class, type, and regime of flows expected, (4) the availability of necessary data, and (5) the availability of time and resources to properly address all essential issues. The following sections discuss the importance of these factors.

a. Study objectives. The type of analytical model selected by the hydraulic engineer should reflect the demands and objectives of the study. The type of model required may not be apparent until the hydraulic engineer becomes well-versed in the problems to be evaluated and spends considerable time with the study manager, economist, and local sponsor, discussing problems and potential solutions. Much of the initial reconnaissance work focuses on this problem. The level of detail relates directly to the model selected, as was described in section 3-1*b*. The study manager or local sponsor may specify or request a certain level of detail that may or may not be appropriate for the stage of the study. The hydraulic engineer must be able to designate the level of detail required for the problems to be studied, stage of the study, and intelligently discuss these requirements with the study manager, and local sponsor. It is the responsibility of the hydraulic engineer to ensure that the level of detail is not too little nor too much for the stage of the study.

(1) Although absolutes cannot be given regarding the level of detail for specific studies, Table 3-2 gives some representative guidance. In general, gradually varied steady flow is appropriate for most feasibility report analyses. Exceptions include those projects that obviously have an extensive effect on sediment regime (major channelization or reservoirs) that require movable boundary analysis in the feasibility phase, or those projects that may significantly change velocity patterns or cause rapid changes in stage (locks and dams, power plant operations, etc.). Movable bed models and unsteady or multidimensional models are often utilized in the design stage, often after a data collection program has been in place to obtain the necessary data with which to calibrate and verify these more complex models.

b. Data availability. While the first consideration should be study stage and level of detail required, the amount of available data also plays a part in the model selection. Gradually varied steady flow models can be calibrated with only highwater marks whereas movable boundary and unsteady or multidimensional models may require data from the entire hydrograph to calibrate. These models also require more hydraulic engineer skill and computer resources than gradually varied steady flow models. The necessity of using more sophisticated models will usually become apparent in the planning process. Occasionally, higher level models must be used in the survey report stage, even without adequate calibration data. While the level of reliability may suffer due to limited or no calibration data, a skilled and experienced hydraulic engineer should be able to utilize such models to evaluate changes or differences due to a project, even though absolute with or without project values are questionable. If accuracy is critical to the results of the feasibility report, a data collection program must be budgeted and planned for during the reporting process.

c. Accuracy considerations. The term "accuracy" is rather nebulous when applied to hydrologic engineering. Physical and numerical models can yield information with a high level of precision, but with accuracy limited by the input data. The field data used to develop, calibrate, verify, and operate models often vary ±10 percent, or more, from the actual values.

(1) The best evidence of the accuracy of the results is the skill and experience of the hydraulic engineer performing the analysis. Rather than specifying a numerical range, an appropriate reply to an accuracy question might be: "Because the model has adequately reproduced known events, the results for other, hypothetical, events are deemed to be representative of what would occur and results can be used with a reasonable level of confidence, provided that the same physical processes dominate in both known and hypothetical events." Implied in the foregoing is the use of sensitivity tests to evaluate the influence of key variables (like n values) on design profiles to judge the sensitivity of project economics to those profiles.

(2) Determination of existing condition profiles requires the most care in the feasibility stage, as these profiles are key in the evaluation of existing potential damages, and flood hazard. Design studies require more accuracy for designing hydraulic components than necessary in the feasibility stage.

d. Modeling requirements (time, experience, and computer resources). Modeling requirements vary with the reporting stage. In general, the more sophisticated the model required, the more time and cost is involved and the more limited is the pool of experienced engineers from which to draw. Only one or two experienced hydraulic engineers (at most) are usually available in any office to perform a hydraulic study requiring a multidimensional or movable boundary model. Other hydraulic engineers can encounter considerable start-up time and cost due to their inexperience with these techniques.

e. Hydraulic considerations. Computation of flow characteristics in natural channels can be a complicated and difficult task. Many design failures and maintenance problems have resulted from the application of inadequate or inappropriate analytical methods for the problem being considered. It is essential, therefore, to choose, develop, and calibrate the proper analytical method or modeling approach from the very beginning of a river hydraulics study. Much of the success of a project evaluation lies in the ability to properly formulate the hydraulic studies as one of the first tasks performed by the study team. The type of analysis needs to be accurately defined prior to selecting the model so that the study objectives dictate the model usage and not the other way around.

(1) As overviewed in Chapter 2, the classification and state of flow should be estimated as best as possible as an aid in selection of an analytical tool. Considerations are:

- Flow Classification: Open channel, Pressure, or Both

- Flow Type: Steady - gradually or rapidly varied Unsteady - gradually or rapidly varied

- Locations of Controls: Subcritical reaches, supercritical reaches, transitions, structures, rating curves

- Boundary type: Fixed or mobile

f. Other considerations. Once the study objectives, funds, study time frame, data and personnel availability are determined, several other important questions and considerations should be made prior to selecting a particular numerical or physical model. These may include:

- Are the data requirements of the model consistent with the study objectives? Personnel costs are usually more significant than computer costs.

- Capacity of the model and available computer hardware and software to provide information required for the study.

- Adequacy of the theoretical basis of the numerical model.

- Degree to which the model has been tested and verified.

- Data requirements in relation to data availability and amount of pre-processing required. Also, are the available data proprietary or public?

- Ease of application of the program. Factors include model documentation, input structure, diagnostic capabilities, output structure, flexibility to display output, and support.

- Data management capabilities (e.g., ability to pass information from one module to another).

- Ease of making program modifications, either in-house or by contract.

- Program efficiency in terms of typical run times and costs.

- Program accessibility. Can the program be run on a computer that is convenient to access? Does it require a mainframe computer or special hardware?

- Accessibility of user-support services (i.e., consultation with someone who is thoroughly familiar with the program).

- Quantity, accuracy, and availability of ready-to-use input data for the study area.

g. Summary. The following summary steps are suggested as a procedure for selecting an appropriate model for conducting river hydraulics studies.

(1) Define study objectives and required products. Identify project time and personnel availability.

(2) Summarize flow classification, state, regime and type as outlined above and estimate the types of data, amount of data, and quality of data needed to evaluate the types of flow characteristics identified.

(3) Prepare a list of essential data needs in tabular form. Data categories may include:

Hydrologic data (flow records, highwater marks, etc.)
Channel and floodplain geometry data
Sediment data
Geomorphologic and historical data
Other information (e.g., previous studies and reports)

(4) Are the data identified above readily available? Also, are they of the quality and proximity to the study site to be appropriate? Are the data proprietary or public? How up-to-date are they? Develop lists of available and missing data.

(5) Estimate the time and costs associated with the collection of the missing data.

(6) Examine Tables 3-2, 3-3, and 3-4 and compare to the results from the estimation of key hydraulic characteristics. Select the most appropriate methods based on results of this examination.

(7) Consider alternative methods based on results of subsequent studies made such as the reconnaissance study. Continually update and improve methods to meet the specific needs of the study.