CIVIL ENGINEERS
AND GEOLOGISTS

T.7. Ruff

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# REVIEW AND ANALYSIS
# OF HEC-6
# SCOUR AND DEPOSITION IN RIVERS AND RESERVOIRS

prepared for

HYDROLOGIC ENGINEERING CENTER
U. S. ARMY CORPS OF ENGINEERS
DAVIS, CALIFORNIA
Contract No. DACW05-82-P-2156

January 1983

401.007

16 North Oak Street, Suite 201, Ventura, CA 93001 (805)653-6440

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# 1.0 INTRODUCTION

HEC-6 is a computer program developed by the Hydrologic Engineering Center for the mathematical modeling of scour and deposition in rivers and reservoirs. Since its release in 1977 it has been used successfully in many studies. However, some users have experienced difficulty in operation, application, or interpretation of results from the model.

In order to better understand those difficulties and to find ways to improve the utilization of HEC-6, the Hydrologic Engineering Center contracted with DMA Civil Engineers and Geologists to provide suggestions and specific examples of modifications to the HEC-6 computer program and/or documentation. DMA was requested to investigate the areas of theoretical soundness, scope of applicability, ease of use, reliability, computational efficiency, and credibility.

Four tasks were outlined for DMA to complete. First was a review of the literature, in particular to identify and summarize critical analyses of HEC-6. Second was to identify specific problem areas in HEC-6 and to identify their origins and/or causes. Third was to make specific recommendations for rectification of problems identified. Fourth was to prepare a report of the findings of the study.

This report is prepared to satisfy the fourth task. It will cover the first three tasks in order.

## 2.0 REVIEW OF THE LITERATURE

The review was to include, but not necessarily be limited to, five specific reports. They were those by W. W. Sayre of University of Iowa, J. Webb of Colorado State University, D. R. Dawdy of NORTEC, P.F. Ruff of Arizona State University, and the National Academy of Sciences panel study on the use of hydrodynamic computer models for flood insurance studies.

The final study was to be included only if results became available prior to the initiation of this contract. They have not, and therefore the NAS report will not be specifically included in this report. However, the general knowledge gained by Mr. Dawdy, a member of that panel and an author of this report, will aid in the preparation of this report, although no panel findings can be included.

The study by P.F. Ruff is in the planning stage. Two sets of data are to be assembled and used for a comparative study of the performance of several models for estimating scour and deposition. One set of data is near completion and the first computer runs with the first set of data are planned for mid-December. Therefore, no results are as yet available and that study will not be discussed further in this report. Sayre's and NORTEC's studies will be referenced in discussions in the text at the appropriate time.

Webb, 1980, reviewed and compared HEC-6 with two other sediment models, KUWASER and Simons and Li's model. Webb's report includes a review of the basic theory and workings of all three models. The review appears to be quite superficial, not much more than what is

presented in the User's Manual for each model. Webb does point out that although the program was developed for the inexperienced user there are some shortcomings in the guidelines given in the User's Manual. This combined with the fact that HEC-6 has the ability to generate much of its data can lead to the inappropriate use of the model.

Brownlie, 1981, has reviewed HEC-6 and points out five areas which he feels are shortcomings in the model. His first objection is that the model uses the step-backwater method and consequently does not truly model unsteady flow. Although this is correct and several other investigators have used the momentum equation to model unsteady flow, it is not a critical point. For the range of applications the use of the energy based step-backwater procedure is adequate and a change in it is not warranted at this time. The second objection follows from the first, that is that the hydraulic and sediment equations are uncoupled. Again with the present state-of-the-art this is the most reasonable approach. One needs to keep in mind that additional complexity does not necessarily lead to increased accuracy. Furthermore the additional computational cost are not justifiable.

Brownlie has a valid objection to the limited number of sediment relations offered in HEC-6. He also points out the lack of guidance in the User's Manual as to the selection of a most appropriate relation. This objection is quite valid and has been observed by other users. This can be remedied by additional work as pointed out in Sections 3 and 4 of this report.

The last two of Brownlie's objections deal with the definition of slope and sediment discharge. In HEC-6 slope is defined by Mannings equation with a known coefficient at each cross-section. Brownlie recommends an alternate approach based upon his work which is not necessarily better. Brownlie's equation is for dunes while most interest in sand bed streams is in the higher flows, probably upper regime, not dunes. Lastly, equilibrium sediment transport for each discharge is assumed in HEC-6. Brownlie suggests an alternative method to determine the sediment transport. Basically it is just a new empirical formula not necessarily any better.

Brownlie's work on an unsteady sediment transport model for sand bed streams shows some interesting results, but they are preliminary at best. At present his model requires a 10-second time step for a reach length of 100 meters and a flow depth of 2 meters. This represents significant computational costs which are not justifiable. However, if this work is continued a better theoretical model may result.

## 3.0 SPECIFIC PROBLEM AREAS IN HEC-6

### 3.1 Stability Criteria Inadequacies

The following basic equations are employed in the HEC-6 model:

(1) Flow-continuity equation:

$$\frac{dQ}{dx} = q_1 \tag{1}$$

(2) Flow-energy equation:

$$\left(h + \frac{\alpha Q^2}{dgA^2}\right)_{k-1} = \left(h + \frac{\alpha Q^2}{2gA^2}\right)_k + H_L \tag{2}$$

(3) Sediment-transport equation:

$$G = \int_y^h Bucdz = G(V, h, y, B, A, S, T, d, \text{etc.}) \tag{3}$$

$$V = \frac{Q}{A} = \frac{1}{(h-y)} \int_y^h Udz \tag{4}$$

(4) Sediment-continuity equation:

$$\frac{\partial G}{\partial x} + pB\frac{\partial y}{\partial t} = 0 \tag{5}$$

or,

$$B\,\frac{\partial[cV(h-y)]}{\partial x} + pB\,\frac{\partial y}{\partial t} = 0 \tag{6}$$

where $A$ = cross-sectional area ($L^2$)

$B$ = movable-bed width (L)

$c$ = sediment concentration (nondimensional)

$d$ = grain diameter of sediment material (L)

$G$ = sediment discharge ($L^3/T$)

$g$ = gravitational accelaration ($L/T^2$)

$H_L$ = head loss between sections k-1 and k (L)

$h$ = water surface elevation (L)

$p$ = volume shape factor (nondimensional)

$Q$ = water discharge ($L^3/T$)

$q_l$ = lateral water inflow per unit width ($L^2/T$)

S = energy gradient (nondimensional)

T = water temperature ($^oF$)

u = velocity component in the x-direction (L/T)

V = mean velocity in the cross section (L/T)

x = longitudinal distance along the channel (L)

y = movable bed elevation (L)

z = vertical distance perpendicular to the x-axis (L)

$\alpha$ = velocity head correction factor (nondimensional)

The sediment-continuity equation (5) is solved by employing an explicit finite-difference scheme as follows:

$$\frac{-(G_{k+1} - G_{k-1})}{p(\Delta x_{k,\,k-1} + \Delta x_{k+1,\,k})} + \frac{B(y_k^{t+\Delta t} - y_k^{t})}{\Delta t} = 0 \qquad (7)$$

This is the central-difference scheme and is subject to the control of numerical stability. In order to control the numerical stability, HEC-6 uses the criterion (Exhibit 6, p. 17 of the User's Manual, ref. 13).

$$\Delta t \equiv \frac{\Delta x}{V} = \frac{DD}{LTI} \qquad (8)$$

where DD is the flow duration (T) and LTI is the total number of integration intervals used in calculating sediment movement.

In the HEC-6 stability criterion confusion arises from the fact that the $\Delta t$ is determined either by 1) a pre-assigned value of LTI=SPI (Exhibit 6, p. 17, or by 2) a default calculation of $\Delta x/V$. In the

first option the Manual recommends the use of a value in the range from 10 to 50 such that the value selected results in the least oscillation. This is a very arbitrary criterion. In the second option, the velocity (V) is selected by the different weighting factors between 0 and 1 from the consequent cross sections. HEC-6 presents two schemes (Exhibit 3, p. 13) to illustrate the sensitivity of the calculation. Once again, this reveals the inadequate treatment of the stability problem. To remedy this deficiency, Sayre, 1979, suggested Chen's concept of a stability criterion (Chen, 1979).

A better stability criterion has to consider the following different stability conditions: 1) The flow transport stability condition. In the most general water and sediment routing model, the unsteady shallow water equation (or Saint-Venant equation) must be retained. From this equation, the condition of stability could be obtained on the basis of the numerical scheme chosen, and in general, ends up with the Courant stability condition (advection condition). (See details in the texts of numerical solution in unsteady open channel flow, e.g., Mahmond, et. al. 1975). 2) The sediment transport stability condition. This stability condition can be found from solving the advection-diffusion equation of suspended-load and bed-load transport (see Section 3.2 , and/or Vanoni, 1975), if a numerical scheme is used. The stability conditions are controlled by the worst case of the Courant condition (advection) or the diffusion condition (Noye, 1978). 3) The sediment continuity stability condition. This is the only stability condition considered

by HEC-6, as discussed before. It is equivalent to solving the first order advection equation (Equation 6) from which the following stability criterion is established (Potter, 1973):

$$\Delta t \leqslant \frac{\Delta x}{cV/p} = \frac{\Delta x}{\alpha V} \tag{9}$$

$$\alpha = c/p \tag{10}$$

Comparing equations (9) and (8) reveals that the appropriate stability criterion for HEC-6 should consider two parameters in addition to velocity and reach length. The first parameter is the volume shape factor, which is related to the porosity of the sediment materials. The second parameter is the concentration of the sediment transport. This implicitly leads to the sediment transport stability condition. Due to the two-dimensional nature of the sediment transport equation, the sediment transport rates are generally obtained without considering the transport mechanism of the sediment concentration (for a detailed discussion of this see Appendix A). As a rule of thumb, the higher the transport (concentration), the smaller the time step ($\Delta t$) which should be adopted. The time step ($\Delta t$) must be chosen in such a way that the total sediment transport does not exceed the available bed materials.

Another important factor to be considered in the selection of the time step in addition to the stability criterion of equation (9) is the physical constraints of the availability of bed material, armoring effects, and the change of composition of bed materials. This only holds true for the HEC-6 model, due to the modeling technique of bed armoring and sediment sorting processes.

A definitive time step cannot be easily achieved in the erodible-bed model, as contrasted to the fixed-bed model. This is due to the nature of the feedback of the local flow and sediment transports, even in a "known discharge" and "uncoupled" model (such as HEC-6 and other models). The dilemna lies in the difficulty introduced by the different time steps derived for numerical stability as well as from the physical justification, such as the availability of local sediment materials. In general, there is a trade-off of the accuracy, computer cost, and physical reasoning. That is, a time step too small requires more cross sections, excessive computer time, and creates the possibility of violation of the physics of the problem. On the other hand, a time step too large will lead to instability. This only can be studied by numerical experimentation, as performed by the writers (NORTEC, 1981).

## 3.2 Theoretical Inadequacies

In order to investigate the theoretical inadequacies of HEC-6, a discussion of the more general theories of water and sediment routing models is worthwhile. As stated in Section 3.1, the governing equations are flow-continuity, momentum, sediment-transport and sediment-continuity. For convenience, the flow-continuity and momentum equations will be called the water routing model, and the sediment-continuity equation will be called the sediment routing model. These two models are as follows:

Water Routing Model:

$$\frac{\partial}{\partial t}(A + By) + \frac{\partial Q}{\partial x} = q_1 \tag{11}$$

$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{\partial Q}{\partial x}\left(-\frac{Q^2}{2gA^2} + h\right) + S = \frac{q_1 V_1}{gA} \tag{12}$$

Sediment Routing Model:

$$G = \int_y^h B\, vc\, dz = G(V, h, y, B, A, S, T, d, \text{etc.}) \tag{13}$$

$$V = \frac{Q}{A} = \frac{1}{(h-y)}\int_y^h u\, dz \tag{14}$$

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + (w - w_s)\frac{\partial c}{\partial z} = \frac{\partial}{\partial x}\left(\epsilon_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial z}\left(\epsilon_z \frac{\partial c}{\partial z}\right) \tag{15}$$

$$\frac{\partial G}{\partial x} + p\frac{\partial (By)}{\partial t} = q_{s1} \tag{16}$$

where $q_{s1}$ = lateral sediment inflow per unit width ($L^2/T$)

$v_1$ = lateral inflow velocity (L/T)

$w$ = velocity component in the z direction (L/T)

$w_s$ = settling velocity for grain particle (L/T)

$\epsilon_x$ = sediment diffusion coefficient in the x-direction ($L^2/T$)

$\epsilon_z$ = sediment diffusion coefficient in the z-direction ($L^2T$)

### 3.2.1 Water Routing Model

A comparison between equations (1) and (11), and (2) and (12) reveals that in the HEC-6 model, "unsteady" terms in the flow transport are neglected, as is the coupling of the feedback or interaction between the water and sediment routing. This implies that HEC-6 belongs to the category of "known discharge" and "uncoupled" water and sediment routing models. An advantage of these assumptions is the simplification in mathematical manipulation and large saving in computational cost. However, the flow and sediment transport must be considered in such a way that the physical reasoning can be justified. As mentioned in Section 3.1, the selection of a suitable $\Delta t$ and $\Delta x$ is vital to the validation of the HEC-6 model. Consequently, HEC-6 should be used with caution in rapidly-changing flow conditions, such as the simulation of flash flood events. Due to these assumptions, there are some concerns about the coupling/feedback between hydraulic computation, sediment transport computations, and scour/deposition computations. This consideration will be deferred until Section 3.4.

### 3.2.2 Sediment Transport Computation

There are five options in HEC-6 to calculate the sediment transport rates, namely: 1) Toffaleti's method; 2) Laursen's relationship modified by Madden for large rivers; 3) a functional relationship between unit-width sediment transport capacity and the depth-slope product; 4) Yang's stream power method; and 5) DuBoys' method. Since all of the options are for sand bed streams and not gravel bed streams

HEC-6 cannot simulate the broad spectrum of rivers which range from large gravel-bed to fine sand-bed channels. In addition HEC-6 cannot be used for cases where the inflowing sediment load is unknown without modifying the input sediment data initialized in the L-card. The authors have found that an equilibrium load can be generated by the use of a dummy cross-section. HEC recognizes this and is aware that an equilibrium load can be developed through sucessive approximations using information provided by C-level output. The User's Manual (Ref. 13) needs to address this issue as it is especially critical for inexperienced users.

THIS IS THE METH WE FOLLOW

Past experience has shown that HEC-6 is not applicable to gravel-bed streams. Prasuhn and Sing, 1980, pointed out that Toffaleti's method, the recommended method in HEC-6, was found to greatly underestimate gravel movement when Cotton Wood Creek and the Sacramento River were analyzed. Therefore, to handle various kinds of rivers, a more versatile set of sediment transport equations should be incorporated. These could be 6) Einstein's method; 7) Modified Einstein's method; 8) Colby's method for sand-bed streams, as well as 9) Meyer-Peter and Mueller's method; or 10) Schoklitsch's method for gravel-bed streams. The adoption of an appropriate sediment-transport function to suit a particular stream is considered one of the more difficult tasks in water and sediment routing because it requires data calibration as well as engineering judgment, intuition, and experience.

BED LOAD

BED LOAD

### 3.2.3 Sediment Routing Model

Although the sediment-continuity equation (16) is the simplest equation of the governing equations, it is the most difficult process to model in water and sediment routing procedures. This stems from the difficulty in defining 1) scour/deposition distribution in a cross-section profile; 2) lateral channel migration of a channel, with adjustment; and 3) armoring effects.

#### 3.2.3.1 Scour/Deposition Distribution in Cross-Section Profile

In HEC-6, the scour/deposition depth is assumed uniformly distributed along the cross-section profile. This is in contrast to other models (Simons and Li, 1979), which distributes the amount of scour/deposition by the relative magnitude of conveyance. A refinement to the distribution of scour amount across the cross-section based on the concept of relative magnitude of conveyance should be considered. The larger the conveyance the larger the tractive force and the deeper the scour. For the deposition process it is acceptable that the cross section be uniformly deposited, or even deposited inversely proportional to the conveyance.

? WHICH MODEL NOT QUITE

#### 3.2.3.2 Lateral Channel Migration on Channel Width Adjustment

HEC-6 is a one-dimensional model with no provision to specify a lateral adjustment of sediment transport rate across the cross sections, nor to simulate the development of river meandering or bank migration. It is evident from equation (16) that the erodible channel width (B) has to be prespecified and kept without change during the sediment routing process. It is felt that a close examination of the work on lateral channel migration, such as developed by Chang, 1982, and

Parker, et. al., 1982, may be worthwhile to investigate even if a one-dimensional model is adopted.

3.2.3.3 Armoring Effects

To consider armoring effects and the hydraulic sorting of the composition of bed material, HEC-6 introduces the concept of "equilibrium depth", "model bottom depth", and "Active and Inactive zones (layers)", "stability of armor layer", etc..

An equilibrium water depth for which sediment with a particular grain-size becomes immobile is obtained by combining Manning's equation, Strickler's equation, and Einstein's bed-load function: (EQ 39 of Manual):

$$Deq = \left(\frac{q}{10.21\ d^{1/3}}\right)^{6/7} \qquad (17)$$

where Deq = equilibrium water depth (L)

q = water discharge per unit top width ($L^2/T$)

d = grain diameter of sediment material (L)

Q = water discharge ($L^3/T$)

w = top width

A problem arises from overbank flow, where unit discharge per unit width of flow might decrease due to a sudden increase of top width, as total discharge increases. This results in an inconsistency of equilibrium depth calculation which has been experienced by the writers (NORTEC, 1981), and the scour decreasing as discharge increases. Therefore it is recommended that the equivalent width (effective width) be used.

This is contradictory to real world observations in scour and fill processes. A second problem occurs when the deviation between the calibrated Manning's coefficient (n) and the Strickler's equation is significant:

$$n = \frac{d^{1/6}}{29.3} \tag{18}$$

Sayre (Ref. 2) has shown that the equilibrium depth is quite sensitive to the n values. (He obtained Deq = 29.7 ft. and 51.9 ft. when using n = .0104 and .020 respectively.) Validation of Strickler's equation is very questionable, especially in the dune regime, as investigated by Burkham and Dawdy, 1976.

For determining the Deq in the mixture of grain sizes at the bed surface, an effective procedure is adopted by the assumptions that the armor layer is equal to a thickness of one grain diameter from which

$$Dse = \frac{2}{3}\frac{SAE \cdot d}{Pc} \tag{19}$$

is obtained. This follows in the same spirit of the definition of the thickness of bed-layer (e.g., Einstein used two grain diameters for bed-layer, Einstein, 1950). It would be interesting to study the sensitivity of the results of the equilibrium depth in a heterogeneous mixture, by assuming several multiples of grain diameter. Simons and Li used a two grain layer definition in their model, HEC2SR.

A final comment about the equilibrium depth is that the equilibrium depth, Drd, is equivalent to the channel regime depth. One such formula is obtained by Laursen, 1957:

$$Drd = \left(\frac{q}{10.81\ d^{1/3}}\right)^{6/7} \qquad (20)$$

The regime depth of a stream is defined as the equilibrium depth from which the stream-bed has no scour under the condition of long-term constant flow. Sediment routing is a dynamic and unsteady process, and the depth of the scour/deposition is estimated from the function of sediment transport. Therefore, to obtain a meaningful solution, the sum of scour depth, the maximum depth the river will reach under long term constant flow conditions, plus the water depth has to be limited to the equilibrium depth, even if there is no rock outcrop restriction. The equilibrium depth is an indicator of the natural armoring process.

In HEC-6, the program designates the zone of material between the bed surface and equilibrium depth as Active, and the zone from equilibrium depth to the model bottom as Inactive. Only the material in the Active zone is subject to scour. When all material is removed from the Active zone, the bed is completely armored for that hydraulic condition. However, the material is allowed to interchange between the Active and Inactive layer. It is argued here that the definition of the model bottom is as important as that of the equilibrium depth. Unfortunately, HEC-6 arbitrarily assigns this value either by a default of 10 ft. or any number as specified by the users. Again, only under the condition of known rock outcrop in the streambed can the model bottom be well determined. In other cases, this is not known "a priori", and is implicitly related to the determination of the depth of stream scour. In the writers experience, the final

result of the scour depth is heavily dependent on the values of the model bottom depth (NORTEC, 1981). In one test, it was found that the scour depth doubled when the value of model bottom depth was doubled.

We tried this but our equation [illegible] drastic.

To update the Active and Inactive layers (or zones), the model must recalculate the gradation of the bed materials (Pc) and the ratio of surface area of potential scour to total surface area (SAE) in Equation (19). This is accomplished by a bookkeeping process in the HEC-6 program. These parameters are related to the stability of armor layer.

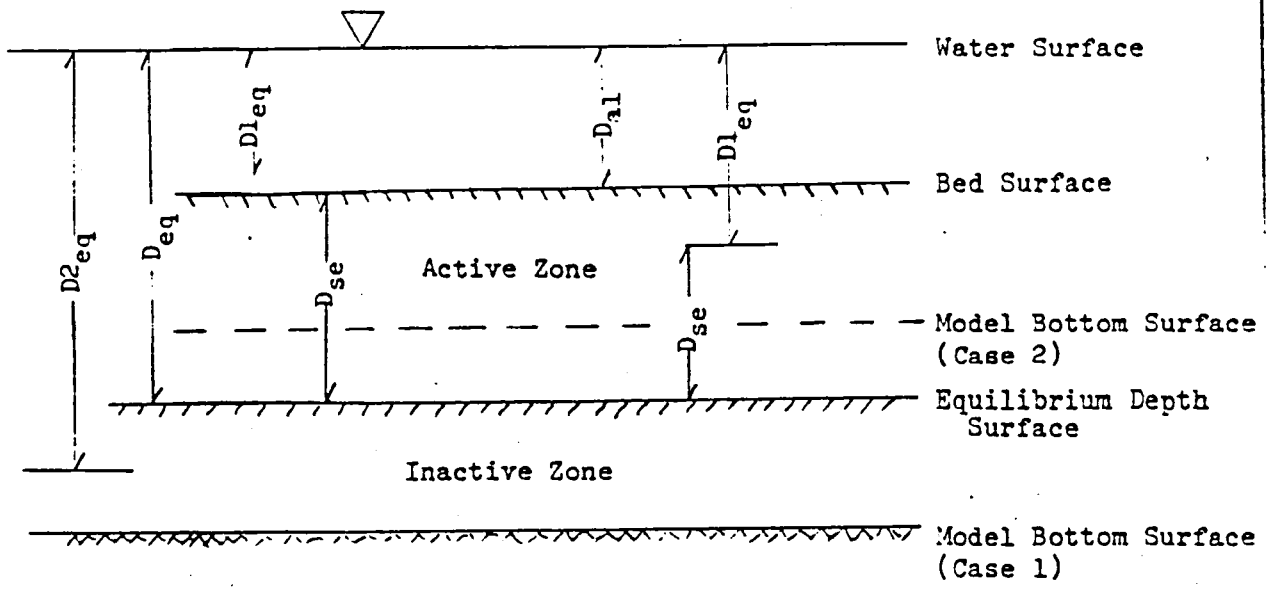
These concepts are best illustrated by figure 1 for the case with and the case without armor layer restrictions. In Case 1 where there is not an armor layer restriction, the equilibrium depth is higher than the model bottom. In this case there is no limitation on the potential scouring. In Case 2 where there is an armor layer restriction, the equilibrium depth is lower than the model bottom and there is a limitation on the potential scouring. The maximum scour depth is the difference between the thalweg elevation and the model bottom. Both cases are differentiated by the following conditions:

Condition A: $D_{al} > Dl_{eq} \Rightarrow D_{eq} = D_{al} + D_{se}$

Condition B: $D_{al} < Dl_{eq} \Rightarrow D_{eq} = Dl_{eq} + D_{se}$

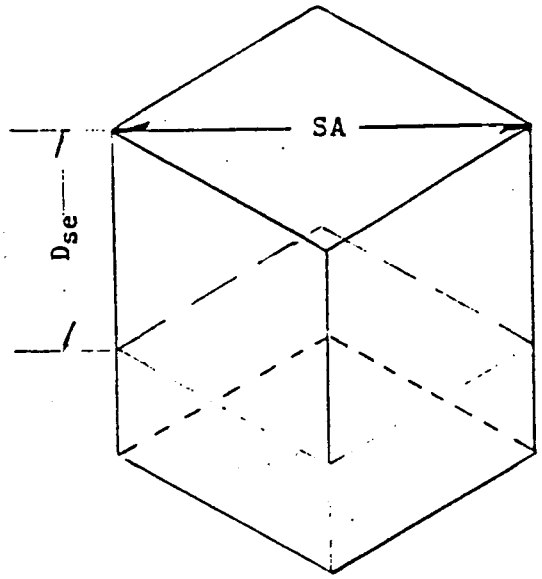
Gessler's concept of the bed stability factor (BSF) (Ref. 16, 17, 18), is introduced in HEC-6 to update the SAE by a linear relationship. It was pointed out by Sayre, 1979, that an inconsistency between the Gessler and HEC-6 formulation was detected. HEC-6 used:

Condition A: $D_{al} > D1_{eq}$ Condition B: $D_{al} < D1_{eq}$




Case 1: No armor-layer restriction

Case 2: With armor-layer restriction




$$VOL_{se} = SA(D_{se}) = (WMB)(DIST)(D_{se})$$

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FIGURE 1
Relationship Between Various Depth and Zone Concepts in HEC-6

$$BSF = \frac{\sum_{i=1}^{NGS} PROB \quad PROB \cdot PI_i \cdot dm_i}{\sum_{i=1}^{NGS} PROB \cdot PI_i \cdot dm_i} \tag{21}$$

While Sayre argued that $dm_i$ should not be included in the denominator and numerator in Equation (21), the authors would have to agree with Sayre (see Appendix B).

It is not clear whether gradation of the composition of bed material both in the Active and Inactive layers is updated after the hydraulic sorting process. By tracing the HEC-6 program, the writers found that the updating of the gradation of the composition of bed materials was through the new storage arrays of Active and Inactive layers. However, the writers found some difficulty in these definitions, which will be delineated in Section 3.3.

### 3.3 Algorithmic Inadequacies

The poor documentation concerning the theoretical basis presented in the User's Manual and the computer program listing make it almost impossible to understand the algorithmic structure and computer programming. The writers have found that it is difficult to track the correspondence between the theoretical formulation, numerical discretization and implementation of the computer programming. This difficulty has been magnified by the limited manual tracing (verification) of the computer program which was undertaken. Therefore, it is admitted that the conclusions in the following are considered only tentative. This handicap can only be circumvented by a more involved program tracing effort, as recommended in Section 4.3.

The main problems arise from the update, transfer, storage, allocation, retrieval, and initialization of the arrays or single variables.

#### 3.3.1 The CC and CE Variables (HEC-6 43)

These two parameters are read from the NC-card of the HEC-2 Format or from the P-Card of the Sediment Format. Both are stored in common block. These two parameters are never stored in Tape (4), as are the n-values. It is stated in the HEC-6 User's Manual that, "Expansion and contraction coefficients cannot be changed from the values set at the start of the data deck." (Exhibit 6, p. 4). However, there also is an instruction, "Insert an NC-Card in the reach where the change is desired." (Exhibit 6, p. 4). Therefore, without storing CC and CE in Tape 4 -- Basic Geometric Data Tape, there will be a contradictory updating of the CE and CC values for the changing reach.

Although the CC and CE values might vary reach by reach, the present algorithm structure cannot achieve this goal. The most serious discrepancy in the backwater computation will occur in the reach where drastic change in the velocity head occurs, such as weirs, bridges, or other hydraulic control structures.

Even admitting that CC and CE cannot be changed from the values set at the start of the data deck, as stated in the HEC-6 Manual, correct values are not possible, due to the following FORTRAN statements (HEC-6 version 2.7, Nov. 1, 1976): HEC-6 288, 289, 322, and 323 in HEC-2 Format, and HEC-6 484, 485 in the Sediment Format (see Appendix C). These contradictions and discrepencies need to be corrected.

WHAT CORRECTIONS ARE SUGGESTED

3.3.2 The CAR (MCAR) and GD (MGD) Arrays — DESCRIBE THE ARRAYS — WHAT ARE THEY FOR — IN BRIEF

These two vector arrays are the most important variables encountered in the HEC-6 program. Without understanding the allocation of each vector, it is not possible to trace the implementation of the computer algorithms. To comment on this "Black box" (Webb, 1980) type of program and also to clarify the original definitions of some basic parameters of the CAR and GD arrays (program listing, HEC-6 3593-3630), the following tables are prepared. Table 1 shows the CAR Array and Table 2 illustrates the GD array. These tables are preparatory to the further comments on the algorithmic inadequacies.

A first check with page 9 of the User's Manual reveals that the inequalities for determining the maximum number of grain sizes should be revised with the following two equations:

TABLE 1

VARIABLES STORED IN THE CAR (MCAR) ARRAY

| VARIABLES | STORAGE |
|---|---|
| SPI | 1 |
| UWD/TON | 2 |
| UWW/TON | 3 |
| SUK | 4 |
| BASE | 5 |
| IBG | 6 = NVS |
| VOLUME SHAPE FACTOR | 6 + NR = NVS + NR = NGR |
| DYLST | 6 + 2NR = NGR + NR = NTC |
| DS COEFFICIENTS | 6 + 2NR + 3NSAND = NAP |
| N-CORRECTION COEFFICIENTS | 6 + 2NR + 3NSAND + 3 = NAQ |
| Q-QS (LOG) RATING TABLE | 6 + 2NR + 3NSAND + 3 + LQ(NGS + 1) = NYV |
| VOLUME VS DEPTH FUNCTION (MOVABLE BED WIDTH) | NYV + NR(LC) = NIS |
| INACTIVE STORAGE | NIS + NR(NGS + 1) = K5 |
| TRIBUTARY Q-QS (LOG) RATING TABLE | K5 + NTRIB(NGS + 1) = NCAR |

TOTAL = (NTRIB + LQ) (NGS + 1) + 3(NSAND + 1) + NR(NGS + 3 + LC) + NVS = NCAR

NVS = 6

LC = 1

TABLE 2

VARIABLES STORED IN THE GD (MGD) ARRAY

| VARIABLES | STORAGES |
|---|---|
| ACTIVE STOARGE | LF + (NGS + 1) = L5 |
| REACH LENGTH | L5 + 1 = L5 + LEB |
| AVG. SEC. NO. | L5 + 2 |
| SAE | L5 + 3 = L5 + ISA |
| SAE | L5 + 4 = L5 + LSA |
| 1-XPI | L5 + 5 = L5 + LPA |
| DXPI | L5 + 6 = L5 + LDA |
| DMAX | L5 + 7 = L5 + LDM |
| MODEL BOTTOM | L5 + 8 = L5 + LMB |
| GAL | L5 + 9 = L5 + LGA = NDS |
| SLOPE | NDS + MNQ = NNV |
| N-VALUE | NNV + MNQ = NTW |
| TOP WIDTH | NTW + MNQ = NED |
| DEPTH | NED + MNQ = NVE |
| VELOCITY | NVE + MNQ = NWS |
| WATER SURFACE | NWS + MNQ = NEB |
| EQUILIBRIUM BED ELEV | NEB + MNQ = NCQ |
| DISCHARGE | NCQ + MNQ |
| INFLOW SEDIMENT | NR(NK) + (MSOR + INTL + 1) NSFR = NGD |

TOTAL = NR (NGS + 8MNQ + NSE) + (MSOR + INTL + 1) NSFR = NGD

NSE = 10, NK = (NGS + 8MNQ + NSE), LF = (IR - 1)(NK), IR = 1, . . ., NR

$$NR(NGS + 8NEQ + 10) + (NSOR + INTL + 1)\ NSFR \leq NGD = 5100 \quad (22)$$

and,

$$(NTRIB + LQ)(NGS + 1) + 3(NSAND + 1) + NR(NGS + 3 + LC) + NVS \leq NCAR = 6{,}000 \quad (23)$$

The storage maps of CAR and GD in Tables 1 and 2 will aid in understanding the theoretical background of the programming and for numerical analysis. If the present structure of the program is maintained, Tables 1 and 2 should be included in an update of the User's Manual.

### 3.3.3 Coefficients of Special Transport Function

There is very poor documentation of the relationship used in the special transport function (option (3) of the Sediment transport computation, Section 3.2.2). By tracing the programming (HEC-6 4475-4498), it was found that the sediment transport equation is related by:

$$GP = STO \left(\frac{DS-C_1}{A_1}\right)^{B_1} \quad (24)$$

where,

$$STO = 0.000001A_2(n^{B_2}) + C_2 \quad (25)$$

Equations (24) and (25) are different from the definitions stated in the J-Card and K-Card (Exhibit 6, p. 26; and Exhibit 7) with $C_2$ added and GP = GP * STO. Since they are the result of a curve fitting process the correctness of those discrepancies could not be judged. However, a consistency should be maintained between the basic theory and the algorithm as well as the input instructions in the User's Manual.

### 3.3.4 Updating of the Gradation of Bed Materials

The accuracy of the process for updating gradation of bed materials is questionable. The justification for this cannot be confirmed without detailed tracing of the program, by submitting different conditions of flow and sediment transport. In the following, only the inconsistency of the units stored in the CAR and GD arrays will be pinpointed for the analysis of updating of the gradation of bed materials. It is recommended that in addition to the tracing, the flow chart of this updating process should be prepared in future work. *

(1) The inactive bed layer is read from the N-Card by grain size fractions (Exhibit 6, p. 30). However, in field 6 of the N-Card, the total of grain size fractions in the bed CAR(K5) was read. This is not true in the algorithm itself, CAR(K5) can never be assigned such as 1.0 in the Manual. It is the summation of the sand grain size fractions only (HEC-6 5554-5558). This is also the case for the active bed layer GD(L5) (HEC-6 5620-5623).

(2) When the variable XPI (N-Card, field 5, Exhibit 6, p. 30) is left blank, the algorithm assigns 0.95 (HEC-6 5538), instead of 1.0 as the Manual says.

(3) There are some additions which have inconsistent units in the updating process of the sand bed materials. For example, HVT=SD(LGS) (HEC-6 3815) has the unit of length (ft). However, this quantity has been mixed with the unit of tons, such as VSE = (HVT + GD(L5))/SAE (HEC-6 4400), VRD = GD(L5) + HVT (HEC-6 4569), SAE = (GD(L5) + HVT)/VSE (HEC-6 4636) and

PI(L) = [GD(LL) + SD(L)] /VRD (HEC-6 4582). The only exception to this mixed mode occurs when WTMB = 0 (HEC-6 4134) or DEQ $\leq$DAL (HEC-6 4326).

(4) How the gradation of bed materials is calculated after the armor process is not clear. The computation is carried out by the following statement: PI(L) = [GD(LL) + SD(L)] / [GD(L5) + HVT] (HEC-6 4582).

However, if this algorithm is right, GD(L5) is the summation of the sand portion only, without considering the clay or silt parts, if those exist. Because potential transport capacity, GP(L) was estimated as 100% of each fraction, PI(L) will be overestimated. This implies outflow sediment discharge of sand, GPR = GP(L) * PI(L) (HEC-6 4583) is overestimated.

These discrepancies should be investigated and corrected as necessary.

### 3.3.5 Inadequate Definition of Variables in Algorithms

The definition of the variables or arrays used in the programming is incomplete or erroneous. Exhibit 4 (Ref. 13) does give some illustrations of the allocation of variables. However, this Exhibit should be checked to verify its accuracy. The missing definitions should be prepared for completeness.

## 3.4 Manner in which Coupling/Feedback Occurs Between Hydraulic Computations, Sediment Transport Computations, and Scour/Deposition Computations

As mentioned in Section 3.2 the HEC-6 Model belongs to the simplest category of water and sediment routing models with the assumptions

of "known discharge" and "uncoupled" conditions. Under these provisions, during a time increment, the water surface profile is calculated from a specified known discharge by using a step-backwater procedure. A sediment transport equation is then chosen to calculate the total sediment load at each cross-section using the hydraulic parameters obtained through the backwater calculation. Finally, the degradation/aggradation at each section is obtained by routing the sediment continuity equation from upstream to downstream.

Due to the complex systems in water and sediment transport in natural streams, the one-dimensional "known discharge" and "uncoupled" model is widely used to keep the mathematical intractability to a minimum and to avoid the extensive cost to operate the model. However, the merit of this model depends upon the appropriate selection of $\Delta t$, the time step, and $\Delta x$, the reach length, as discussed in Section 3.1.

A good comment on the coupling/feedback between hydraulic computations, sediment transport computations, and scour/deposition computations has been made by Sayre, 1979, and will not be repeated here. In general, to obtain reliable results, owing to the uncoupled nature of the backwater computation, the sediment discharge computation, and the sediment routing, the time increment, $\Delta t$, should be kept short enough to assure that the feedback between water and sediment routing will be negligible. If the updated cross-sections are used to perform a new backwater calculation during a time increment the changes of bed profile as a result of the changes of previous backwater calculations should be insignificant.

In HEC-6, during a flow duration, DD, no matter how long or short, the hydraulic computation and sediment transport capacity are calculated once and are not recalculated until the next flow duration. However, the gradation of bed material and sand sediment discharge can be updated SPI times. This will create not only the coupling/feedback problem, but also a stability problem (see Section 3.1). To handle these two problems it is recommended that the $\Delta t$ as determined by the stability criterion, plus specification of the condition of SPI = 1, should be used rather than the Manual instructions. This is all the more necessary when simulating rapidly-changing flow conditions.

The sediment transport formula chosen for a given model and the manner in which its output is computed are important factors in modeling water-sediment routing. Most sediment transport formulae have either velocity or bed shear stress as a parameter. If bed shear stress is based upon local energy slope, problems can result. The negative feedback characteristic of step-backwater computations does not hold for computed local energy slope. For example, the local energy slope computed by HEC-2 can be strongly oscillatory. It is not unusual for results for a reach to appear quite acceptable in terms of the hydraulic parameters, yet to have variations of an order of magnitude in computed energy slope. This is a mathematical artifact of the solution algorithm, and does not affect the accuracy of computations of water surface elevation, depth, and velocity.

Modelers use several approaches to overcome this problem in sediment

routing modeling. For example, HEC2SR by Simons and Li compute bed shear stress as:

$$\tau_o = \frac{f_o}{8} V^2 \tag{26}$$

where $\tau_o$ is bed shear stress, $f_o$ is Darcy-Weisbach friction factor and V is mean velocity of flow. Because $V^2$ is not greatly affected by the oscillatory characteristic and $f_o$ is either constant or is a function of depth which also is not greatly affected, the slope problem is avoided. Similarly, in KUWASER and UUWSR an empirical power function of velocity and depth is used. Chang approaches the problem by using the geometric mean of the energy slope at two adjacent sections to compute effective energy slope in his FLUVIAL models. Thus, if oscillations are proportional, that is doubling the slope for one cross-section halves it for the next, then the geometric mean yields "correct" values of energy slope. However, the FLUVIAL width adjustment is strongly related to the variation in energy slope along the stream, as will be discussed in Section 4.1.2. Any errors of approximation in step-backwater are thrown into the computed energy slope values. For example, in HEC-2, if WSEL is within .01 foot of CWSEL or if TRIAL = 20, the approximation algorithm stops. The results are "good enough" for everything but slope, if slope is used directly in subsequent calculations.

Incorrect downstream boundary conditions can produce major oscillations in computed local energy slope. Use of thse values will impact upon the resulting estimates of sediment transport and of scour and deposition.

The sediment transport mechanism would have negative feedback and stabilize if the channel had a fixed bed. However, it does not. The movable bed introduces a positive feedback. Example: Assume a prismatic channel with a downstream elevation boundary condition which is computed at normal depth, and which is too low. This creates a slope too steep and a velocity too high with relation to the true world. More sediment transport will be modeled at the downstream boundary than at the point where results converge under rigid boundary flow assumptions. Therefore, the downstream cross-section scours. Next time step normal depth is even lower, etc. A similar illustration can be shown for setting the elevation too high.

Similarly sediment input set as an upstream boundary condition can induce positive feedback. Too much sediment input creates fill, increases slope to pass the load. Next section then fills to pass the sediment. Eventually the entire reach approaches a new equilibrium slope with velocities sufficient to transport the input sediment.

# 4.0 RECOMMENDATIONS FOR FURTHER WORK

Many recommendations have been made in passing in Section 3 of the report. This section will summarize those recommendations. Some will be expanded upon, others merely will be referenced back to the text where they are explained. Recommendations will be presented in terms of extensions of the theoretical basis of HEC-6, extensions of the practical uses of HEC-6, improvements (or corrections) of the computer code, and improvements in the documentation of HEC-6.

## 4.1 Extensions of the Theoretical Basis of HEC-6

Theoretical basis is meant as those aspects of the model which involve the basic equations governing the sediment routing model. These include the stability criterion for the equations, interactions introduced by the physical system, and extensions of the model to include more aspects of the physical system.

### 4.1.1 Choice of Stability Criterion

If HEC-6 is to be used for site specific analyses where dynamic cross-section rather than stable long-term reach scour and fill is of interest, a semi-research project should be undertaken. A study area should be selected where plentiful data exist in terms of frequency of cross-section. The Federal Flood Insurance Program undoubtedly has generated some of these. One example is the Umpqua River and its tributaries in Douglas County, Oregon. The USGS did a regional planning study in conjuction with the FIS, and many more cross-sections than normal were collected. The Rio Grande at Bernallilo, New Mexico, has cross-sections over time plus a considerable amount of sediment data.

Similarly, the Corps may have reaches which were studied for navigation and for which a dense set of cross-sections are available. The Umpqua is relatively free of man-made constructions, as is the Rio Grande. Another study area could be chosen on the basis of the existence of such constrictions.

Having chosen the study sites, two related problems could be attacked. First, what is the effect of $\Delta x$, $\Delta t$ and reach length, and how sensitive are results to violation of the Courant stability criterion? Second, given that only part of the data is used for analysis, can these results be used to develop a means to interpolate results at intermediate, "too dense" cross-sections? Split sample testing could be used to develop predictions for each cross-section to check against computer model calculations.

4.1.2 Bank Erosion and Migration

At present HEC-6 has no bank erosion or migration algorithms. Erosion/deposition is assumed to occur uniformly along the bed of the cross-section. The possibility of attacking this problem should be considered.

Two methods exist in the literature to model adjustments in the channel cross-section, and they have quite different approaches. One is Howard Chang's bank erosion algorithm and the other is Gary Parker's meander migration theory.

Chang's approach is through the minimum stream power concept. In finite difference form, total stream power is:

BUT THE SPECIFIC WEIGHT VARIABLE MISSING?

$$P = \sum_{i=i}^{N-1} \tfrac{1}{2} (Q_i S_i + Q_{i+1} S_{i+1}) \Delta x_i \qquad (27)$$

MISSING VARIABLE

where N is the number of cross-sections in the reach, __ is specific weight of the flow mixture, $Q_i$ and $S_i$ are discharge and energy slope at the $i^{th}$ cross-section, and $\Delta x_i$ is the distance between cross-sections. P minimum is found by adjusting the variations in weighted average energy gradient

$$\overline{Si} = \frac{Si-1 \Delta x_{i-1} + Si+1 \Delta x_i}{2(\Delta x_{i-1} + \Delta x_i)} \qquad (28)$$

subject to constraints on width changes for each time step. Thus, excess sediment outflow is allocated first to bank erosion, then to bed erosion/deposition. The width of the cross-section is changed to create a more uniform study reach.

A strong drawback to the application of this method is the oscillatory nature of local slope values computed in step-backwater algorithms. Chang partly overcomes that by the use of a weighted average energy slope, but there remains a chance of widely erroneous results derived from the mathematical artifact of the solution algorithm.

Where Chang attacks the problem of local bank erosion during the passage of a design storm, Parker attacks the problem of the normal bank erosion which results in meander development and migration. Parker uses stability analysis to derive both linear and second order approximations for bend development. For the linear case,

the bend equation is:

$$\frac{\partial^2 y}{\partial x \partial t} + 2C_f \frac{\partial y}{\partial t} = \frac{\partial^3 y}{\partial x^3} - C_f(A + F^2) \frac{\partial^2 y}{\partial x^2} \tag{29}$$

a meander stability criterion is:

$$k = \sqrt{2}\ C_f\ (A + F^2)^{1/2} \tag{30}$$

and downstream migration speed at maximum instability is:

$$C_{DM} = 1.17\ k_{DM} = 1.17(1.50\ C_f) \tag{31}$$

where $C_f$ is the reciprocal of the Darcy-Weisbach resistance coefficient, A is a parameter, F is the Froude number.

Parker's approach has had limited application, but appears to have potential. How it responds to variability in flow and whether it can be adapted for design storm analysis are open questions. Chang SAN DIEGO and Parker UNIV. of MINNESOTA have entirely different approaches to answer different problems. Both should be investigated for inclusion in HEC-6.

### 4.1.3 Bed Armoring and Sediment Sorting Processes

Several aspects of the bed armoring and sediment sorting process were discussed earlier. In particular, what seem to be specific programming errors or areas of uncertainty in interpretation will be covered separately.

The bed sorting-armoring algorithm has a major impact on results. The sorting algorithm affects bed size distribution. If bed size affects resistance to flow, as it should, then that algorithm has a

major impact on velocity, depth, and sediment transport. If the sediment transport formula is based on velocities, a strong interaction is set up with the sorting algorithm.

HEC-6 seems to have a bias in its sorting algorithm. For example two cases, San Lorenzo River and Salt River are case studies available because they previously were performed for the NAS-NRC study.

| Stream | Starting Size $d_{50(mm)}$ | Ending Size $d_{50(mm)}$ |
|---|---|---|
| San Lorenzo | 0.27 | 0.63 |
| | 0.34 | 0.70 |
| | 0.53 | 1.16 |
| | 0.93 | 1.55 |
| Salt | 64.00 | 24.00 |

All finer gradations of sediment became coarser and the coarser gradations of sediment became finer. More cases should be considered to determine whether this is a theoretical bias or a result of these data only.

Concepts of equilibrium depth, thickness of the bed layer, and the Active-Inactive zones are covered in 3.2.3 and the questions raised there should be investigated and, if possible, answered.

### 4.1.4 Addition of Sediment Transport Functions

At present HEC-6 uses Laursen's relationship, Toffaleti's formula, Yang's method and DuBoy's method ~~or~~ and an empirically derived shear relation as sediment transport functions. Simons and Li, Chang, RMA, and NORTEC use other functions. More versatility can be added

SIMONS & LI USE ONLY A COMBINED MPM + EINSTEIN APPROACH THERE IS NO DOUBT

to HEC-6 by including more sediment transport functions. However, those models which do provide such versatility do not provide adequate guidelines for a proper choice. More versatility should be incorporated in HEC-6, but only with an adequate set of guidelines for the choice of a sediment transport function.

### 4.2 Computer Code and Algorithms

The algorithmic inadequacies and questions raised in Section 3.3 should be addressed. The computer program should be tested by an example tracing of a data set which produces anomalous results as well as one which produces reasonable results. A detailed flow chart for the program should be provided, especially in the sediment routing portion. More structured programming should be used so that the flow of the program is easier to understand and it can be more easily adapted to mini-computers. The new sediment transport functions should be coded and tested, as should the different concepts of the bed armoring process mentioned earlier.

#### 4.2.1 Selection of River Cross-Sections

More guidance should be given on selection of river cross-sections and their spacing. The requirements for water surface profile determination by backwater computations are quite different from requirements for scour and deposition. In particular, if cross-section rather than reach changes are important, spacing becomes critical.

The elevation of the water surface profile may be determined by a few critical cross-sections. Dawdy and Motayed, 1978, state: "Three major points are seen. . .. First, the step-backwater elevations

are controlled by a few critical reaches flowing almost at normal depth. Second, judicious choice of those controlling cross-sections gives results just as good as the more detailed data with much less effort. Third, those cross-sections may be picked from an accurate topographic map and give just as good answers."

This is not the case for movable beds. Based on their study of the Middle Rio Grande in New Mexico, Culbertson and Dawdy, 1964, state: "Therefore, it seems that the scour and fill that occurs during high water often may be local in extent. In narrow or contracting sections, the bottom scours during periods of increasing flow and fills during periods of diminishing flow. In wide or expanding sections the opposite seems to be true." Thus optimal choice of cross-sections for HEC-2 is not optimal for HEC-6.

In a meandering stream, control sections are at the cross-over points where the outside of the meander switches from one bank to the other. Those control sections are approximately rectangular in shape. The selection of all cross-sections at such control sections probably would result in accurate determination of water surface profiles. However, it would indicate little or no scour or fill during a storm event because each cross-section would be similar in geometry and sediment.

The differences between the two problems and their differing data requirements should be developed. Perhaps a Guidance Memorandum such as Training Document No. 13 should be written on the selection of cross-sections.

### 4.2.2 Effects of Boundary Conditions

The HEC-6 documentation does not have a sufficient discussion of boundary conditions and their effect on results in terms of scour and fill. HEC-2 has a built in negative feedback. If a downstream elevation is chosen too high or too low, the M-1 and M-3 curves cause results to converge upstream, and results to coincide after a reach, the length depending upon the initial error. (This applies to stage, velocity and depth, but not to local slope, as discussed earlier.)

The sensitivity of boundary conditions are known to the staff at HEC, but are only hinted at in the documentation. A report such as Training Document No. 13 should be prepared. It should show examples of "correct" and "incorrect" boundary conditions and their output. This will aid users in recognizing their problems and correcting them. Further, it will aid the user in understanding the modeling of scour and deposition. Perhaps as important, it will show the user that the model is not wrong and he is not grossly misusing it. Thus, confidence on the part of the user in using and interpreting the model output may result.

## 4.3 Preparation of Guidelines for Use of HEC-6

As discussed in Section 3, several sets of guidelines should be prepared. First is a set of guidelines for the proper choice of the number of cross-sections and their location. The differences between criteria for HEC-2 and HEC-6 should be covered. Second is guidelines for the selection of downstream and upstream boundary

conditions. This should discuss interactions within the program, and how the boundary conditions affect those interactions. Third, a general set of guidelines should be prepared which expands upon Training Document No. 13. It should describe minimum data sets necessary for solution of different types of problems, further aids in calibration and validation of the model, and should cover applications and limitations of the model.

Computer graphics could be introduced as an option for HEC-6. Line printer output seldom is adequate and each computer and plotter combination has peculiarities which make a universal plotter package impossible. However, some guidance concerning what can be shown, how it can be shown, and how it can be used to judge and interpret model output would be helpful.

### 4.4 User Documentation

Several mistakes and misprints in the User's Manual have been identified and should be corrected. The User's Manual should be extended to give a more thorough picture of what takes place in the various parts of the program. The several guidance memoranda mentioned in Section 4.3 along with others already available could be included in a subsequent overall revision of the User's Manual. A Programmer's Manual should be prepared which also includes the revisions suggested earlier.

# APPENDIX A

The transport of sediment concentration is governed by equation 15, p. 9:

$$\frac{\partial c}{\partial t} + U\frac{\partial c}{\partial x} + (w - w_s)\frac{\partial c}{\partial z} = \frac{\partial}{\partial x}\left(Ex\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial z}\left(Ez\frac{\partial c}{\partial z}\right) \qquad (15)$$

Equation (15) is a two dimensional (in the x-z plane) and unsteady. Solution of equation (15) requires the distribution of velocity fields u, w, and $w_s$. The simplify the mathematics Einstein (Ref. 7) assumed conditions of steadyness and uniformness in the channel reach (i.e., $\frac{\partial}{\partial t} = \frac{\partial}{\partial x} = 0$) thereby reducing equation (15) to:

$$(w - w_s)\frac{\partial c}{\partial z} = \frac{\partial}{\partial z}\left(Ez\frac{\partial c}{\partial z}\right) \qquad (15a)$$

Furthermore Einstein replaced the vertical velocity term, w, with Rouse's (Ref. 25) logrithmic velocity distribution, and introduced his bed boad equation to evaluate sediment discharge, G, as follows:

$$G = \int_y^h B\,u\,c\,dz = \underbrace{\int_y^a B\,u\,c\,dz}_{\text{bed load}} + \underbrace{\int_a^h B\,u\,c\,dz}_{\text{suspended load}}$$

where a is the elevation of two grain size above some arbitrary datum (equal to y + 2d). The details of this can be found in Ref. 7. Most of the sediment transport equation such as Toffaleti's, Modified Einstein's, Colby's, etc. were derived from this original Einstein concept (Ref. 25).

It is evident that the sediment discharge, G, is obtained by the integration of sediment concentration and is implicitly related to the hydraulic and sediment parameters, without solving the two-dimensional equation (Eq. 15) governing the transport mechanism of the sediment concentration.

# APPENDIX B

From Gessler (Ref. 8, eq. 10 and eq. 18):

$$P_o(k) = \int_{k=kmin}^{k} p_o(k)dk$$

and

$$\bar{q} = \frac{\int_{kmin}^{kmax} q^2 p_o dk}{\int_{kmin}^{kmax} q p_o \, dk}$$

Differentiating the first equation results in:

$$dP_o(k) = p_o(k) \, dk$$

Substituting into the second equation:

$$\bar{q} = \frac{\int_{kmin}^{kmax} q^2 p_o \, dk}{\int_{kmin}^{kmax} q p_o \, dk} = \frac{\int_{kmin}^{kmax} q^2 dP_o(k)}{\int_{kmin}^{kmax} q \, dP_o(k)}$$

which can be approximated by:

$$\frac{\sum q^2 \Delta P_o}{\sum q \Delta P_o} = \frac{\sum_{i=1}^{NGS} PROB \cdot PROB \cdot PI_i}{\sum_{i=1}^{NGS} PROB \cdot PI_i}$$

An example of how to calculate $\bar{q}$ is given by Gessler (Ref. 8).

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# APPENDIX C

```
      NCH=0                                                             HEC6     287
      CC=1.                                                             HEC6     288
      CE=1.                                                             HEC6     289
      ICG=ITL(KP)                                                       HEC6     290
      NR=0                                                              HEC6     291
      TAN=0.                                                            HEC6     292
      CRL=0.                                                            HEC6     293
      WRITE (LP,1320)                                                   HEC6     294
      WRITE (LP,1325) ICG,ALER,ASEL,CE,CC,LFA                           HEC6     295
C                                                                       HEC6     296
C                                BRANCH TO  1200 FROM  1220.01  1235.01 HEC6     297
C                                    1235.04  1245.02  1255.06  1825.01 HEC6     298
 1200 STENCL=0.                                                         HEC6     299
      STENCR=0.                                                         HEC6     300
      READ (IN,1010) ICG,IDT,FLD                                        HEC6     301
C     TEST FOR EJ CARD   (END OF JOB CARD)                              HEC6     302
      IF(ICG.NE.ITL(KE)) GO TO 1205                                     HEC6     303
      II=KE                                                             HEC6     304
      JJ=KJ                                                             HEC6     305
      IF(IDT.NE.ITL(KJ)) GO TO 1255                                     HEC6     306
      GO TO 1830                                                        HEC6     307
C                                                                       HEC6     308
C     TEST FOR NC-CARD  (N-VALUES,CC AND CE)                            HEC6     309
C                                BRANCH TO  1205 FROM  1200.03          HEC6     310
 1205 IF(ICG.NE.ITL(KN)) GO TO 1240                                     HEC6     311
      IF(IDT.NE.ITL(KC)) GO TO 1225                                     HEC6     312
      IF(FLD(1).GT.0.)XNVR(1)=FLD(1)                                    HEC6     313
      IF(FLD(2).LE.0.)GO TO 1210                                        HEC6     314
      XNVR(3)=FLD(2)                                                    HEC6     315
      NPAR=0                                                            HEC6     316
C                                BRANCH TO  1210 FROM  1205.03          HEC6     317
 1210 IF(FLD(3).LE.0.)GO TO 1215                                        HEC6     318
      XNVR(2)=FLD(3)                                                    HEC6     319
      NPAR=0                                                            HEC6     320
C                                BRANCH TO  1215 FROM  1210.00          HEC6     321
 1215 IF(FLD(4).GT.0.)CC=FLD(4)+1.                                      HEC6     322
      IF(FLD(5).GT.0.)CE=1.-FLD(5)                                      HEC6     323
      WRITE (LP,1320)                                                   HEC6     324
      WRITE (LP,1220)CE,CC                                              HEC6     325
 1220 FORMAT (22X,2F10.6)                                               HEC6     326
      GO TO 1200                                                        HEC6     327
C                                                                       HEC6     328
C     TEST FOR NV CARD                                                  HEC6     329
C                                BRANCH TO  1225 FROM  1205.01          HEC6     330
 1225 IF(IDT.EQ.ITL(KV))GO TO 1230                                      HEC6     331
      IF(KN
```

```
      READ (IN,1125) ICG,ICT,ISI,(X(I),I=1,NWTC)                        HEC6
      WRITE (LP,1175)ICG,ICT,ISI,(X(I),I=1,NWTC)                        HEC6
      WRITE (4) (X(I),I=1,NWTC)                                         HEC6
C                                   BRANCH TO  1315 FROM  1310.00       HEC6
 1315 CONTINUE                                                          HEC6
C                                                                       HEC6
C     READ P CARD                                                       HEC6
C     FLD       (1)  (2)  (3)(4)(5) (6) (7) (8)                         HEC6
C     READ      ALER,ASEL,CE,CC,XFA,XLL,TAN,CRL                         HEC6
      READ (IN,1000)ICG,FLD                                             HEC6
C     SET COEFFICIENTS OF CONTRACTION AND EXPANSION                     HEC6
      IF(FLD(1).GT.0.)ALER=FLD(1)                                       HEC6
      ASEL=FLD(2)                                                       HEC6
      CE=FLD(3)                                                         HEC6
      CC=FLD(4)                                                         HEC6
      LFA=FLD(5)+1.1                                                    HEC6
      NR=FLD(6)+0.1                                                     HEC6
      TAN=FLD(7)                                                        HEC6
      CRL=FLD(6)                                                        HEC6
      WRITE (LP,1320)                                                   HEC6
C                                   BRANCH TO  1320 FROM  1155.12  1215.02 HEC6
 1320 FORMAT( //81H     ALER       ASEL        CE         CC         LFA HEC6
     .        NR       TAN       CRL  )                                 HEC6
      WRITE (LP,1325)ICG,ALER,ASEL,CE,CC,LFA,NR,TAN,CRL                 HEC6
C                                   BRANCH TO  1325 FROM  1155.13       HEC6
 1325 FORMAT (1X,A1,4F10.6,2I10,F10.6,F10.2)                            HEC6
      CC=CC+1.                                                          HEC6
      CE=1.-CE                                                          HEC6
C                                                                       HEC6
C     READ CROSS SECTION DATA SETS                                      HEC6
C     READ A CARD                                                       HEC6
C     FLD       (1)  (2) (3) (4)  (5) (6)(7)                            HEC6
C     READ      AVGS,IDF,NXY,MEID,NCH,SE,SL,          KOCH              HEC6
C                                   BRANCH TO  1330 FROM  1330.11  1825.02 HEC6
 1330 READ (IN,1000)ICG,FLD                                             HEC6
C                                                                       HEC6
C     PROGRAM EXPECTS AN A CARD                                         HEC6
      II=KA                                                             HEC6
      JJ=KBL                                                            HEC6
```

```
C     VERSION 1.4.[illegible]7 [illegible]19[illegible]
C     VERSION 1.3   28[illegible].72
C     VERSION 1.2  27APR72                                              HEC6    3584
C     VERSION 1.1 30MAR72                                               HEC6    3585
C     VERSION 1.0  12JAN1972                                            HEC6    3586
C     *                                                                 HEC6    3587
C     THIS MODULE REQUIRES SUBROUTINES *****CITIN,EFFDIA,BEDGRA*****    HEC6    3588
C     THIS SUBROUTINE CALLS  ***CITIN,EFFDIA,BEDGRA,DUBOY,ELMOD7,INLOAD, HEC6   3589
C                                 SPOWER,TFMOD6***                      HEC6    3590
C     *                                                                 HEC6    3591
C     SEDIMENT ROUTING PROGRAM                                          HEC6    3592
C     GD ARRAY=GRAIN SIZE DATA, DEPOSITS IN RESERVOIR,                  HEC6    3593
C     CAR ARRAY=COEFFICIENT ARRAY                                       HEC6    3594
C                                                                       HEC6    3595
C     STORAGE MAP CAP(ARRAY)                                            HEC6    3596
C     SPI                        1                                      HEC6    3597
C     TON/UWD                    2                                      HEC6    3598
C     UWW                        3                                      HEC6    3599
C     SUK                        4                                      HEC6    3600
C     BSAE                       5                                      HEC6    3601
C     VOLUME SHAPE FACTOR        +NR                                    HEC6    3602
C     NOT USED                   +NR                                    HEC6    3603
C     DS COEFFICIENTS            +3*NGS                                 HEC6    3604
C     N-CORRECTION COEF.         1*NGS                                  HEC6    3605
C     Q-QS RATING TABLE          +LQ*(NGS+1)                            HEC6    3606
C     VOLUME VS DEPTH FUNCTION+NR                                       HEC6    3607
C     INACTIVE STORAGE           +NR*(NGS+1)                            HEC6    3608
C     TOTAL                      LQ*(NGS+1)+3*(NGS+1)+NR*(NGS+4)+5      HEC6    3609
C                                                                       HEC6    3610
C     STORAGE MAP GD(ARRAY)                                             HEC6    3611
C     ACTIVE STORAGE       L5=(NGS+1)                                   HEC6    3612
C     REACH LENGTH               +1                                     HEC6    3613
C     AVG. SEC. NO.              +2                                     HEC6    3614
C     IDENTIFY USE OF SAE        +3                                     HEC6    3615
C     SAE                        +4                                     HEC6    3616
C     P1                         +5                                     HEC6    3617
C     D1                         +6                                     HEC6    3618
C     D2                         +7                                     HEC6    3619
C     MODEL BOTTOM               +8                                     HEC6    3620
C     NOT USED                   +9                                     HEC6    3621
C     SLOPE                LF +NC                                       HEC6    3622
C     N-VALUE                    +NO                                    HEC6    3623
C     TOP WIDTH                  +NO                                    HEC6    3624
C     DEPTH                      +NO                                    HEC6    3625
C     VELOCITY                   +NO                                    HEC6    3626
C     WATER SURFACE              +NO                                    HEC6    3627
C     EQUILIBRIUM BED ELEV       +NO                                    HEC6    3628
C     DISCHARGE                  +NO                                    HEC6    3629
C     TOTAL                      (NGS+8*NO+10)*NP                       HEC6    3630
```

```
C                                   B    .  T.  515.  .RCI  515...3          HEC6    3804
 5155 GTSL=GTSL+GS(I)                                                        HEC6    3805
      IF(KSW(13).GT.0) WRITE (LP,5160) GTSL,(GS(I),I=ISGS,LSGS)              HEC6    3806
C                                   BRANCH TO  5160 FROM  5200.01  5640.01  HEC6    3807
 5160 FORMAT(30X,6H SILT=,    6F15.2)                                        HEC6    3808
      ISUB=IALP+ILSA                                                         HEC6    3809
      GD(ISUB)=GD(ISUB)+GTSL*DD(N)/(UWSL*ACFT)                               HEC6    3810
C                                   BRANCH TO  5165 FROM  5150.00           HEC6    3811
 5165 IF(MTC.EQ.0) GO TO 5180                                                HEC6    3812
      ILSA=ILSA+1                                                            HEC6    3813
      GT=0.                                                                  HEC6    3814
      HVT=SD(LGS)                                                            HEC6    3815
      DO 5170 I=IGS,LGS                                                      HEC6    3816
 5170 GT=GT+GS(I)                                                            HEC6    3817
      IF(KSW(13).GT.0) WRITE (LP,5175) GT,(GS(I),I=IGS,LGS)                  HEC6    3818
C                                   BRANCH TO  5175 FROM  5215.01  5845.01  HEC6    3819
 5175 FORMAT(19X,17H SAND AND LARGER=  ,6F15.2 /(51X,5F15.2))                HEC6    3820
      ISUB=IALP+ILSA                                                         HEC6    3821
      GD(ISUB)=GD(ISUB)+GT*DD(N)/(UWD*ACFT)                                  HEC6    3822
C                                                                            HEC6    3823
C     MAJOR COMPUTATION LOOP, TRANSPORT CAPACITY, VOLUME OF DEPOSIT OR       HEC6    3824
C     SCOUR AND CHANGE IN CROSS SECTION CALCULATED                           HEC6    3825
C     IR=LOOP INDEX, USED TO CALCULATE SUBSCRIPT OF X-SECTION CURRENTLY      HEC6    3826
C     BEING ANALYIZED                                                        HEC6    3827
C                                   BRANCH TO  5180 FROM  5165.00           HEC6    3828
 5180 DO 5875 IR=1,NR                                                        HEC6    3829
C     DATA FROM BACKWATER PROGRAM IS STORED FROM DNST TO UPST                HEC6    3830
C     COMPUTE SUBSCRIPT TO PICK UP DATA IN REVERSE ORDER FROM STORAGE        HEC6    3831
C     LF=FIRST ADDR ABOVE THAT FOR L=1                                       HEC6    3832
      LPR=0                                                                  HEC6    3833
      LF=(NR-IR)*NK                                                          HEC6    3834
      L5=LF+NGS+1                                                            HEC6    3835
      ITV=L5+1                                                               HEC6    3836
      IXS=L5+2                                                               HEC6    3837
      KF=(NR-IR)*(NGS+1)+NIS                                                 HEC6    3838
      K5=KF+NGS+1                                                            HEC6    3839
      IRC=NR-IR+1                                                            HEC6    3840
      NDS=LF+NGS+NSE                                                         HEC6    3841
      NNV=NDS+MNO                                                            HEC6    3842
      NTW=NNV+MNO                                                            HEC6    3843
      NED=NTW+MNO                                                            HEC6    3844
      NVE=NED+MNO                                                            HEC6    3845
      NWS=NDS+5*MNO                                                          HEC6    3846
      NEB=NDS+6*MNO                                                          HEC6    3847
      NCO=NDS+7*MNO                                                          HEC6    3848
      LPST=0                                                                 HEC6    3849
      IF(INTL.LE.0) GO TO 5225                                               HEC6    3850
      IF(LTFP.NE.IFC) GO TO 5225                                             HEC6    3851
```

```
                                                                          HEC6   4093
                                                                          HEC6   4094
                                                                          HEC6   4095
                                  B   CH .0   340 FROM   5335.03   5335.14 HEC6   4096
      0 C   INL                                                           HEC6   4097
        GO TO 5350                                                        HEC6   4098
C                                 BRANCH TO   5345 FROM   5335.01         HEC6   4099
 5345 IF(TFA.LT.STSD) GO TO 5350                                          HEC6   4100
      IF(KSW(13).GT.0) WRITE (LP,5315) TFA,STSD                           HEC6   4101
C                                 BRANCH TO   5350 FROM   5340.01   5345.00 HEC6   4102
 5350 WSDA=0.                                                             HEC6   4103
      WSDI=0.                                                             HEC6   4104
      DO 5355 I=ISGS,LSGS                                                 HEC6   4105
      ISUB=LF+I                                                           HEC6   4106
      WSDA=WSDA+GD(ISUB)                                                  HEC6   4107
      ISUB=KF+I                                                           HEC6   4108
C                                 BRANCH TO   5355 FROM   5350.02         HEC6   4109
 5355 WSDI=WSDI+CAF(ISUB)                                                 HEC6   4110
      ISUB=LBSL+IRC                                                       HEC6   4111
      GPS(ISUB)=GTSL                                                      HEC6   4112
C     CORRECT FOR DENSITY CHANGE DUE TO COMPACTION AND CALCULATE VOLUME   HEC6   4113
      WSC=CCSD*TIME                                                       HEC6   4114
      CWSA=UWSL+WSC*.5                                                    HEC6   4115
      IF(CWSA.GT.PUSD) CWSA=PUSD                                          HEC6   4116
      VSDA=WSDA/CWSA                                                      HEC6   4117
      VSDI=WSDI/PUSD                                                      HEC6   4118
      VSD=VSDA+VSDI                                                       HEC6   4119
      IF(KSW(14).EQ.0) GO TO 5365                                         HEC6   4120
      WRITE (LP,5360)TIME,CWSA,VSDA,VSDI                                  HEC6   4121
 5360 FORMAT(21H TIME CWSA,VSDA,VSDI=,15X,F15.6,2F15.4,2F15.2)            HEC6   4122
C                                                                         HEC6   4123
C                                                                         HEC6   4124
C     ***********************************                                 HEC6   4125
C      SAND AND GRAVEL IS PRESENT IF MTC=+, CALCULATE TRANSPORT HERE      HEC6   4126
C                                 BRANCH TO   5365 FROM   5330.00   5355.09 HEC6   4127
 5365 IF(MTC.EQ.0) GO TO 5860                                             HEC6   4128
      IF(KSW(13).GT.0) WRITE (LP,5370)                                    HEC6   4129
 5370 FORMAT  (/5H SAND  )                                                HEC6   4130
      WSNI=CAF(K5)                                                        HEC6   4131
      WSNA=GD(L5)                                                         HEC6   4132
C     BYPASS ALL EQUILIBRUIM DEPTH CALCULATIONS IF NO BED MATERIAL PRES   HEC6   4133
      IF(LTMB.GT.0.) GO TO 5380                                           HEC6   4134
C     NO EQUILIBRIUM DEPTH COMPS POSSIBLE                                 HEC6   4135
      VSF=HVT                                                             HEC6   4136
      GAL=IMAX                                                            HEC6   4137
      SGC=0.                                                              HEC6   4138
      ISUB=L5+LMB                                                         HEC6   4139
      EBE=GD(ISUB)                                                        HEC6   4140
      EXB=EBE                                                             HEC6   4141
      ISUB=NWS+N                                                          HEC6   4142
```

```
C                                   BRANCH TO  5450 FROM  5425.01
C                                   5440.14
 5450 DEC=DU +(DED2-DU  )*(1.-SA1)/(SAA-SA1)
      GAL=UDF/(FNTN(5,DEQ)+DFQ+DEC+DEQ)
C                                   BRANCH TO  5455 FROM  5445.04
 5455 IF(KSW(13).LE.0) GO TO 5475
      WRITE (LP,5465) DEC,DAL,DED1,DED2,D2
      WRITE (LP,5460)IMDS,IMD,LGS,SAE,SAA,SA1
 5460 FORMAT ( 25H IMDS,IMD,LGS,SAE,SAA,SA1,11X,3I5,3F15.6 )
C                                   BRANCH TO  5465 FROM  5455.01
 5465 FORMAT ( 36H DEC,DAL,DED1,DED2, D2                ,15X,5F15.8)
      WRITE (LP,5470)SAE,SGC,GAL
 5470 FORMAT ( 12H SAE,SGC,GAL,24X,15X,5F15.8)
C
C     CALCULATE VOLUME OF SCOUR TO EQUILIBRIUM
C                                   BRANCH TO  5475 FROM  5455.00
 5475 ISUB=NWS+N
      EXB=GD(ISUB)-DAL
      IF(DEQ.GT.DAL) GO TO 5485
      DEQ=DAL
C     TRANSFER ALL MATERIAL FROM ACTIVE TO INACTIVE LAYER
      EBE=EXB
      GD(L5)=0.
      DO 5480 I=IGS,LGS
      ISUB=KF+I
      JSUB=LF+I
      CAR(ISUB)=CAR(ISUB)+GD(JSUB)
      GD(L5)=GD(L5)+SD(I)
C                                   BRANCH TO  5480 FROM  5475.06
 5480 GD(JSUB)=SD(I)
      WSNI=WSNI+WSNA
      CAR(K5)=WSNI
      WSNA=0.
      GO TO 5550
C                                   BRANCH TO  5485 FROM  5475.02
 5485 ISUB=NWS+N
      EBE=GD(ISUB)-DEC
      ISUB=L5+LMP
      IF(EBE.GE.GD(ISUB)) GO TO 5510
      IF(KSW(13).LE.0) GO TO 5500
```

```
      ..(CF..  E.(  ..
      ..JB=..  1
      TMP=RTO*GD(ISUB)
      GO TO 5540                                  BRANCH TO  5535 FROM  5530.02
C
 5535 ISUB=KF+I
      TMP=RTO*CAR(ISUB)                           BRANCH TO  5540 FROM  5530.05
C
 5540 ISUB=LF+I
      GD(ISUB)=GD(ISUB)+TMP
      ISUB=KF+I
      CAR(ISUB)=CAR(ISUB)-TMP
      GD(L5)=GD(L5)+TMP
      CAR(K5)=CAR(K5)-TMP                         BRANCH TO  5545 FROM  5530.01
C
 5545 CONTINUE                                    BRANCH TO  5550 FROM  5480.04  5510.04
C
 5550 IF(SAE.LT.1.E-7) SAE=1.E-7
      VSE=(HVT+GD(L5))/SAE
      ISUB=NEB+LEB
      GD(ISUB)=EBE
C     FIRST, SECOND AND THIRD ALTERNATIVES FOR CALCULATING D65 AKE
C             ACTIVE LAYER, INACTIVE LAYER AND PROBABILITY FUNCTION
      TMP=GD(L5)
C     FIRST CHOICE IF POSITIVE
      IF(TMP.GT.0.) GO TO 5580
C     SECOND CHOICE IF POSITIVE
      TMP=CAR(K5)
      IF(TMP.GT.0.) GO TO 5570
C     THIRD CHOICE=LAST RESORT                    BRANCH TO  5555 FROM  5370.16  5375.04
C
 5555 SPB=0.
      DO 5560 I=IGS,LGS
      TMP=SD(I)
      TFC=CTC*TMP
      TCTA=TFC/TFA
      CALL CITIN (IBPD,MNI,PBT,TINT,TCTA,PROB,IFL)
      PI(I)=PROB
      SPB=SPB+PROB                                BRANCH TO  5560 FROM  5555.01
C
 5560 CONTINUE
C     CORRECT TO 100 PERCENT
      DO 5565 I=IGS,LGS
      PI(I)=PI(I)/SPB                             BRANCH TO  5565 FROM  5560.01
C
 5565 CONTINUE
      GO TO 5590                                  BRANCH TO  5570 FROM  5550.07
C
 5570 DO 5575 I=IGS,LGS
```

```
      6        430
HEC6           4385
HEC6           4386
HEC6           4387
HEC6           4388
HEC6           4389
HEC6           4390
HEC6           4391
HEC6           4392
HEC6           4393
HEC6           4394
HEC6           4395
HEC6           4396
HEC6           4397
HEC6           4398
HEC6           4399
HEC6           4400
HEC6           4401
HEC6           4402
HEC6           4403
HEC6           4404
HEC6           4405
HEC6           4406
HEC6           4407
HEC6           4408
HEC6           4409
HEC6           4410
HEC6           4411
HEC6           4412
HEC6           4413
HEC6           4414
HEC6           4415
HEC6           4416
HEC6           4417
HEC6           4418
HEC6           4419
HEC6           4420
HEC6           4421
HEC6           4422
HEC6           4423
HEC6           4424
HEC6           4425
HEC6           4426
HEC6           4427
HEC6           4428
HEC6           4429
HEC6           4430
```

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      C                                BRANCH TO  5650 FROM  5640.01  5640.05 HEC6    4496
 5650 CONTINUE                                                          HEC6    4497
      C                                                                 HEC6    4498
      GO TO 5660                                                        HEC6    4499
      C                                                                 HEC6    4500
      C     MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM HEC6    4501
      C     TRANSPORT BY LAURSENS METHOD AS MODIFIED BY ED MADDEN, SWD, CORPS HEC6  4502
      C                                BRANCH TO  5655 FROM  5610.00    HEC6    4503
 5655 CALL ELMOD7 (EML,VEL,EFD,EFW,EDG,SLO,PI,UWW,N,CF,L5)              HEC6    4504
      C     MMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM HEC6    4505
      C                                                                 HEC6    4506
      C                                BRANCH TO  5660 FROM  5615.01  5620.03 HEC6    4507
      C                                           5630.02  5650.01      HEC6    4508
 5660 IF(KSW(13).GT.0) WRITE (LP,5665) (GP(I),I=IGS,LGS)                HEC6    4509
 5665 FORMAT(36H TRANSPORT CAPACITY(FINE TO COARSE) ,15X,5E15.8 /       HEC6    4510
     . (51X,5E15.8))                                                    HEC6    4511
      C                                BRANCH TO  5670 FROM  5715.05    HEC6    4512
 5670 FORMAT(26H VOLUME OF DEPOSITS(TONS) ,10X, 6E15.8 /(51X,5E15.8))   HEC6    4513
      C                                                                 HEC6    4514
      C     DISTRIBUTE SEDIMENT IN RESERVOIR BY EXNER EQUATION          HEC6    4515
      C                                                                 HEC6    4516
      C     BMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMG HEC6    4517
      C     CALCULATE BED MATERIAL COMPOSITION FROM INFLOWING LOAD      HEC6    4518
      IF(IBG.LE.0) GO TO 5690                                           HEC6    4519
      CALL       BEDGRA (IBG,GP,GS,PGD,PI,SAE )                         HEC6    4520
      IBG=IBG-1                                                         HEC6    4521
      IF(IBG.GT.0) GO TO 5610                                           HEC6    4522
      DO 5675 I=IGS,LGS                                                 HEC6    4523
      ISUB=LF+I                                                         HEC6    4524
      C                                BRANCH TO  5675 FROM  5670.05    HEC6    4525
 5675 GD(ISUB)=GD(L5)*PI(I)                                             HEC6    4526
      IF(IR.GE.NR) GO TO 5680                                           HEC6    4527
      IBG=CAR(LIBG)                                                     HEC6    4528
      GO TO 5875                                                        HEC6    4529
      C                                BRANCH TO  5680 FROM  5675.01    HEC6    4530
 5680 IBG=0                                                             HEC6    4531
      WRITE (LP,5055)                                                   HEC6    4532
      WRITE (LP,5685)                                                   HEC6    4533
 5685 FORMAT (58H BED GRADATION WAS CALCULATED FROM INFLOWING SEDIMENT L HEC6   4534
     .OAD  )                                                            HEC6    4535
      CAR(LIBG)=0.                                                      HEC6    4536
      GO TO 5135                                                        HEC6    4537
      C     BMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMGBMG HEC6    4538
      C                                                                 HEC6    4539
      C                                BRANCH TO  5690 FROM  5670.01    HEC6    4540
 5690 DT=DIST/VEL                                                       HEC6    4541
      IF(SPI)5705,5700,5695                                             HEC6    4542
 5695 LTI=SPI
```

```
      SPI  GS,  DU,  S
    5 L  .SP                                                          HEC6   4543
      GO TO 5710                                                      HEC6   4544

      C                                  BRANCH TO  5700 FROM  5650.01          HEC6   4545
 5700 LTI = .1+E64CO.*DD(N)/DT                                                   HEC6   4546
      IF(LTI.GT.1) GO TO 5710                                                    HEC6   4547
      C                                  BRANCH TO  5705 FROM  5650.01          HEC6   4548
 5705 LTI=1                                                                      HEC6   4549
      C                                                                          HEC6   4550
      C                                  BRANCH TO  5710 FROM  5695.01  5700.01 HEC6   4551
 5710 FLTI=LTI                                                                   HEC6   4552
      DUR=DD(N)/FLTI                                                             HEC6   4553
      DO 5715 L=IGS,LGS                                                          HEC6   4554
      GSR(L)=0.                                                                  HEC6   4555
      GS(L)=GS(L)*DUR                                                            HEC6   4556
      GP(L)=GP(L)*DUR                                                            HEC6   4557
      C                                  BRANCH TO  5715 FROM  5710.02          HEC6   4558
 5715 CONTINUE                                                                   HEC6   4559
      IF(KSW(14).LE.0) GO TO 5725                                                HEC6   4560
      WRITE (LP,5720) LTI,SPI,DUR,DT                                             HEC6   4561
      ISUB=IGS+LF                                                                HEC6   4562
      JSUB=LGS+LF                                                                HEC6   4563
      WRITE (LP,5670) GD(L5),(GD(I),I=ISUB,JSUB)                                 HEC6   4564
      C                                  BRANCH TO  5720 FROM  5715.02          HEC6   4565
 5720 FORMAT(21H 4325 LTI,SPI,DUR,DT=,15X,I15,3F15.4)                            HEC6   4566
      C                                  BRANCH TO  5725 FROM  5715.01          HEC6   4567
 5725 DO 5790 NTI=1,LTI                                                          HEC6   4568
      VRD=GD(L5)+HVT                                                             HEC6   4569
      IF(SAE.GE.0.) GO TO 5730                                                   HEC6   4570
      SAE=0.                                                                     HEC6   4571
      GO TO 5735                                                                 HEC6   4572
      C                                  BRANCH TO  5730 FROM  5725.02          HEC6   4573
 5730 IF(SAE.GT.1.) SAE=1.                                                       HEC6   4574
      C                                                                          HEC6   4575
      C                                  BRANCH TO  5735 FROM  5725.04          HEC6   4576
 5735 GSAE=SAE**BSAE                                                             HEC6   4577
      DO 5770 L=IGS,LGS                                                          HEC6   4578
      SDA=0.                                                                     HEC6   4579
      GSD=SD(L)                                                                  HEC6   4580
      LL=LF+L                                                                    HEC6   4581
                                                                                 HEC6   4582
```

```
C                                       BRANCH TO  5750 FROM  5745.02
 5750 STO=GS(L)-GPR*FSAE
      IF(STO.LT.0) GO TO 5755
      GSR(L)=GSR(L)+GS(L)
      GO TO 5770
C                                       BRANCH TO  5755 FROM  5750.01
 5755 REM=GD(LL)+STO
      IF(REM.GT.0.) GO TO 5760
      GD(L5)=GD(L5)-GD(LL)
      GSR(L)=GSR(L)+GS(L)+GD(LL)
      STO=-GD(LL)
      GD(LL)=0
      GO TO 5765
C                                       BRANCH TO  5760 FROM  5755.01
 5760 GD(L5)=GD(L5)+STO
      GSR(L)=GSR(L)+GS(L)-STO
      GD(LL)=REM
C                                       BRANCH TO  5765 FROM  5740.05  5755.06
 5765 VSE=VSE+STO*SDA
C
C                                       BRANCH TO  5770 FROM  5735.01  5735.09
C                                           5740.03  5750.03
 5770 CONTINUE
      IF(KSW(14).LE.0) GO TO 5785
      IF(LPR.GT.NTI) GO TO 5785
      WRITE (LP,5775) NTI,SAE,(PI(I),I=IGS,LGS)
 5775 FORMAT(16H 4345 NTI,SAE,PI,20X,I6,F6.5,5F15.4/(51X,5F15.4))
      WRITE (LP,5780)(GSR(I),I=IGS,LGS)
 5780 FORMAT ( 51X, 5E15.8)
      LPR=LPR+LTI/10
C
C                                       BRANCH TO  5785 FROM  5770.01  5770.02
 5785 SAE=(GD(L5)+HVT)/VSE
C                                       BRANCH TO  5790 FROM  5725.00
 5790 CONTINUE
      ISUB=L5+LSA
      GD(ISUB)=SAE
      ISUB=L5+LGA
      GD(ISUB)=GAL
      GT=0.
      DO 5795 I=IGS,LGS
      GS(I)=GSR(I)/DD(N)
C
C                                       BRANCH TO  5795 FROM  5790.06
 5795 GT=GT+GS(I)
      ISUB=LBSA+IFC
      GPS(ISUB)=GT
      VNM=(GD(L5)+CAR(K5))/UKD
C
```

```
      ISUB=L5+LPA                                                       HEC6    5510
      GD(ISUB)=FLD(5)                                                   HEC6    5511
      ISUE=K5                                                           HEC6    5512
      CAR(ISUB)=FLD(6)                                                  HEC6    5513
      DO 6480 I=1,KEN                                                   HEC6    5514
      ISUB=KF+I                                                         HEC6    5515
C                                   BRANCH TO  6480 FROM  6475.14       HEC6    5516
 6480 CAR(ISUB)=FLD(I+6)                                                HEC6    5517
      ISUB=KF+5                                                         HEC6    5518
      JSUB=KF+NGS                                                       HEC6    5519
      IF(NGS.GT.4)READ(IUNIT,6485)(CAR(I),I=ISUB,JSUB)                  HEC6    5520
 6485 FORMAT(8X,9F8.0)                                                  HEC6    5521
C     VARIABLES ON NEXT CARD =      SAE        DMAX        DXPI        XPI HEC6    5522
      ISUB=L5+LSA                                                       HEC6    5523
      JSUB=L5+LDM                                                       HEC6    5524
      KSUB=L5+LDA                                                       HEC6    5525
      LSUB=L5+LPA                                                       HEC6    5526
      MSUB=KF+1                                                         HEC6    5527
      NSUB=KF+KEN                                                       HEC6    5528
      WRITE (LP,6110) ICG,IDT,ISI,GD(ISUB),GD(JSUB),GD(KSUB),GD(LSUB),  HEC6    5529
     . CAR(K5),(CAR(I),I=MSUB,NSUB)                                     HEC6    5530
      ISUB=KF+5                                                         HEC6    5531
      JSUB=KF+NCS                                                       HEC6    5532
      IF(INGS.LT.0) WRITE (LP,6490) (CAR(I),I=ISUB,JSUB)                HEC6    5533
 6490 FORMAT (9X,9F12.3)                                                HEC6    5534
      ISUB=L5+LPA                                                       HEC6    5535
      IF(GD(ISUB).GT.0.) GO TO 6495                                     HEC6    5536
      ISUB=L5+LPA                                                       HEC6    5537
      GD(ISUB)=.95                                                      HEC6    5538
      ISUB=L5+LDA                                                       HEC6    5539
      GD(ISUB)=SD(LGS)                                                  HEC6    5540
C                                   BRANCH TO  6495 FROM  6490.02       HEC6    5541
 6495 ISUB=L5+LPA                                                       HEC6    5542
      GD(ISUB)=1.-GD(ISUB)                                              HEC6    5543
      ISUB=L5+LSA                                                       HEC6    5544
      IF(GD(ISUB).LE.0.) GD(ISUB)=1.                                    HEC6    5545
      ISUB=L5+ISA                                                       HEC6    5546
      JSUB=L5+LSA                                                       HEC6    5547
      GD(ISUB)=GD(JSUB)                                                 HEC6    5548
      ISUB=L5+LDM                                                       HEC6    5549
      IF(GD(ISUB).LE.0.) GD(ISUB)=SD(LGS)                               HEC6    5550
      ISUB=L5+LDA                                                       HEC6    5551
      IF(GD(ISUB).LE.0.) GD(ISUB)=SD(LGS)                               HEC6    5552
      READ (IUNIT,6105)ICG,IDT,ISI,(FLD(K),K=2,10)                      HEC6    5553
```

```
      SU  )T
      D(    )=   (2)
      ISUB=L5+LGA
      GD(ISUB)=FLD(3)
      ISUB=NEB+LEB
      GD(ISUB)=FLD(4)
      ISUB=L5+LPA
      GD(ISUB)=FLD(5)
      DLYCC(IR)=FLD(6)
      DLYPU=DLYCC(IR)
      ISUB=L5+LSA
      SAE=GD(ISUB)
      ISUB=LF+1
      JSUB=LF+NGS
      READ (IUNIT,6540) (GD(L),L=ISUB,JSUB)
 6540 FORMAT (8X, 6F12.0)
      ISUB=L5+LGA
      JSUB=NEB+LEB
      KSUB=L5+LPA
      LSUB=LF+1
      MSUB=LF+NGS
      WRITE (LP,6545) GD(IT),SAE,GD(ISUB),GD(JSUB),GD(KSUB),
     . DLYPU,(GD(I),I=LSUB,MSUB)
                                        BRANCH TO  6545 FROM  6540.06
C
 6545 FORMAT (1X,1HO,F7.2,2F8.6,F8.3,F8.4,F8.3 /(1X,7X,6F12.0))
      IF(IR.EQ.NR)IUNIT=5
      READ (IUNIT,6105) ICG,IDT,ISI, (FLD(K),K=2,10)
      DO 6550 I=ICS,LCS
      ISUB=LF+I
                                        BRANCH TO  6550 FROM  6545.03
C
 6550 GD(L5)=GD(L5)+GD(ISUB)
```



```
                                        BRANCH TO  6555 FROM  6535.02
C
 6555 CONTINUE
                                        BRANCH TO  6560 FROM  6525.01
C
 6560 LALP=NR*NK
      INTL=0
      IF(MNTL.GT.0) INTL=NTEL(MNTL)
      NGD=LALP+(MSOR+1+INTL)*NSFR
      NCAR=LO*(NGS+1)+3*(MSAND+1) +NR*(NGS+4)+NVS
C
      ENTER TRIBUTARY INFLOW DATA IF PRESENT
```