Mathematical Model for Estimating Scour Through Bridge Crossings

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ABSTRACT

Changes in bed level in alluvial channels are an important design consideration for bridge crossings. The general problem of scour at bridge crossings involves degradation, aggradation, and local scour. Three types of interrelated scour phenomena are found at bridges: (a) local scour caused by piers and abutments disturbing the flow, forming vortices and eddies; (b) scour due to contraction of the flow at the crossing, causing increased velocities in the contracted width; and (c) degradation or aggradation of a stream channel over relatively long reaches and over a long time due to bed-level controls, changes in sediment supply, and changes in river form. A model of these scour phenomena has been developed by Simons, Li & Associates using a known-discharge sediment-routing procedure called HEC2SR. The model determines scour in reaches of a river system based on available sediment supply, local hydraulic conditions, and sediment-transport capacity. Hydraulic conditions for the river are determined using the U.S. Army Corps of Engineers HEC-2 computer program. The procedure was designed to take advantage of the bridge hydraulic modeling routines in HEC-2. Output from the modeling procedure includes detailed hydraulic and sediment-transport data as well as cross-sectional information. Application of the model to a complex site is shown. The analysis procedure provides important information pertinent to the design of river-training measures used in conjunction with bridge crossings.

HEC2SR is a sediment-routing procedure developed by Simons, Li & Associates (SLA), Inc., for routing watershed sediment yield and determining the subsequent degradation and aggradation in a mainstem river. The staff of SLA continues to improve and expand the capabilities of HEC2SR as it is applied to new river systems and hydraulic design problems. An area in which it has been applied extensively by SLA is the hydraulic design of bridges. In this paper the use of HEC2SR in modeling riverbed-level changes and how information from the model is incorporated in the hydraulic design of bridges are discussed.

The model HEC2SR was developed to provide detailed information on bed-level changes in natural channels with hydraulic structures. The procedure incrementally computes a series of water-surface profiles for varying discharges in river channels of any cross section or flow state (subcritical or supercritical) using the U.S. Army Corps of Engineers program HEC-2. The effects of natural obstructions to flow and of hydraulic structures can be simulated by HEC-2. Procedures used in program HEC-2 provide an acceptable method for determining the hydraulics of a bridged channel. HEC-2 supplies hydraulic data that is used to calculate the sediment-transport capacity of river reaches. Sediment supply from upstream and tributary watersheds is also calculated as an additional supply input to the mainstem river reach. The procedure can model a variety of hydraulic structures including bridges, culverts, weirs, grade-control structures, channel improvements, embankments, and levees. Hydraulic information summarized from the HEC-2 program during the procedure allows determination of local scour at piers and abutments and determination of sediment-wave movement such as antidunes in upper regime flow.

The principal use of HEC2SR has been in the design of hydraulic structures on very dynamic rivers, which in many cases have been disrupted by development activities. The simulated bed-level changes and related local scour information are used to evaluate the burial depth for piers, abutments, bank protection, and minimum freeboard requirements at hydraulic structures. Although the procedure evaluates only bed-level changes, it can be very useful in identifying critical reaches where lateral migration is likely. When used in conjunction with other methods in fluvial geomorphology and river mechanics (1), the HEC2SR procedure provides additional refinement and detail necessary for complete hydraulic structure design.

HEC2SR WATER- AND SEDIMENT-ROUTING PROCEDURE

Theoretic Basis

The HEC2SR simulates the movement of alluvial sediment in a river channel for the duration of a flood event. This model can be categorized as a known-discharge, uncoupled water- and sediment-routing model. Known discharge means the discharge in the study reach is given by the upstream inflow unless there is a lateral inflow (tributary). The lateral inflows are added to the mainstem and carried to the downstream reaches. The unsteady flood-wave movement is considered secondary in the known-discharge model. Uncoupled routing means that water and sediments are routed separately. For each time step, the backwater profile is determined first and then the sediment routing is performed based on the hydraulic parameters obtained through the backwater computations. As the name implies, HEC2SR utilizes the HEC-2 backwater computation model to determine the backwater profile. The Meyer-Peter and Mueller bed-load equation (2) combined with the Einstein suspended-load computation procedure (3) is adopted in the model to estimate bed-material transport capacities. The actual transport rate for each river reach is determined by considering both soil availability and transport capacity in the reach. The computed bed-material discharges are further corrected for the fine-sediment concentrations based on Colby's empirical relation (4). Sediments are routed by size in this model. Transport rate, armoring effect, and bed-material changes are considered for individual size fractions. The modified Universal Soil Loss Equation (MUSLE) developed by Jimmy Williams and H.D. Berndt (5) is used to compute the wash-load discharges from the upstream and tributary watersheds.

For computational efficiency and stability the main river is subdivided into a series of computational reaches. Each of these subreaches is a section of the main river in which hydraulic and geomorphic characteristics are similar. The sediment inflow to each subreach is from the upstream reach of the main river. Additional sediment and water discharges may enter a subreach from tributary watersheds. The channel degradation or aggradation in each subreach is governed by sediment continuity. If there is more sediment inflow than outflow, aggradation occurs in the reach. If sediment inflow is less than outflow, degradation results. The volume of aggradation or degradation for each reach is uniformly distributed along the length of the reach, but the bed-elevation change for each cross section is weighted according to the flow conveyance across the section.

The cross-sectional data are modified at the end of each time step. Because the HEC2SR procedure is intended for application on fairly dynamic river reaches for a single runoff event, this frequent modification of the channel cross-sectional data is warranted. Elevation changes of less than 0.01 ft are ignored.

The amount of material transported or deposited in a channel reach is the result of the interaction of two processes. The first is the transport capacity of the reach. This is determined in part by the hydraulic conditions that are a direct result of water discharge, channel configuration, and channel resistance. Transport capacity also depends on the sediment sizes present in the riverbed. Smaller particles can be transported at higher rates than larger particles under the same flow conditions. The second process is the supply of sediment entering the reach. This is determined by the characteristics of the watershed and river system upstream of the study reach.

When the sediment supply is less than the sediment transport capacity, channel degradation, or bank erosion, or both occur to reduce the sediment deficit. In some cases degradation can be limited by the development of an armor layer. If the sediment supply is greater than the capacity, the excess sediment will be deposited in the channel, causing aggradation.

In HEC2SR the Meyer-Peter and Mueller equation (2) is used to compute the bed-load transport for each sediment size fraction. The suspended sediment ratio (suspended load to bed load) is estimated by a simplified Einstein procedure. A detailed description of this procedure is presented elsewhere (3). The resulting equations are as follows:

The bed-load formula is

$$q_b = 12.85/(\rho^{1/2})\,\gamma_s\,(\tau_o - \tau_c)^{1.5} \tag{1}$$

where

q_b = bed load (cfs/ft),
ρ = density of water (slugs/ft^3),
γ_s = specific weight of sediment (lb/ft^3),
τ_o = boundary shear stress (psf), and
τ_c = critical tractive force to initiate particle motion (psf).

The critical shear stress τ_c in Equation 1 is

$$\tau_c = 0.047\,(\gamma_s - \gamma)\,d_s \tag{2}$$

where

τ = specific weight of water and
d_s = size of sediment (ft).

The boundary shear stress acting on the grain in Equation 1 is

$$\tau_o = (f_o/8)\,\rho\,V^2 \tag{3}$$

where

f_o = Darcy-Weisbach friction factor (dimensionless) and
V = mean velocity of flow (fps).

The suspended bed-material discharge is based on exchange theory using Einstein's approach, where

$$q_s = (q_b/11.6)\,[G^{w-1}/(1-G)^w]\,\left\{[(V/U_*) + 2.5]\,I_1 + 2.5\,I_2\right\} \tag{4}$$

and where

q_s = suspended load (cfs/ft),
G = relative thickness of bed layer (dimensionless),
U_* = shear velocity (fps), and
w = dimensionless parameter given by
$w = V_s/\kappa U_*$ where $\kappa = 0.4$

I_1 and I_2 are integrals that cannot be evaluated directly. One must use either tables or numerical techniques. In HEC2SR, these integrals are evaluated using a Newton first-order approximation. Calibration of Equations 1 and 4 to known transport conditions involves adjustment of parameters describing the boundary shear or the relative thickness of the bed-layer zone of sediment transport. The boundary shear stress is adjusted using the Darcy-Weisbach friction factor, f_o, within accepted limits. Adjusting the bed-layer thickness, G, directly influences the suspended sediment concentration. Both parameters are input variables in the HEC2SR procedure.

The bed-material distributions are updated at each time step throughout the entire flood period according to the estimated scour or deposition. The bed-material distributions are allowed to vary; this is an essential capability for simulating an armoring process in a river channel. The presence of coarser particles can significantly influence degradation through channel armoring.

Wash load is estimated based on a modified version of the Universal Soil Loss Equation (5) where

$$C_w = 95\,Q^{0.56}\,\forall^{-0.44}(K_e)(LS)(CP) \tag{5}$$

and where

C_w = wash-load concentration (ppm),
Q = hydrograph peak (cfs),
$\forall$ = hydrograph volume (acre-feet),
LS = USLE slope-length factor (dimensionless), and
CP = USLE cover-practice factor (dimensionless).

The wash-load concentration is assumed to be constant for the duration of the storm. The sediment discharge is corrected for the effect of water temperature, wash load, and sediment size using factors developed by Colby. The correction factor is given by

$$K = 1 + (k_1 k_2 - 1)\,0.01 k_3$$

where

K = Colby correction factor (dimensionless),
k_1 = water-temperature correction factor (dimensionless),
k_2 = fine-sediment correction factor (dimensionless), and

k_3 = mean particle-size correction factor (dimensionless).

The correction factors as presented by Colby (4) have been digitized for use in HEC2SR.

Computational Method

Spatially the HEC2SR procedure recognizes two components of the watershed-river system in a distinct fashion. Each tributary and the upstream portion of the main channel contain a watershed. HEC2SR computes a wash-load concentration and bed-material discharge for each of these watershed areas. In the case of the upstream watershed, the user has the option to directly input either sediment load. This allows the modeling to be decomposed at grade controls (i.e., a bedrock outcrop or man-made drop structure) or where relatively stable reaches may exist in the river system. This option can also be used when sediment inputs have been modeled in detail or actual sediment concentrations are known.

The basic geometric unit for description of the river channel is the cross section. In describing the cross-sectional geometry and reach lengths for HEC2SR, the river should be considered in exactly the same manner as it is viewed by program HEC-2. The modeler should understand the capabilities and limitations of one-dimensional backwater-profile calculation in simulating various flow conditions. In fact, the water-surface profile portion of the HEC2SR can be run and checked before executing the full sediment-routing procedure. This is advisable because the sediment-routing portion of the procedure adds significantly to the complexity of the procedure. Several limitations are placed on the HEC-2 input when it is used in conjunction with the model procedure HEC2SR. These limitations are discussed later in this paper and are for the most part minor constraints.

The sediment-routing component of HEC2SR uses river reaches identified by the user. These reaches consist of several channel cross sections and are defined as portions of the river that have similar hydraulic or geomorphic characteristics. Division of the river into reaches is based on a number of considerations. First, HEC-2 water-surface profiles should be run over the range of flows to be considered in the modeling. Plots of depth, top width, velocity, and main-channel discharge versus distance along the channel should be prepared and reviewed. Portions of the channel displaying similar behavior for the range of discharges considered can be combined as a single reach. Maps and aerial photographs should also be consulted in selecting reaches. Portions of the river of special concern in the modeling, such as bridges or grade-control structures, should be handled separately. Suggested approaches for modeling hydraulic structures using HEC2SR are given later in this paper.

Temporally, the HEC2SR procedure uses time steps specified by the user. All inputs are made discrete using these time steps. Time steps that provide a reasonable approximation of the main-channel hydrograph should be selected. The time steps can vary in length depending on the shape of the hydrograph, that is, a rapidly rising portion of the hydrograph may use several short time steps whereas a long recession limb could be adequately described using a few long time steps.

HEC2SR procedure consists of a series of programs linked sequentially by job-control statements. Figure 1 shows a flow chart of the HEC2SR model that exhibits the execution procedure of the programs included in the model. At the beginning of routing, a data set describing the channel geometry is prepared in HEC-2 format and a river and watershed information data set is prepared and stored in a separate data file. The river and watershed data file includes reach delineation, particle size distributions, and hydrographs. This file is then subdivided into several data files in program FLMSB5 for use in subsequent programs. Program STDSB5 expands any condensed information on the HEC-2 file. For example, some cross sections may use the GR cards of the previous cross section (set field 2 of the X1 card equal to zero). The resulting HEC-2 file contains channel geometry for each cross section so that each cross section can be updated independently after water and sediment routing. If the original HEC-2 data are already in the desired format, program STSB5 can be skipped.

As stated previously, the HEC-2 program is used to determine the backwater-surface profile for a given discharge. The hydraulic parameters are extracted from tape 96 in program INFSB5 after running HEC-2. Program RCHSB5 estimates the average hydraulic parameters for each reach to be used in computing sediment discharges.

Program SEDSB5 is the major module for sediment transport and routing. The fine-sediment concentration and the bed-material transport capacities are computed for each reach. The actual transport rate is determined and compared with the sediment inflow. The channel degradation or aggradation volume is computed and stored for later use in modifying the cross-sectional data, and a new surface-sediment layer is computed establishing a new sediment size distribution within the reach.

After the channel aggradation or degradation has been determined, program CHDSB5 updates the HEC-2 data file. The scoured or deposited sediments are distributed uniformly along the defined reach. In this way, each cross section in the reach has the same amount of change in cross-sectional area. The distribution of the aggraded or degraded area across the section (normal to the flow) is weighted according to the flow conveyance of each portion of the flow area. Finally, program CHDSB5 also updates the stage-discharge data in the HEC-2 file to be used in the following time step.

After program CHDSB5 has been run, the model is ready to execute the water and sediment routing for the next time step. Before this, program OUTSB5 outputs all the hydraulic and sediment transport parameters of the study reach for the investigated time step. Program OUTSB5 also writes out the thalweg elevation changes for each cross section. In addition, the updated HEC-2 data file is stored in a separate data file so that the channel geometry for each cross section during flood routing can be retrieved if more detailed study is required.

After program OUTSB5 has been run, the model repeats the procedure for a predetermined number of time intervals that span the flood period. After the last time interval the model exits from the water- and sediment-routing loop. Finally, program ELMIN5 prints out the maximum water-surface elevation and minimum thalweg elevation encountered for each cross section throughout the entire flood period.

Data Requirements

The input data required for HEC2SR are an HEC-2 data file and a river and watershed data file. The HEC-2 data can include all of the encroachment and bridge constriction cards necessary. The condensed format of the X1 card (field 2 is zero or field 9 is not zero) is allowed, but the channel improvement (CI) and additional points for cross section (X4) options should be explicitly expressed and incorporated into

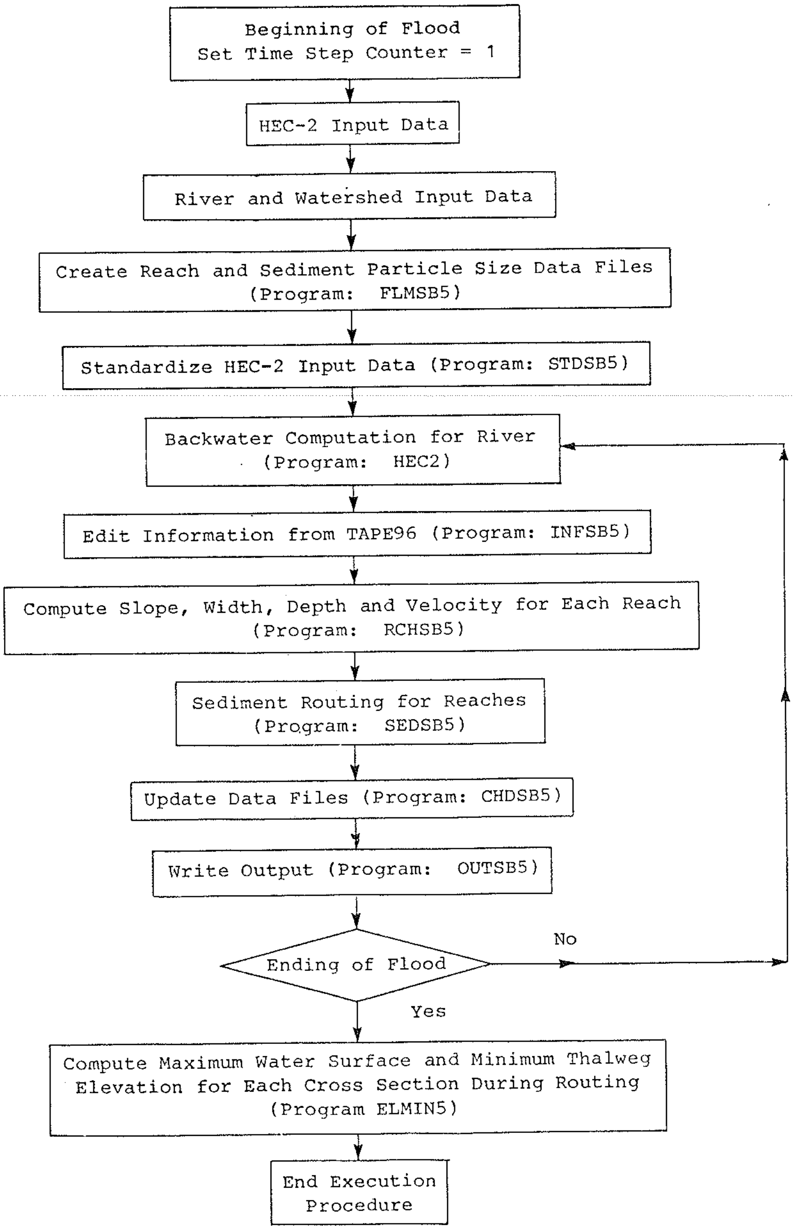

FIGURE 1 Flow chart for model HEC2SR.

the GR cards before running the model. The option to use known water-surface elevations is not applicable (X5) to the procedure and therefore not allowed.

In the river and watershed data file, the river-reach delineation (including the number of cross sections and the extent of each reach) and soil data (sediment size distributions for the subsurface and surface layers and the potential armor depth) are given first. The downstream stage relationship is then given or, if the slope-area or critical-depth method is used, the approximate water-surface elevations. The upstream and lateral-inflow hydrographs are then provided with the time step lengths for the digitized stage and discharge hydrographs. The data to compute the sediment loading (wash load and bed-material load) from the watersheds are also given in this portion of the data if the option of computing sediment yield of the upstream and lateral watersheds is desired.

The additional data collection that is required in developing a complete and accurate data set for the HEC2SR procedure are sediment samples of surface and subsurface material in the channel. The data collected should be sufficient to identify the variation of sediment size along the river system and vertically within a cross section. Geologic mapping should also be reviewed and any geologic controls of the river profile identified. Available sampling data should be reviewed carefully and a preliminary field survey conducted before any new data collection effort is made.

Assumptions and Their Limitations

The major assumptions made in the sediment-routing procedure are that during any time step the flow is steady, gradually varied, and moving predominantly in the downstream direction. Unsteady aspects of flood-wave movement, such as attenuation of the flood peak, are ignored. Routing of the flood is based on conservation of mass alone. If the unsteady behavior of the flood wave is known, certain adjustments can be made to the original flood hydrograph. This can be accomplished by using artificial tributaries to add or delete water mass from the mainstem of the river and by suppressing the sediment inflow calculations for these tributaries. Depletion hydrographs are allowable in the river and watershed data file, but careful review should be given to the net hydrograph resulting from such tributary inflows and outflows. A net negative hydrograph will terminate program execution. There is no explicit means in the HEC2SR procedure to determine the unsteady behavior of flood-wave movement.

The limitation of the steady-flow assumption regarding the movement of sediment is generally minor. The associated movement of the sediment wave is many times less than that of the flood wave and the refinement of this assumption using full dynamic models is usually unwarranted. The one-dimensional assumption can present more limitations if there are areas of channel that may receive a substantial sediment load due to a lateral flow. Breaching of levees or complex floodplain areas are examples of conditions that can be interpreted as sediment "sinks" that cannot be directly assessed in the HEC2SR procedure.

HEC2SR is limited in its inability to incorporate and predict localized scour or deposition. The model does not account for bank erosion either in the case of an incised channel with severe degradation or in the case of a river that may be altering its meander pattern. Secondary currents and superelevation caused by accelerating flow around a river bend initiate local scour and deposition patterns that will not be recognized by the one-dimensional assumption in this model. The model assumes a uniform aggradation or degradation pattern along each reach as it is defined. In reality the spatial distribution of the deposition or scour is a function of sediment settling distance, local variation in sediment transport rates, and channel geometry.

Despite these limitations, this model has been successfully applied to sand- and gravel-bed rivers for analysis of existing structures and for bridge design. If the discharge, bed-material, and cross-sectional data are properly input, the river reaches appropriately defined and sediment discharge measurements available to validate the employed sediment equations, this model can reasonably predict channel response to floods of various magnitudes. HEC2SR offers the options of inputting sediment inflow directly or internally generating sediment-loading data by considering the sediment-transport capacities in the upstream supply and tributary reaches. The modular structure of this model also enables users to easily understand and modify each individual functional component.

SIMULATION OF BED-LEVEL CHANGES THROUGH BRIDGES

Reach Definition

The analyst has two options for computing bed-level changes through a bridge. The method chosen depends on the degree to which the bridge affects the hydraulics of the channel. In river reaches where the bridge does not constrict the flow, a single reach is sufficient to model the aggradation or degradation process. River reaches with a bridge that severely constricts the flow require two computational reaches to model the aggradation or degradation process.

Figure 2 shows the general layout of cross sections in the vicinity of a bridge. A subcritical profile is assumed and the location of the sections is in keeping with the recommendations made in Appendix IV of the HEC-2 users manual (6). Summarizing these cross-sectional locations in relation to the sediment transport process is done as follows:

Section 4 is located upstream of the bridge at the minimum distance where the flow lines are not distorted by the bridge (approximately equal to the

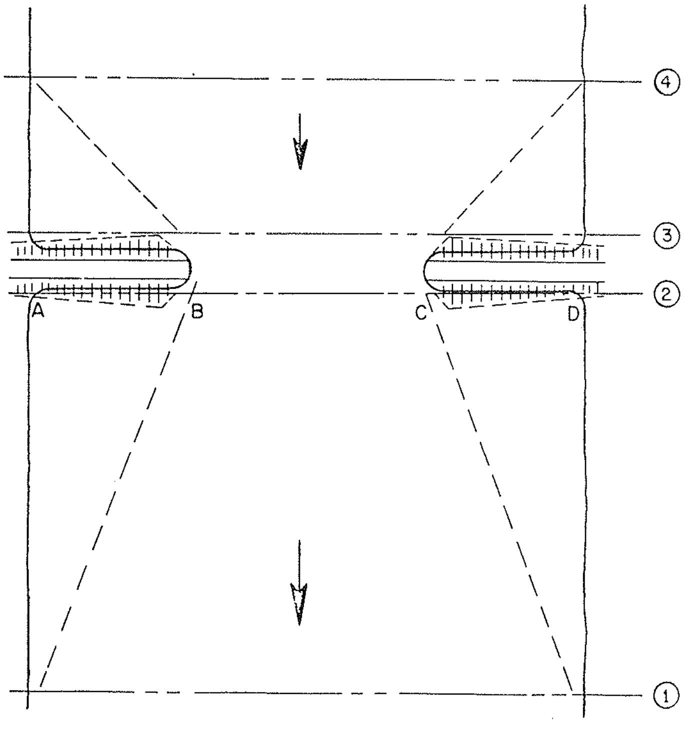

FIGURE 2 Locations of cross sections in the vicinity of bridges.

width of the bridge opening, B-C, or, in the case of wide floodplains with narrow bridge openings, equal to the longer approach, A-B or C-D). The incoming sediment load is conveyed across this section from the upstream reach. This sediment load is derived from upstream watershed and river processes including deposition and scour.

Sections 3 and 2 are located immediately above and below the bridge to represent the effective flow through the bridge. Hydraulic conditions at these points are computed using either the normal bridge method or the more detailed momentum equations of the special bridge method. As a result of these altered hyraulic conditions, the sediment-transport rate is changed as well, leading to scour or deposition as the transport rate adjusts. When the sediment-transport capacity through the bridge waterway is increased, the general scour that occurs is often referred to as contraction scour.

Section 1 is downstream of the bridge at a location where the flow can first be recognized as fully expanded and no longer affected by the bridge (approximately four times the average constriction distance). Sediment-transport capacity will be similar to that of section 4; however, the sediment supply will have been affected by scour or deposition at the bridge constriction.

Two reach definition schemes are used in modeling bridge constrictions using HEC2SR. First, when the flow remains subcritical through the reach (class A flow), it is recommended that all sections be included as one computational reach. The mean hydraulic characteristics of the reach provide a reasonable estimate on which to base sediment-transport capacity. The mean hydraulic characteristics are based on a distance weighting of each parameter and therefore add emphasis to conditions at the bridge site (typically 40 percent or more). Given the uniform nature of the flow under class A conditions, a single reach is adequate to describe sediment-transport characteristics through the bridge.

When the flow passes through critical depth at the bridge (class B flow), hydraulic conditions on each side of the bridge are sufficiently different to warrant a refinement in reach designation. In this case a substantial backwater condition is created upstream of the bridge, followed by a brief supercritical zone, hydraulic jump, and subcritical tailwater. Cross sections 1 and 2 are therefore combined as one reach and cross sections 3 and 4 as another reach. Under class B flow, deposition above the bridge may occur followed by additional scour below the bridge. For a bridge or culvert that substantially constricts the flow, modeling will indicate a sequence of deposition, which may cause plugging and overtopping of the structure, followed by flushing of the deposition during the recession limb of the hydrograph.

Local Scour

For analysis of bed-level changes at a bridge to be complete, several local phenomena that contribute to the total scour at the bridge must also be included. Additional phenomena that can be determined are local scour at piers and sand-wave movement. Solutions of Shen's equation and Neill's equation are generally used to determine scour at piers. Scour at the abutments can also be determined using Liu's equation (1). Kennedy's equation for antidune height is used to determine the effect of sand-wave movement (8). Sand-wave movement contributes to both increased scour and water-surface depth as the sand wave passes through the bridge.

Total scour at a bridge site is therefore the sum of general degradation plus local scour. Low chord elevation will be based on the sum of general aggradation plus the sand-wave height. Low chord elevation should also include consideration of debris passage and superelevation of the water surface.

Other Considerations

River reaches showing large aggradation or degradation adjacent to a bridge reach should be given special consideration. A large profile adjustment will not occur without some effect on channel alignment. HEC2SR provides enough information on profile changes to evaluate their consequences if the nature of fluvial processes is understood. For example, aggradation of a reach with a high sinuosity relative to the river in general may indicate a strong likelihood of channel evulsion, or a reach with a degrading profile may indicate the possibility of significant bank failure. Either condition should alert the designer to the need for other river-training measures to protect the bridge site.

EXAMPLE APPLICATION

The movable-bed characteristics of the Rillito River system were studied extensively by Simons, Li & Associates, Inc. (9), using the HEC2SR sediment-routing procedure. The results for two bridges in this study are presented to illustrate the two different approaches to modeling scour through a bridge crossing.

The first bridge site was located on the Agua Caliente Wash, a tributary of the Rillito River east of Tucson, Arizona. A 6-mile reach of the Agua Caliente was studied assuming existing development conditions would prevail during the 100-year storm event of 10,000 cfs. An existing box culvert (10 ft high, 20 ft wide) at Tanque Verde Road with a capacity of approximately 3,000 cfs was included in this reach. The box culvert was expected to create a significant backwater effect and therefore induce deposition upstream of the culvert. Separate subreaches were used to model the pattern of deposition and scour, with one subreach above the culvert and one below.

Results of the routing analysis show the dynamic process of aggradation and degradation at the site. Figures 3 and 4 show this process over the duration of the 100-year flood hydrograph. The reach above the bridge initially scours. Then, as the hydraulic capacity of the structure is exceeded ($\cong$ 3,000 cfs), a backwater is created that causes significant aggradation. On the recession limb of the hydrograph, scour removes 1.7 ft of sediment. Below the bridge the channel bed responds in the opposite manner with upstream scour causing downstream deposition.

The second bridge site was located on the Rillito River at Alvernon Road within metropolitan Tucson. The reach at Alvernon Road was not constricted by a bridge crossing. The subreach, including the bridge site, was part of an extensive river and watershed system for the Rillito River and Tanque Verde Creek. This system consists of 58 subreaches, three tributaries, and an upstream watershed input. The three major tributaries in the system are Pantano Wash, Sabino Creek, and Agua Caliente Wash. In addition to the tributaries, seven water-discharge nodes were included in the system to account for the variation in discharge due to flood attenuation and floodwater contributions from smaller drainages. Sediment input to the routing procedure occurred at the three tributaries. Upstream sediment supply was assumed to equal the transport capacity of the first upstream subreach.

The results of the sediment routing at the Alvernon Road site show both aggradation and scour

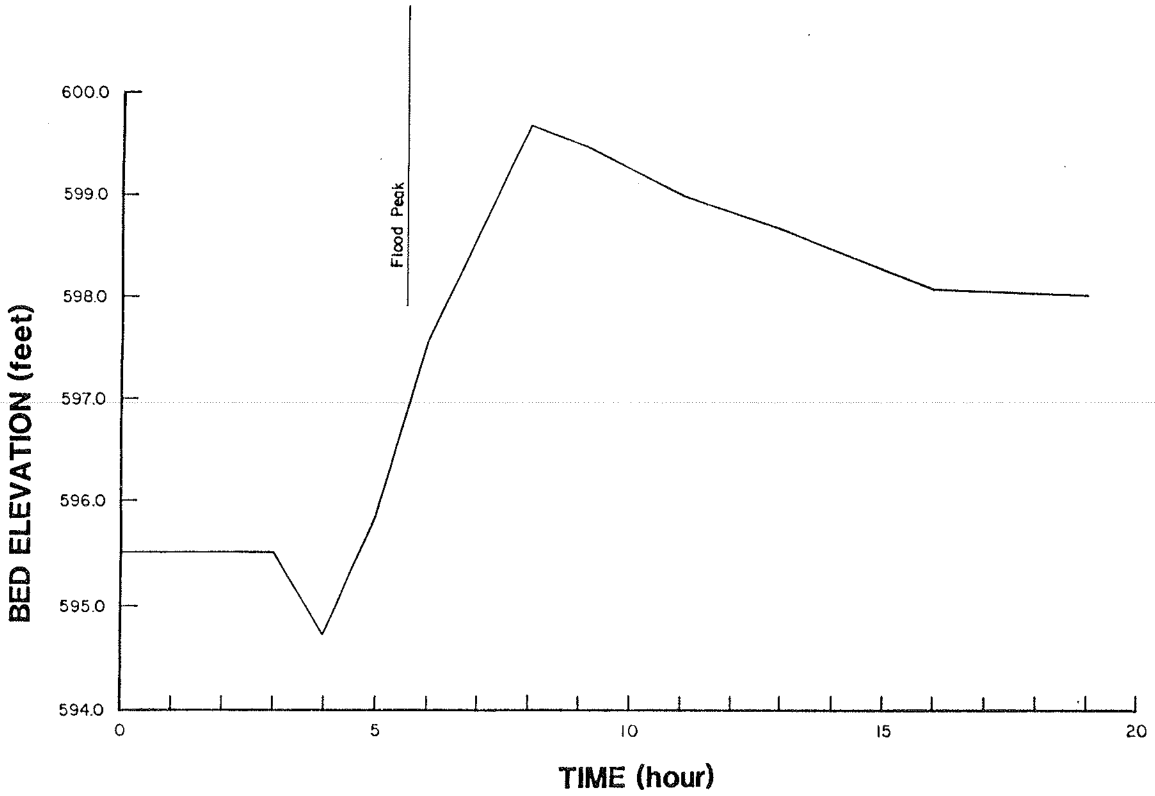

FIGURE 3 Agua Caliente Wash bed-elevation change above Tanque Verde Road, 100-year flood.

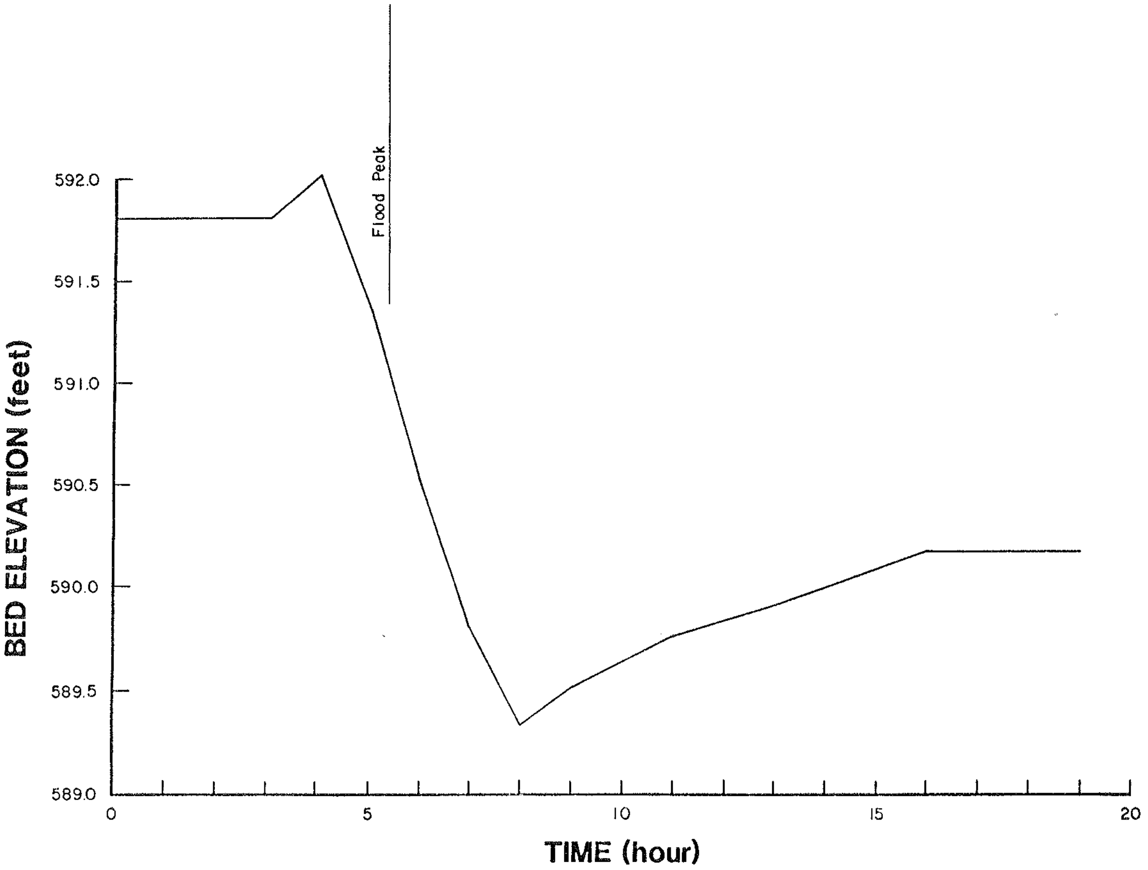

FIGURE 4 Agua Caliente Wash bed-elevation change below Tanque Verde Road, 100-year flood.

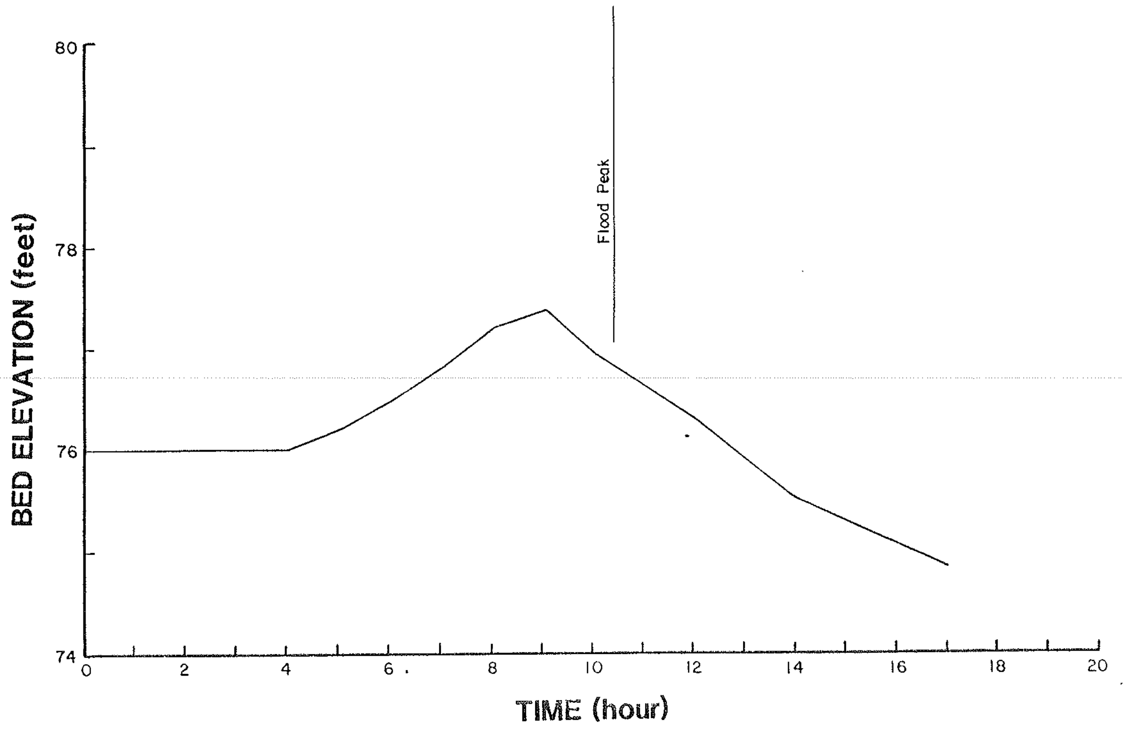

FIGURE 5 Aggradation and degradation of Rillito River at Alvernon Road, 100-year flood.

demonstrating a complex interaction with sediment-transport characteristics in the upper river reaches. Figure 5 shows a period of aggradation on the rising limb of the hydrograph followed by scour during the recession of the flood.

CONCLUSION

HEC2SR provides a useful and complementary addition to a standard water-surface profile analysis using HEC-2. The procedure is essential for analysis of dynamic river reaches where bed-level changes have a significant effect on bridge design. The procedure addresses both general and local scour effects at bridge sites. The analysis also yields important results pertinent to the design of river-training measures used in conjunction with bridge crossings.

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