Role of Calibration in Application of HEC-6

D. MICHAEL GEE

ABSTRACT

Calibration, the process of adjusting model parameters so that model results conform with observed prototype behavior, is an essential ingredient of any modeling effort, be it physical or mathematical. Calibration strategies for movable boundary numerical modeling (i.e., HEC-6) vary widely depending on the type and availability of field data and study scope and objective. The process of calibrating HEC-6 and interpreting field data and model results is described. Examples drawn from past project studies are used to illustrate important points. The theoretical and numerical limitations on extrapolation of model results beyond the calibration range are described. Sensitivity of model results to key input data is discussed. Applicability of HEC-6 to bridge design is addressed. The future research and development program for movable boundary mathematical modeling at the Hydrologic Engineering Center is also presented.

HEC-6 (1) is a one-dimensional movable boundary open channel flow model designed to simulate streambed-profile changes over fairly long periods (typically years). The continuous-flow record is broken into a sequence of steady flows of variable duration. For each flow a backwater profile is calculated that provides energy slope, velocity, and so forth at each cross section. Potential sediment-transport rates are then computed at each section. These rates combined with the duration of the flow make possible a volumetric accounting of sediment for each reach. The amount of scour or deposition at each section is then computed and the shape of the cross section adjusted accordingly. The computations proceed to the next flow in the sequence and the cycle is repeated beginning with the updated geometry. The sediment calculations are performed by grain size fraction thereby allowing for the simulation of hydraulic sorting and armoring. Many options and features are available such as capability to include tributary and distributary flows, automatic channel dredging, gravel mining, and graphical display of simulation results. HEC-6 has been widely distributed and is frequently used by the U.S. Army Corps of Engineers, other government agencies, universities, and the private sector.

Experience has shown that successful application of movable boundary models often requires substantial effort to reproduce field observations; that is, the model must be calibrated. Consequently the focus of this paper is on the process used and variables adjusted during the calibration phase of a study.

The key components of the calibration and verification process for HEC-6 applications, which will be described in this paper, are

1. Comprehending the historical behavior of the stream system.
2. Developing representative geometric, sediment, and hydrologic data.
3. Performing the calibration by (a) selecting calibration measures of changes in bed profile, changes in cross-sectional geometry, changes in volumes of sediment, rating curve shifts, and other characteristics that suit study level and objectives; (b) selecting the calibration time period; (c) identifying acceptable model performance; and (d) adjusting parameters.
4. Verifying the calibration.

In calibrating a complex fluvial hydraulics model such as HEC-6 it is important to distinguish between the following three types of data: (a) run data--the specific input information required to operate the mathematical model; (b) calibration data--prototype measurements used to adjust various model parameters so that model results conform to the observed prototype behavior; and (c) verification data--an independent set of measurements, not used in calibration, that is used to test the validity of the calibrated model.

HISTORICAL BEHAVIOR OF THE STREAM SYSTEM

It is essential for the modeler to comprehend the historical behavior of the stream system early in the study. Development of appropriate representative data and assessment of the model's performance require such an understanding. Historical behavior refers to an engineering time scale rather than the geologic time scale. Contemporary engineering analyses address time frames ranging from single flood events to project life spans.

Selection of the study area requires certain considerations. The area should extend far enough upstream from the problem area so alternatives being evaluated do not produce changes to the streambed profile or sediment load at the upstream boundary of the area being modeled. The study area should also include all major sediment-producing tributaries. Usually the location of stream gauging stations will determine the limits of a study area. Hydraulic structures may also be used as a study boundary; they are more appropriate as a downstream boundary than as an inflow boundary.

To ascertain the historical behavior of the stream system, assemble all information from office files: maps; surveyed cross sections; observed water-surface profiles; aerial photographs; ground photographs; flow hydrographs; stage hydrographs; stage-discharge rating curves; water-temperature records; suspended-sediment loads; total sediment loads; gradation of the suspended and total loads; gradation of the streambed material; the location, date, and size of all impoundments; the location, date, and extent of all bridge construction activities; the location, date, and extent of all construction activities adjacent to the stream channels; the location, date, amount, and material gradation for each dredging activity in the study area; land use and soil types; and prior studies.

The availability of each type of data may be shown on a time line. This is particularly useful for flow data used to determine a base period for calibration. Having organized and inventoried available data, begin a detailed study to accomplish each of the following tasks.

1. Establish a general knowledge of extreme events in the study area and of how the system responded in terms of channel changes and amount of sediment transported;
2. Establish a general awareness of the response time of the stream system in terms of rate of movement of flood hydrographs, rate of response to changes in sediment load, and so forth;
3. Evaluate the impact of recent impoundments on the water-discharge hydrograph and the sediment load;
4. Reach a general understanding of the historical behavior of the stream system--the part of the behavior that would have occurred naturally and the part that may be attributed to man's activities in the study area (land use as well as stream use);
5. Locate anomalies in geometric, hydrologic, hydraulic, and sediment characteristics within the study area;
6. Refine the study objectives, identify possible project alternatives and appropriate analytical approaches; and
7. Identify missing data that can be supplied only by additional field measurements or field reconnaissance.

It is important to view the study area with someone who is intimately familiar with it. Particularly note all locations where scour or deposition occurred and the stream did not return to its original cross section or alignment. Locate and date each bridge crossing, each cut-off (natural or man-made), each encroachment, each levee, each diversion or bifurcation. Note overbank areas that flood first and locate their natural levees.

The streambed and banks must be studied to locate rock outcroppings or other geologic formations that will resist scour and therefore control the vertical movement of the streambed. The grain size of sediment on the point bars should be observed and locations of abrupt changes noted. Of particular interest are locations where the gradual change from coarse to fine particles in the downstream direction is interrupted by a sudden change that persists in the downstream direction.

DEVELOPMENT OF REPRESENTATIVE DATA

Specific input data requirements for the operation of HEC-6 are presented in the users manual (1). The quantity of data necessary to operate HEC-6 for long-term simulations can be quite large. Therefore it is beneficial to have a systematic procedure for storing, manipulating, and displaying those data (2,3). This section addresses the problem of developing representative data. Representative data are not necessarily averages of many samples. For example, representative geometry preserves channel width, depth, and roughness and allows the numerical model to transport sediment with changes in bed elevation that match prototype observations. The representative inflowing sediment load preserves both volume of sediment and rate of sediment inflow at the upstream boundary of the study area. The representative bed-material gradation and gradation of inflowing sediment load allow the model to transport observed sediment discharges while reproducing observed changes to the bed elevation. Representative water discharges include flow rate and, to a lesser extent, flow volume and amount of attenuation of flood hydrographs as they move down the system.

Having flows match the appropriate flow duration relationship is extremely important, (i.e., representative flows for the calibration period are those that occurred during that period, whereas representative flows for the study period are those producing the long-term flow duration curve). Beginning with geometric data, procedures for developing representative data are suggested. These are by no means all-inclusive guidelines, but they stress the most important characteristics of the real physical system that should be preserved.

Geometric Data

Geometric data consist of cross sections, their locations, and boundary roughness (Manning n values). Cross sections should be located at major changes in bed profile, at points where channel or valley width changes, at tributaries, and at all pertinent points where calculated results are required (e.g., stream gauging stations). The geometric model should extend sufficiently far upstream from bridge crossings so that it will be beyond any backwater effects. A portion of each cross section must be specified as movable (Figure 1). This requires good engineering judgment and may require adjustment during calibration.

Avoid locating cross sections too close together. The shorter the distance between sections, the shorter the computation interval has to be in HEC-6. Short computation intervals require more computer time and, therefore, should be avoided in long-period studies. This may prove particularly troublesome because the simulation of scour at a bridge location is a local phenomenon that implies use of a fine-grid analysis. Short time steps (hours or less) may therefore be necessary. It appears that the resulting study would focus on a single-event analysis.

Checking Geometric Data for Errors

Movable streambed calculations are much more sensitive to errors in boundary geometry than are fixed-bed water-surface profile calculations; consequently, more care is required to prepare geometry than is typically required for fixed-bed water-surface profile studies. A cross section that is too wide or too deep will show up as a point of deposition; one that is too narrow or too shallow will exhibit a tendency to scour. Not only will that section be affected, but calculated results will be incorrect at sections upstream and downstream from it. Geometric data errors, therefore, are difficult to locate when HEC-6 is executing in the movable-bed mode. For this reason the first step in debugging and calibrating geometric data is to run the model in fixed-bed mode. This allows calibration of the geometric and hydraulic portions of the study separated from the sediment portions. This is a critical first step because the validity of subsequent sediment computations is dependent on having an accurate hydraulic description of the system as well as representative sediment data.

Selection of n Values

Appropriate values for Manning's n should be determined by running HEC-6 in the fixed-bed mode (i.e., as a step-backwater program). This is necessary to compare calculated water-surface elevations with observed (or calculated, e.g., HEC-2) water-surface profiles or rating curves.

Careful consideration should be given to the selection of n values. Changing n values with distance should be justified by changes in channel appearance or sediment size. Avoid changes where the only reason is to reconstitute an observed stage (4). It is often more logical to approximately reconstitute the stages at several gauge locations over a long reach using a constant n value for a given discharge than it is to change n values at

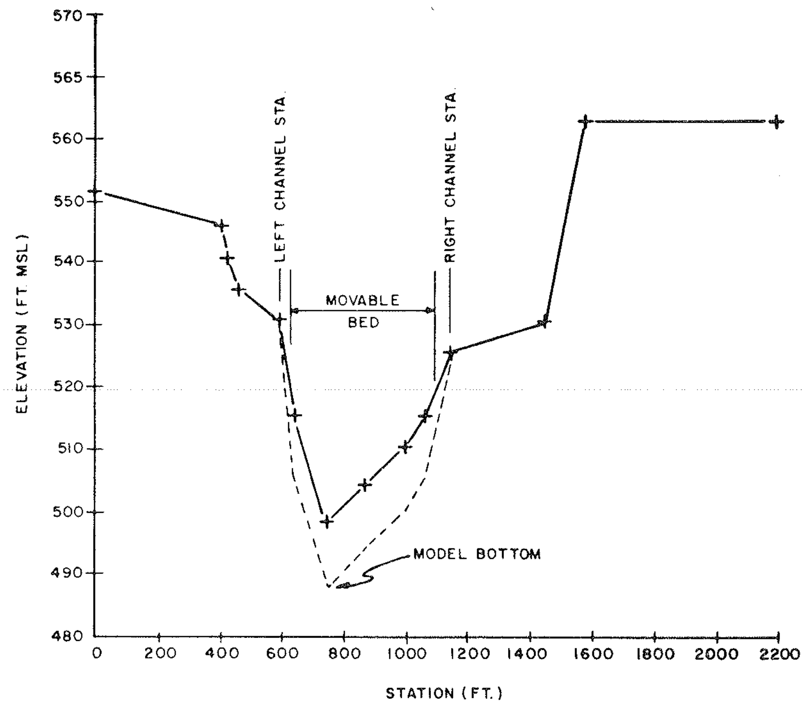

FIGURE 1 Example cross section.

each gauge to exactly match observed stages. Also, n values may vary with discharge, that is, the bed form of alluvial rivers often changes during the passing of a flood event. As yet it is not possible to accurately predict such changes (5-7). Until a theoretical basis is developed one should consider acknowledging such a change by associating n values with water discharge if field data for the particular river support such a variation.

Sediment Data

Preparation of accurate sediment data and development of a representative inflowing sediment load curve are essential. The overall objective in preparing sediment data for river studies is to establish the sediment load that accompanies river flows and determine the proper size distribution and character of the bed material. The most common approach is to plot observed water discharge versus observed sediment load as shown in Figure 2. These plots usually exhibit a log cycle of scatter. The representative load curve produces the proper annual volume of sediment when integrated with the water-discharge hydrograph for the year in question. The total inflowing load, and distribution of grain

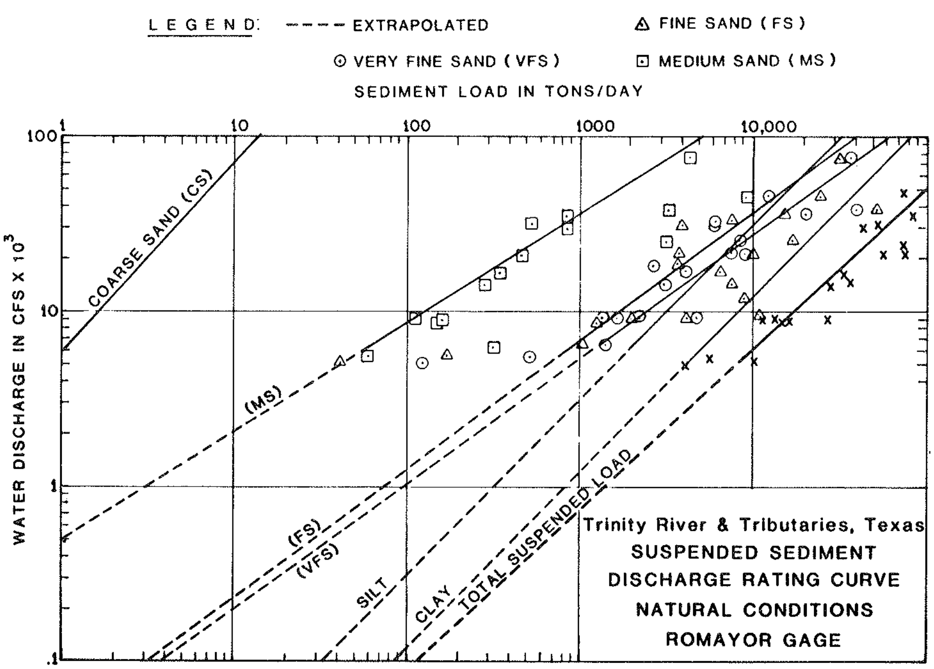

FIGURE 2 Sediment discharge rating curve.

sizes within that load, must be adjusted until a representative curve has been established.

Note that for the purpose of simulating scour at bridge crossings the fine materials (clays and silts) may be irrelevant. These materials are included in suspended load measurements, however, and may, therefore, have to be included in the model input data to reproduce the measured average annual total loads.

Once representative inflowing sediment load curves have been identified for all size classes, bed-material gradation curves must be developed from field samples (see Figure 3). Figure 4 shows an example plot of profiles of grain size gradation versus river mile. Plots such as these assist the modeler in understanding the stream's behavior by illustrating grain size changes along the study reach, which reflect the influences of geologic controls, tributaries, and so forth.

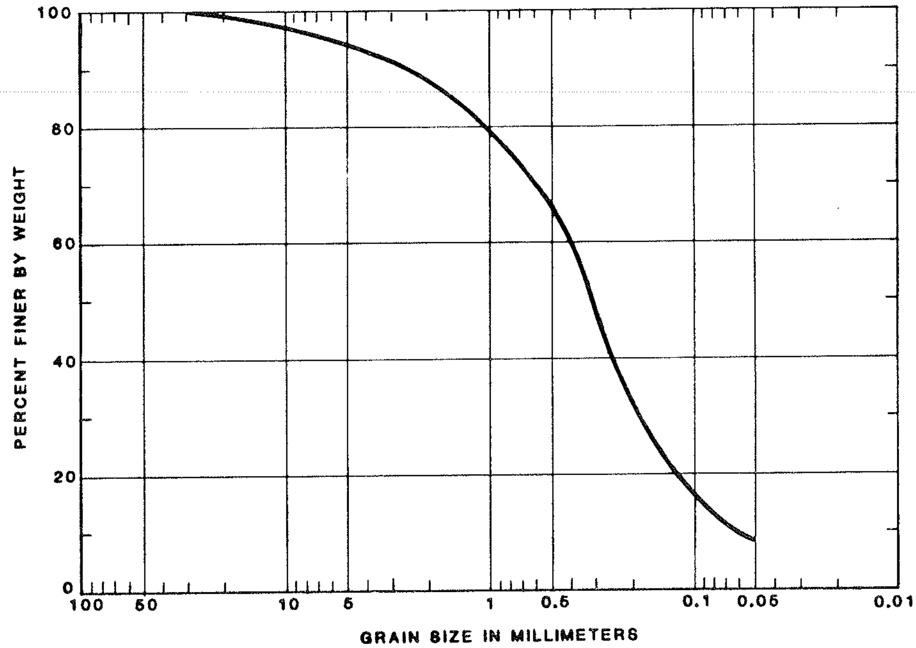

FIGURE 3 Grain size distribution of bed material.

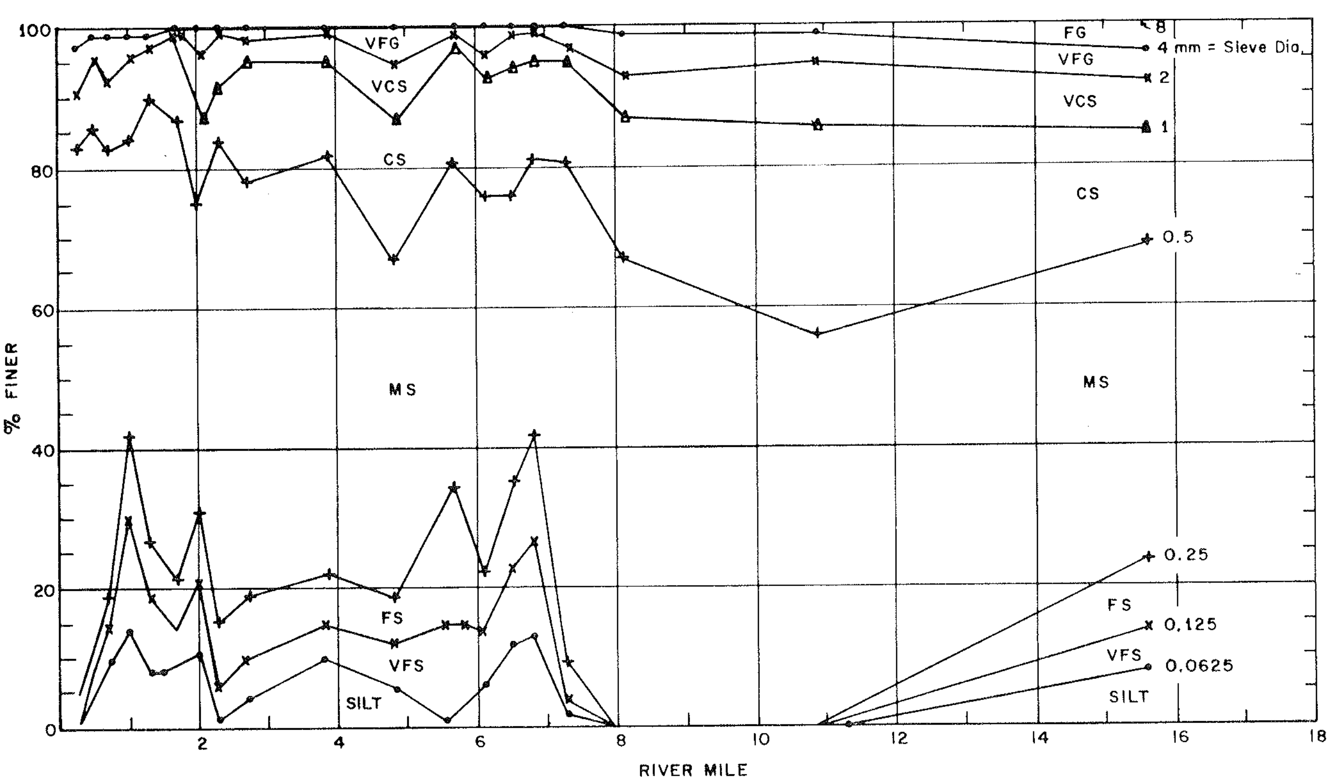

FIGURE 4 Example of profiles of bed sediment size, Big Sandy River, Huntington, West Virginia.

Hydrologic Data

Hydrologic data consist of (a) inflowing water discharges for the mainstem and for all local inflow or outflow points; (b) the stage hydrograph, rating curve, or operating rule giving water-surface elevation at the downstream end of the model; and (c) temperatures for the inflowing water discharges [see (4) for explanation of importance].

ESTABLISHMENT OF COMPUTATION INTERVALS

The computation interval (or time step) used by HEC-6 is usually variable; short time steps must be taken during flood events when large amounts of sediment are moving and the hydrograph is rapidly changing. Longer time steps should be used during low-flow periods (Figure 5). In general the closer the cross sections, the smaller the required time step. The modeler is confronted with the dilemma of wanting to use small time steps for an accurate solution and large time steps for a cheap solution. A procedure for selecting an optimum time step is outlined elsewhere (8). At present, the HEC uses a data preprocessor that automatically develops a variable time step flow record from mean daily flows based on an estimation of the volume of sediment entering the study reach each time step. For a multiyear simulation the time step typically ranges from 1 day to 1 month.

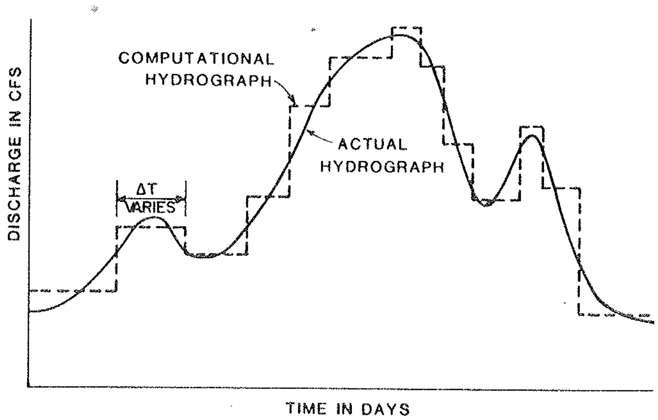

FIGURE 5 Water discharge hydrograph.

Operation of the model for a test period (perhaps an average year) should be performed as a check on data consistency and reasonableness before calibration runs are attempted. The flow record for an average year can be constructed from the flow-duration relationship. Key items to check at this time are

1. Silt and clay should not deposit in the channel under natural river conditions. Any cross section that exhibits a reduction in silt or clay load passing through that section should be carefully checked. The cross section may be too large or a false channel control may exist downstream.

2. The sand load should approach a steady value, approximately equal to the inflowing load, from section to section rather than an erratic variation. It must be remembered that cross sections used in HEC-6 are representative of reaches; therefore, some smoothing of field data may be required. Sections that have very little transport capacity should be checked for errors in cross-sectional geometry, reach length, n values, limits of movable bed, or perhaps bed-material gradation.

If the model performance simulates in all respects the behavior that would be expected in the prototype, the computation interval and the other parameters have been determined. Otherwise, one must determine what is causing the questionable performance. For example, excessive fill may mean the limits of the movable bed are too narrow or the natural levee is too low. If the prototype is depositing sediment above the overbank elevation, expand the movable-bed limits to include the overbank. If water is spilling onto the overbank in the computer model but that area is not effective for conveyance in the prototype, raise the natural levees. If excessive scour is indicated by the computed results, it may mean that the prototype has an armored, nonerosive, or rocky bottom that is resistant to scour.

PREPARING FLOW RECORDS

The three main points to consider in developing flow records are (a) preserve the total volume of water in the observed hydrograph, (b) preserve the total volume of sediment that was transported during the hydrograph period, and (c) make the computation intervals as long as possible and still preserve computational stability (9).

There is usually a strong correlation between the annual volume of water that passes a gauge and the annual sediment yield of that basin. The rate of sediment movement, called sediment load, is not a function of water volume. It is a function of water discharge (Figure 2) and of the availability of sediment material. In many cases, three-quarters of the annual sediment yield will be transported in less than one-quarter of the year. Therefore, it is necessary that all flow records contain flood peaks.

CALIBRATION MEASURES

Selection of appropriate calibration measures for a movable boundary model such as HEC-6 is not straightforward. Ideally, one would have complete sets of surveyed cross sections and measured sediment-transport rates periodically throughout the calibration period. Such data sets are extremely rare. Consequently, different calibration measures may be used for different studies depending on study objective, data availability, and so forth (8). A useful calibration measure is the observed drift of the rating for a stream gauge. This is a good measure because the rating curve integrates, to a certain extent, behavior of a stream reach rather than a single point or cross section. Care should be taken that the rating-curve drift is being caused by scour or deposition and not roughness changes. The gauge selected for use in calibration should not be within the influence of the downstream boundary. An example reproduction of a rating-curve shift is shown in Figure 6.

Should surveys of cross sections be available over an appropriate time interval, care must be taken to correctly compare model results and field data. Amounts of scour and deposition may not be exactly reproduced at specific locations of cross sections. Regions of scour or deposition should correspond between model and prototype. In some cases it is appropriate to compare volumes of scour and deposition as a calibration measure (10,11).

Before using a numerical model such as HEC-6 for the analysis of projects, the model's performance needs to be evaluated. Evaluation normally consists of two phases: calibration and verification. Calibration is intended to make computed results as accurate as possible. Measured or observed values from the prototype are compared with computed

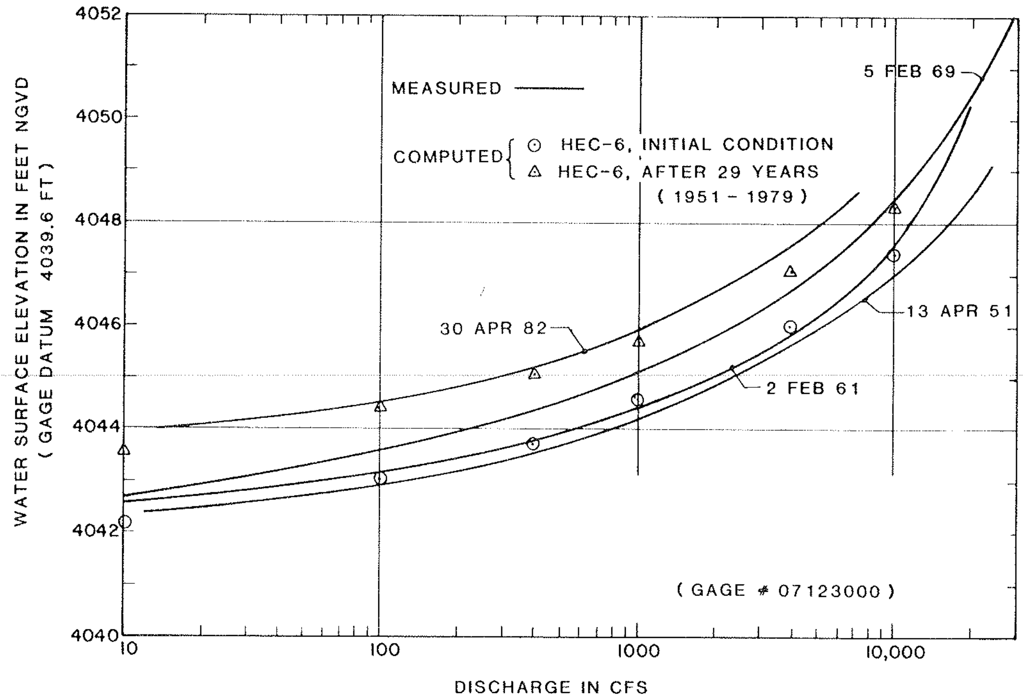

FIGURE 6 Rating curves, Arkansas River at La Junta, Colorado.

results to pinpoint input data deficiencies or physically unrealistic coefficient values. Model parameters are adjusted accordingly to improve the simulation. Calibration, however, does not mean the use of physically unrealistic parameters to force a poorly conceived model to satisfying prototype data. If there is a discrepancy between model results and calibration data, either there is something wrong in the physical realism of the model (a model deficiency as a result of limiting assumptions) or there is something wrong with the measured data or the interpretation of that data for model input (a data deficiency). Therefore, if calibration cannot be accomplished through the use of physically realistic parameter values, the measured prototype data should be checked for possible errors and then the entire model (input data and limiting assumptions) should be examined, data coding should be checked, and boundary specifications should be examined. Experience has shown that the process of rectifying discrepancies between model results and prototype observations can substantially assist the engineer to understand a river's behavior. When it has been calibrated, a model needs to be verified by checking its performance against a situation not used in the calibration.

SENSITIVITY OF SIMULATION RESULTS TO DATA UNCERTAINTIES

The sensitivity of simulated bed-profile changes to various data can best be evaluated in light of the reliability of field measurements of those data. In addition to field data there are various model parameters that cannot be measured directly and must be estimated by the model user and adjusted if necessary during the calibration process. Guidance on selection of model parameters is given elsewhere (8). A qualitative assessment, based on experience gained from many past applications of HEC-6, of the model sensitivity to variations in the various input data is given in Table 1. Note that, in any particular study where uncertainty exists in the value of any particular input item, the model can be run for a range of values of that particular input item to assess the resultant variation in simulation results. This information can then be used to identify what, if any, additional field measurements are necessary to accomplish the study objectives.

APPLICATIONS TO BRIDGE DESIGN

Bridge crossing design must confront both long-term river behavior (particularly lateral migration) and single flood-event response. Applications of HEC-6 to bridge crossing design would probably focus on the latter. This is a relatively new area of use of HEC-6 and many questions remain. Foremost is the stochastic nature of watershed sediment production. The behavior of any river reach is determined not only by local hydraulics, perhaps as modified by bridge construction, but also by the amount and size of sediment transported into the reach from up-

TABLE 1 Sensitivity of Model Results to Field Data

Data Item	Field Measurement Reliability	Model Sensitivity	Remarks
Geometry			
Cross sections	H	H	
Movable bed limits	L	H	Field estimation and calibration
Roughness	M	M	Field estimation and calibration
Sediment			
Bed material gradation	M	H	
Inflowing load	L	H	H locally, M elsewhere
Hydrology			
Flow record	H	M	Developing long-term flow records can be difficult; see (5)
Rating curve	H	L	Local effect
Temperature	H	L	

Note: H = high, M = medium, L = low.

stream. The condition of the watershed at any particular time (e.g., recently burned) is not deterministic (12). Therefore, it is difficult to ascertain, for a given hypothetical flood hydrograph, the appropriate inflowing-load curve.

For single-event bridge scour problems, it may be adequate to assume that the problem is governed by transport of bed material, neglecting wash load. Inflowing load can then be approximated based on equilibrium transport in the reach several stream widths upstream of the bridge site (depending on flood hydrograph duration). HEC-6 applies to this problem providing that local scour phenomena are not coupled with multidimensional hydrodynamic phenomena in the vicinity of the bridge. For two-dimensional, near-bridge problems RMA-2 (13) may be useful.

Another use of HEC-6 in bridge design is prediction of long-term trends in stream-bed profile behavior. Analysis can be made of the impacts of various scenarios regarding upstream and downstream actions (e.g., headcutting) at the bridge site. Note that, for either long-term or single-event studies, HEC-6 is best used to evaluate the relative impacts of different designs (e.g., design A versus base condition, design A versus design B, and so on).

FUTURE RESEARCH AND DEVELOPMENT

The research and development program at the HEC in the area of movable boundary modeling consists of two integrated components. The first component consists of enhancements and improvements to HEC-6; the second, long-range component is the development and implementation of a second-generation movable boundary model.

Several improvements to HEC-6 are under way at this time. The major items are development of a method of allowing the movable bed width to vary with width of the water surface (i.e., water-surface elevation). At present, the scour or deposition at each cross section is applied to a fixed, user-selected portion of that cross section regardless of discharge. Incorporation of an algorithm to automatically identify which portion(s) of the cross section are submerged at each computational time step for scour and deposition calculation will provide a more physically realistic and less user-judgment-dependent solution.

One of the primary features that has contributed to successful application of HEC-6 is its capability to route sediments by grain size fraction. Movement

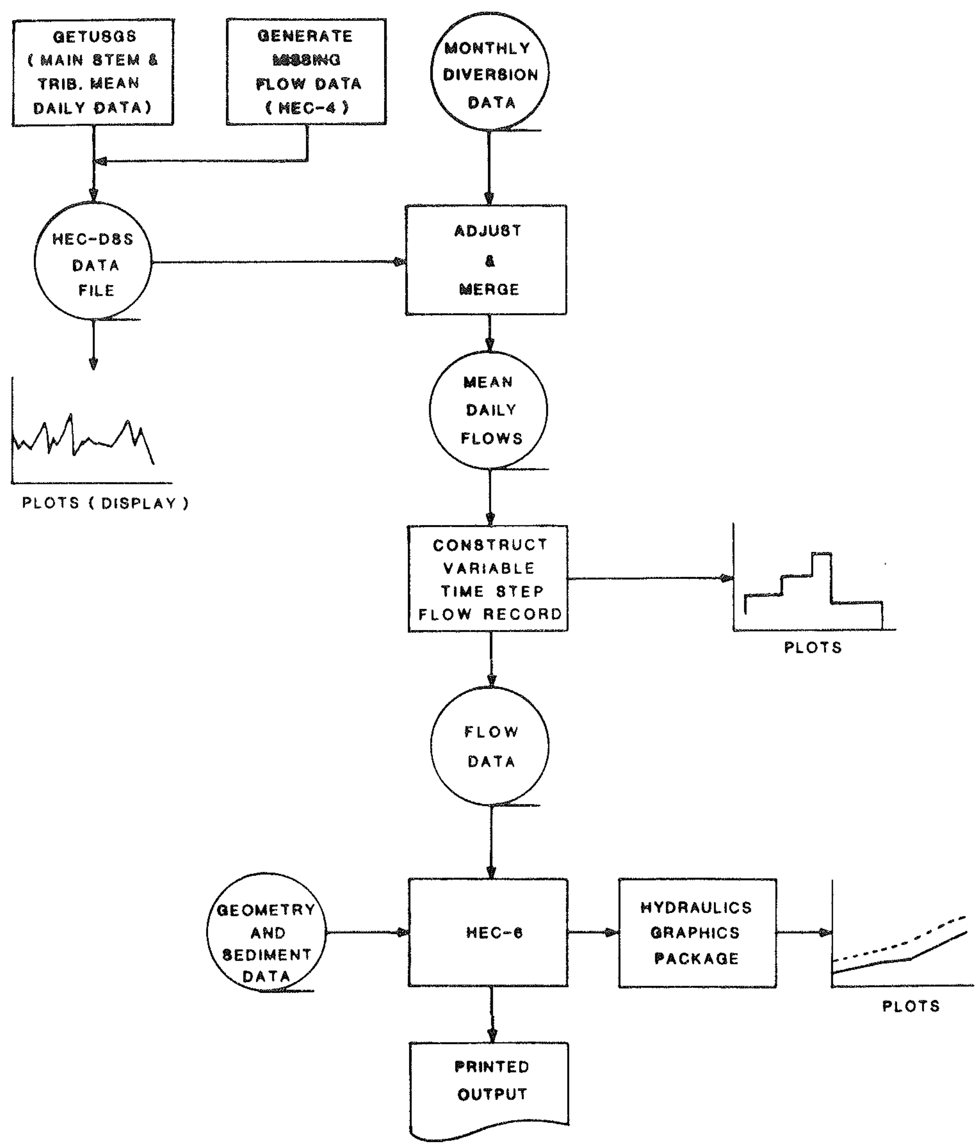

FIGURE 7 HEC-6 data flow and program linkage.

of one clay size, four silt sizes, and ten sizes of sands and gravels can be simulated. This provides the capability to simulate sorting and armoring of the bed material because fines are transported much more rapidly than coarse materials. The algorithm that performs the accounting calculations for all the grain sizes in the bed has evolved over the past 10 years, incorporating the best available theories for the sorting and armoring processes. It has been noticed that a significant amount of computation effort is used by this particular algorithm. It is thought that significant gains in computational efficiency can be achieved by redesigning and simplifying this algorithm. Furthermore, the current algorithm requires the user to specify a (somewhat arbitrary) number of iterations within each computational time step for recalculation of the bed-material gradation. A theoretical investigation has been undertaken to identify a better method of tracking bed-material gradation using a physically based procedure for updating bed-material gradation.

HEC-6 incorporates many of the capabilities and features necessary for a one-dimensional movable boundary river model. An important component not currently available is a method for tracking lateral migration of a river. It appears that viable theories are now becoming available for prediction of meander migration (14). Consideration is being given to incorporating this capability into the next generation of the movable boundary model.

HEC-6 is a widely used model. It has been developed over the past 10 years with features being added as required by various studies. The level of effort necessary to support the model is becoming significant. HEC is, therefore, considering development of a second-generation movable boundary model that would employ the concepts of structured programming and algorithmic modularization. The purpose, use, theoretical basis, and so on would be similar to those of HEC-6. Some new capabilities, such as a lateral movement component, would be added, and obsolete or little-used components discarded. The experience gained with the many applications of HEC-6 provides a valuable basis for the construction of a new model. Development of a new code will emphasize theoretical improvements, computational efficiency, structured programming, user ease, and interfaces with data management systems.

COMPUTATIONAL ASPECTS

Application of a movable boundary model such as HEC-6 can require major computational resources, particularly for long-period studies (50 to 100 years). Operation of the simulation model is only one component of the computational requirements. It is also important to have software available for storage and manipulation of hydrologic data and graphic display of input data and simulation results. The linkage of the various software packages and data files developed for a recent study at the HEC is shown in Figure 7. This support software has become an integral and necessary component of any major movable boundary modeling effort at the HEC. Single-event analyses are less computationally intensive because the study reach is relatively short, the hydrographs are synthetic and of short duration, and the sediment loads can also be synthetically generated. Calibration data are rarely available for single-event analyses.

ACKNOWLEDGMENT

The concepts of calibration of HEC-6 presented herein are those of William A. Thomas, original author of the model. The findings and opinions expressed herein are those of the author and not necessarily those of the U.S. Army Corps of Engineers.

REFERENCES

1. HEC-6 Scour and Deposition in Rivers and Reservoirs, Users Manual. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif., 1977.
2. D.M. Gee. Prediction of the Effects of a Flood Control Project on a Meandering Stream. Rivers '83: A Specialty Conference on River Meandering. ASCE, New Orleans, Oct. 24-26, 1983, proc. in press.
3. The Hydrologic Engineering Center, Data Storage System (HEC-DSS), An Overview. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif., 1982.
4. V.A. Vanoni, Ed. Sedimentation Engineering. Manuals and Reports on Engineering Practice No. 54. ASCE, 1975.
5. H.H. Barnes, Jr. Roughness Characteristics of Natural Channels. Water Supply Paper 1849. U.S. Geological Survey, 1967.
6. H.A. Einstein and N.L. Barbarossa. River Channel Roughness. Transactions, ASCE, Vol. 117, 1952, pp. 1121-1146.
7. D.B. Simons and E.V. Richardson. Resistance to Flow in Alluvial Channels. Professional Paper 422J. U.S. Geological Survey, 1966.
8. Guidelines for the Calibration and Application of HEC-6. Training Document No. 13. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif., 1981.
9. Sediment Transport. IHD Vol. 12. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif., 1977.
10. G.R. Dyhouse. Sediment Analysis for Urbanizing Watersheds. Journal of the Hydraulics Division, ASCE, Vol. 108, No. HY3, March 1982.
11. D.T. Williams. Effects of Dam Removal: An Approach to Sedimentation. Technical Paper No. 50. Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, Calif., Oct. 1977.
12. R.C. MacArthur. Evaluation of the Effects of Fire on Sediment Delivery Rates in a Southern California Watershed. In Proc., D.B. Simons Symposium on Erosion and Sedimentation, Fort Collins, Colo., 1983.
13. W.R. Norton and I.P. King. User's Guide and Operating Instructions for the Computer Program RMA-2. Resource Management Associates; Sacramento District, U.S. Army Corps of Engineers, Dec. 1976.
14. Rivers '83: A Specialty Conference on River Meandering. ASCE, New Orleans, Oct. 24-26, 1983, proc. in press.

Publication of this paper sponsored by Committee on Hydrology, Hydraulics and Water Quality.