PROCEEDINGS
OF THE
FOURTH FEDERAL INTERAGENCY
SEDIMENTATION CONFERENCE
MARCH 24-27, 1986
LAS VEGAS, NEVADA
Subcommittee on Sedimentation
Interagency Advisory Committee on Water Data
Agricultural Research Service
Bureau of Land Management
Bureau of Mines
Bureau of Reclamation
Corps of Engineers
Department of Energy
Department of Housing and Urban Development
Environmental Protection Agency
Federal Energy Regulatory Commission
Federal Highway Administration
Forest Service
Geological Survey
National Oceanic and Atmospheric Administration
Office of Surface Mining
Soil Conservation Service
Tennessee Valley Authority

VOLUME I
IN MEMORIAM

Paul C. Benedict, long-time member of the Technical Committee of the Subcommittee on Sedimentation, Interagency Advisory Committee on Water Data, and pioneer in the field of sedimentation in the United States, died on January 23, 1985. Mr. Benedict, who was with the Water Resources Division of the U.S. Geological Survey for almost 55 years, was a recognized authority on fluvial sedimentation and river mechanics. From 1941 to 1945, he conducted research at the University of Iowa's Institute of Hydraulic Research, on fundamental laws governing sediment transport, and on the design of equipment and methods for determining sediment discharge in streams and for measuring fall velocity of sediment particles. The principles established during that research are the basis for much of the current sampling methodology, and they continue to serve as the foundation and standard for today's equipment and methods development.

Mr. Benedict received the Department of Interior Meritorious Service Award in 1960, and the Department's highest award, the Distinguished Service Award in 1973. In addition, he won ASCE's Karl Emil Hilgard Prize in 1976 for participation in the preparation of the ASCE Manual "Sedimentation Engineering," and in 1979, he was honored with the University of Colorado's Distinguished Engineering Alumnus Award.

Beginning with his research in 1941, he served continuously on the Technical Committee of the Subcommittee on Sedimentation, or its equivalent, until his death. During his tenure, he significantly influenced the direction of research and development on methods and equipment used in the measurement and analysis of sediment loads in streams. His foresight, enthusiasm, and dedication will be sorely missed, but his contributions endure.
PREFACE

These proceedings of the Fourth Federal Interagency Sedimentation Conference* contain 102 technical papers which were submitted by representatives of 11 Federal agencies for presentation at the conference. The papers are organized under eight general topics which correspond with the conference symposium topics. These proceedings were prepared in advance of the conference so that this material could be accessible to conference participants during the conference.

The conference is sponsored by the Subcommittee on Sedimentation of the Interagency Advisory Committee on Water Data (IAACWD). The Subcommittee on Sedimentation is an interagency advisory group which, as its main function, fosters coordination of agency activities in the collection, analysis, and interpretation of sedimentation information. This includes the exchange of information on environmental considerations associated with the physical, chemical, and biological aspects of sedimentation, including the identification and mitigation of environmental impacts. The Subcommittee has been a focal point for interagency coordination since its establishment in 1946. Presently, 16 Federal agencies participate on the Subcommittee.

Complex issues and problems involving sedimentation or its effects arise frequently in such areas as water quality, stream stabilization, water resources development and construction. The sedimentation aspects of these types of activities frequently have major economic and environmental significance. Efforts to address these concerns and provide solutions are ongoing in many Federal agencies. Since the Third Federal Interagency Sedimentation Conference in 1976, various agencies have made considerable progress in assembling and applying new knowledge in the sedimentation field. The need to gather and disseminate this information to all government agencies and the private sector led to the planning of the Fourth Federal Interagency Sedimentation Conference by the Subcommittee on Sedimentation.

Initial planning for the conference began in August 1983 with the appointment of a four-member task force to determine the feasibility of holding an interagency conference similar to those held in 1947, 1963, and 1976. The task force reported favorably on the proposal and, in March 1984, the Subcommittee voted to proceed with the conference. A conference chairman was elected by the Subcommittee and four conference committees were established to carry out the necessary arrangements.

* The three previous Federal Interagency Sedimentation Conferences were held in Denver, Colorado, May 6-8, 1947; in Jackson, Mississippi, January 28 - February 1, 1963; and in Denver, Colorado, May 22-25, 1976. Proceedings of the conferences were published by the Bureau of Reclamation, U.S. Department of the Interior, in January 1948, by the Agricultural Research Service, U.S. Department of Agriculture, Miscellaneous Publication No. 970, in June 1965, and by the Water Resources Council in 1976, respectively.
The Subcommittee members who participated in setting up the conference are:

Chairman:

G. Douglas Glysson, U.S. Geological Survey

Planning Committee:

G. Douglas Glysson, U.S. Geological Survey
William F. Mildner, Soil Conservation Service

Publications Committee:

Yung-Huang Kuo, Corps of Engineers
Donald K. Leifeste, U.S. Geological Survey
Daniel S. O'Connor, Federal Highway Administration

Proceedings Committee:

David Farrell, Agricultural Research Service
Robert E. Thronson, Environmental Protection Agency
Waite R. Osterkamp, U.S. Geographical Survey
C. D. Clarke, Soil Conservation Service
Dean Knighton, Forest Service
D. C. Woo, Federal Highway Administration
Shou-Shan Fan, Federal Energy Regulatory Commission

Finance and Registration Committee:

Robert T. Joyce, Tennessee Valley Authority
Roy Rush, Bureau of Reclamation

The Subcommittee acknowledges the administrative support and assistance given by its parent committee, the Interagency Advisory Committee on Water Data, and expresses appreciation to the many individuals who assisted with the conference preparations. Particular thanks go to Robert V. Barton of the Bureau of Reclamation for his assistance with financial, registration and tour arrangements; Cathy Sage of the U.S. Geological Survey for on-site clerical support and spousal tour arrangements; Fay S. Carpenter of the Tennessee Valley Authority and Susan M. Cummings of the Bureau of Reclamation for on-site clerical support; Rachel Algaze of the Agricultural Research Service for secretarial assistance to the planning committee; and Patrick A. Glancy and Charles O. Morgan of the U.S. Geological Survey for tour arrangements.

Special recognition goes to Mr. G. Douglas Glysson, the Conference Chairman, for his major contributions in planning the conference and his capable handling of innumerable arrangements for the conference.
OPENING SESSION

The Conference will be opened by Mr. Roy H. Rush, Chairman, Subcommittee on Sedimentation with a call to order.

A welcome address will be given by Mr. Philip Cohen, Chairman, Interagency Advisory Committee on Water Data.

Mr. Robert N. Broadbent, Assistant Secretary for Water and Science, Department of the Interior, will speak on the subject SEDIMENT, SCIENCE & SOCIETY: MUDDY WATERS FOR PUBLIC POLICY. Concern about sediment, and its role in water development, was once relegated to a small group of specialized engineers and scientists. With increasing concern over the long-term effects of sedimentation on the environment, sediment is rapidly becoming a political issue. He will discuss several research programs of the Department of the Interior aimed at examining the effects of sedimentation on the Grand Canyon ecosystem and the water quality implications of sediment from agricultural drainage water.

Mr. Orville G. Bentley, Assistant Secretary for Science and Education, Department of Agriculture, will speak on the subject AGRICULTURAL STRATEGIES FOR REDUCING SEDIMENTATION. Protection of this Nation's natural resources to ensure the long-term productivity of agriculture, remains one of the highest priority goals of the Department of Agriculture. Research, education, technical assistance to farmers, and the cost sharing of conservation programs are the principal strategies which the Department uses to achieve this goal. Several new and emerging technologies show considerable promise for increasing farmer acceptance of conservation practices and reducing sedimentation and chemical contamination of lakes, streams, and reservoirs.

Mr. Robert K. Dawson, Assistant Secretary for Civil Works, Department of the Army, will discuss the outlook for the Army civil works program, including legislative, financing, and regulatory aspects.

Dr. Dallas L. Peck, Director, Geological Survey, Department of the Interior, will describe the sedimentation related activities of the Geological Survey. He will discuss the Survey's research programs such as the Hazardous Substances in Surface Waters and Sediments and research in volcanic activities as related to sedimentation. The Survey's support of the equipment development work being performed at the Hydrologic Instrumentation Facility and the Federal Interagency Sedimentation Project also will be discussed.
APPLICATION OF HEC-6 TO EPHEMERAL STREAMS

By P. F. Ruff, Professor of Civil Engineering, Arizona State University, Tempe, Arizona; D. W. Dust, Civil Engineer, Doug Toy Engineering, Inc., Phoenix, Arizona and M. T. Bowers, Assistant Professor of Civil Engineering, University of Cincinnati, Cincinnati, Ohio.

ABSTRACT

Three ephemeral streams in Arizona were studied to determine the applicability of computer model HEC-6 to quantify sediment scour and deposition in a stream channel. Two topographic maps, of before and after a flood or series of floods, were used for each stream study. The HEC-6 geometric data, consisting of stream bed elevations, etc., was obtained from the pre-flood(s) map; the hydrologic input data comprised discretized hydrograph(s) of the study period. The geometric output data, of stream bed elevations, etc., was compared with data from the post-flood(s) map. Geometric, sediment and hydrologic data development strategies are discussed. Two supplemental computer programs are presented that greatly facilitate the utilization of HEC-6. The results of the study indicate that HEC-6 can be a useful adjunct for the analysis of scour and deposition in streams when the assumptions of the program are rigorously observed.

INTRODUCTION

HEC-6 is a computer simulation program developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center, to analyze the quantity of scour and deposition in rivers and reservoirs (HEC, 1977). Several other sediment transport computer programs exist and have been used to analyze streams with a wide variation of channel geometry and bed composition (National Research Council, 1983). However, HEC-6 is non-proprietary and, therefore, readily available to the professional engineer. HEC-6 was developed primarily for perennial streams that are characterized by relatively stable banks, well defined main channel, fine sediments and flood flows of fairly long duration. Typically, in the U.S. Southwest, the streams are braided, transport sediments of large size range, and have storm hydrographs of short duration and instantaneous peak discharges.

THEORETICAL AND NUMERICAL BASES OF HEC-6

The program is designed to calculate scour and deposition in rigid-bank channels by simulating steady, gradually-varied water flows and unsteady sediment flow. The principal assumptions in the model are (a) flow is one-dimensional and hydrostatic pressure prevails at all locations in the flow, (b) Manning's n is applicable to gradually-varied flow and can be expressed as a function of water-surface elevation or water discharge, (c) the entire movable-bed part of all cross sections has sediment scoured or deposited at the same uniform rate, and (d) the channel slope is small.

The basic relationships used in the program are the flow-continuity, sediment-continuity and the flow-energy equations; the general structure of HEC-6, consisting of the main program and 29 subroutines, is shown in Figure 1. The program solves the continuity and energy equations, and uses the iterative "standard step method" to calculate the basic hydraulic parameters: velocity, depth, width and slope. These parameters are then employed to calculate "representative hydraulic parameters" using weighting factors. The default values of the weighting factors allow for the "most sensitive" scour and deposition calculations. However, weighting factors can be specified in the program that result in the "most stable" calculations (HEC, 1977).
HEC-6 simulates stream bed armoring by calculating an equilibrium depth (water depth for the condition of no sediment transport) for each grain size and each discharge in the discretized hydrograph. The depth of bed material is then determined that must be removed to attain the equilibrium depth. This depth is very sensitive to the Manning n-values specified for the main channel (DMA, 1983). The depth of sediment between the channel bed surface and the equilibrium depth is the only material subject to scour. The stability of the armor layer is determined by calculating and adjusting the bed surface area exposed to scour.

With representative hydraulic parameters specified, HEC-6 calculates the sediment transport capacity, for each grain size, at the beginning of each time step of the discretized hydrograph by using one of the following relationships that are included in the HEC-6 program: Laursen, Toffaleti, Yang, Duboys, or a special function (HEC, 1977; DMA, 1983). The sediment transport relationships of Colby, Ackers and White, Meyer-Peter and Muller, Schoklitsch, Engelund and Hansen, and Shields were also utilized in the study. Sediment loads are calculated by an iterative technique that determines the number of computational time intervals $\Delta t$ in a time step (T) of the discretized hydrograph. The function of the iterative technique is to minimize computational instability and evaluate the changes in the sediment transport load caused by bed armoring and changes in sediment gradation within a time step. The sediment transport capacity is not adjusted for changes in the hydraulic parameters during a time step, that is, the computer model is "uncoupled." The basis for the simulation of bed changes is the use of an explicit finite-difference scheme to solve the sediment-continuity equation. This solution scheme is only "conditionally stable," that is, with unstable conditions, the numerical errors grow unbounded and result in oscillating values of the channel bed elevation. Therefore, stability tests must be performed during the hydrologic input data development.

**DATA DEVELOPMENT STRATEGIES**

The input data for HEC-6 are of three basic components - geometric, sediment and hydrologic.

Geometric Data. Cross sections of the stream were chosen at locations that define channel geometry transitions and at crossover points in meandering channels. The selection of reach length or distance between cross sections is an important consideration because this distance does influence the computational stability of the sediment transport computations. The HEC-6 program requires that the cross sections are divided into three subsections -
left overbank, channel and right overbank. These subsections, and their corresponding Manning n-values, are used in the backwater computations of the program.

The program also requires that the movable bed boundaries are specified in the input data. These boundaries designate the part of the cross section allowed to move vertically as a result of calculated scour or deposition. In selecting movable bed boundaries, chronological series of aerial photographs and cross section plots are valuable references. The specified elevation of the movable bed bottom designates the vertical dimension of bed material subject to the sediment transport process. Sensitivity tests indicate that if the specified bed elevation is too deep, the computed movable bed volumes (cubic feet) may become large enough to cause execution termination because of word length limitations of the computer system. Tests also indicate that if the specified bed elevation is too shallow. Ineffective flow areas, that is, cross sectional areas below the water surface elevation that are not capable of passing flow, are an important consideration in braided stream problems and must be identified.

The Manning n-value is used in equilibrium depth and head loss calculations. Studies by Dust (1983) and Bowers and Ruff (1983) indicate that bed change calculations are very sensitive to even reasonable discrepancies in selected n-values. Methods for the determination of n-values are given by Chow (1959) and Thomas et al. (1981).

Sediment Data. The requisite information is the initial bed material gradation, inflowing sediment rates to the study reach and armoring data. This data essentially provides the initial conditions and boundary conditions for the sediment gradation and movement parameters. The initial bed material gradation, which may be obtained from sediment frequency curves, influences the sediment transport rates, armoring formation and the stability computations. It is important that representative bed sediment samples are used in developing the data.

The inflowing sediment load at the upstream boundary of the study reach is coded in the input data as a table of sediment discharge for each grain size vs water discharge. Field collected sediment data should be used. However, in the absence of field data, the inflowing sediment load can be generated iteratively with HEC-6. One technique is to run the program with zero inflowing sediment; and then use the computed sediment discharge at the downstream-most section or at a section within the study reach, as the inflowing load at the upstream section. This technique should be iterated until the calculated sediment discharges converge to an equilibrium discharge for each grain size. Then, dummy or duplicate cross sections, adjusted to maintain the existing bed slope, should be added upstream of the study reach to reduce the significance of the errors in the generated inflowing sediment load data. Bowers and Ruff (1983) and Dust (1983) found that only one iteration was required for convergence of the inflowing sediment load when studying rivers in Arizona and California.

To simulate initial bed armoring, the percentage of the movable bed protected by armoring is specified in the input data. However, the influence of the specified initial bed armoring on the calculated bed changes is potentially insignificant because the bed armoring formation and stability calculations are usually performed several times within each time step.
Hydrologic Data. The basic components are the discretized discharge hydrograph, water temperature and downstream rating curve. HEC-6 requires that a continuous discharge hydrograph be coded as a sequence of discrete steady flows with duration in days. As previously indicated, the following parameters can influence the numerical stability of the solution scheme used in HEC-6: flow durations or time steps ($\Delta t$), computed or specified computational time interval ($T$) as determined by iterations of the transport load, distances between cross sections; and the computed sediment transport rates which are a function of: water discharge, specified transport relationship, hydraulic weighting factors, bed gradation, inflowing sediment load and channel geometry. Of these parameters, only the flow durations are essentially arbitrary. The flow duration is, therefore, the parameter adjusted to produce stable HEC-6 calculations. The procedure of estimating the maximum stable computational interval $T_m$ is referenced in Thomas et al. (1981). It is necessary to frequently check the computational stability of HEC-6 calculations because some of the parameters listed above change with time. This check for computational stability is best made with the supplemental computer programs MAXTREND and STAP (Dust, Bowers, Ruff, 1985). The flow durations also govern the significance of the "uncoupled" nature of HEC-6. It is recommended that the time step should be reduced when the calculated bed change at any cross section exceeds one foot or 10% of the water depth within the time step ($T_m$).

The transport capacity relationships, with the possible exception of Larsen, are relatively insensitive to temperature (Vanoni, 1978). This implies, and was verified by sensitivity tests, that HEC-6 computations are not sensitive to the specified water temperatures.

The HEC-6 water surface requirements at the downstream boundary of the study reach can be satisfied by specifying a stage-discharge relationship at the boundary, or assigning a zero water surface elevation at the boundary and allowing HEC-6 to attempt to perform an iterative backwater analysis. If the program is unable to make this analysis, the program defaults to the critical water depth. When the zero water surface elevation is assumed, a rigid bed should be specified for the downstream-most cross section. Several downstream dummy sections should also be incorporated into the data to minimize the influence of the end of the study reach on the computations.

SUPPLEMENTAL PROGRAMS

The computer programs, MAXTREND and STAP, were developed to analyze HEC-6 executions. The algorithms used in the programs are shown in Figures 2 and 3. MAXTREND was used to determine the maximum stable computational time steps or flow durations; and identify flows and corresponding time steps which resulted in computations that violate the criterion of less than one foot of calculated bed change per time step. After the input data sets were calibrated, MAXTREND was used to evaluate the final trends and extreme values in the calculated bed changes.

The objective of STAP was to evaluate the sediment routing aspects of a HEC-6 simulation. With the geometric data for the initial and actual final conditions specified, STAP calculates the change in volume of bed material ($V_a$) and the change in bed elevation ($E_a$) for each reach of the channel. The program also calculates for the initial and HEC-6 calculated final conditions, the change in sediment volume ($V_c$) and bed elevation ($E_c$). The values of the changes are compared by computing, for each channel reach: volume percent
error, \((\text{Va-Vc})/\text{Va} \times 100\); volume change ratio, \((\text{Vc/Va})\), depth percent error, \((\text{Ea-Ec})/\text{Ea} \times 100\); and depth difference \((\text{Ea-Ec})\). The following statistics are then computed: the percent of the channel reaches for which the correct trend is calculated by HEC-6; the percent of the reaches for which the volume change ratio \((\text{Vc/Va})\) is greater than or equal to 0.50 and less than or equal to 2.00; the mean of the percent errors for those reaches with volume change ratios greater than or equal to 0.50 and less than or equal to 2.00; and the mean and standard deviation of the volume change ratio \((\text{Vc/Va})\) and the depth difference \((\text{Ea-Ec})\). As a calibration tool, STAP was used to perform sensitivity tests on various parameters that resulted in the selection of their "appropriate" values. The computed "volume change ratios" and "percent errors" gave a direct quantitative evaluation of the specified sediment transport relationship and, therefore, the "most appropriate" relationship available for the particular HEC-6 study. After the input data set was complete, the computed "volume change ratios" and "percent errors" provided a quantitative evaluation of HEC-6 ability to calculate bed changes.

CASE STUDY #1: RILLITO CREEK

Rillito Creek has a watershed of 950 square miles. It is a typical desert stream that is dry much of each year but can flow at high rates in response to intense thunderstorms. A peak flow of 29,000 cfs occurred in October, 1983. The stream has a well defined, meandering channel configuration with approximately 85 percent of the banks soil cemented or protected by wire gabions. The stream bed material is composed primarily of gravely sand with \(D_{50} = 1.7\) mm and \(D_{90} = 9.5\) mm.
The cross sections of the 2.4 mile study reach were developed from two sets of photo-topographic maps (1982 and 1984) with 2 foot contour line intervals. The movable bed elevation was set at 50 ft below the stream bed. An alternate value of 30 ft was tested, but was found to be too shallow. Photo-topographic maps and field observations showed that Rillito Creek has no ineffective flow areas. Initially, the default or "most sensitive" hydraulic weighting factors were specified in the data set. However, sensitivity tests as evaluated by program STAP, determined that the "most stable" factors improved the correlation of the bed change calculations.

Bed sediment samples were collected at three locations. Analyses indicated that the grain size distributions were similar, and a mean distribution was used. Figure 4. Inflowing sediment load data was not available for Rillito Creek. Therefore, the entire study reach was used to generate sediment data for 3 separate discharge hydrographs of 1,000, 10,000, and 30,000 cfs; and for the following relationships: Laursen, Yang, Ackers and White, Engelund and Hansen, and Shields Table 1 shows the computed sediment data using the Yang relationship and three discharges. From field observations, there was no evidence of bed armoring and, therefore, initial armoring conditions were not specified in the HEC-6 input data.

The discharge histogram for the study was the October 1983 flood that had a duration of approximately 4 days and two peak discharges of 23,000 and 29,000 cfs. Figure 5 (a). The instability of the HEC-6 calculated bed changes, as a function of time, is shown in Figure 5(b)-(f). The stable magnitude of the bed changes is reached when the plot becomes horizontal, i.e., independent of time. The computational stability tests are summarized in Table 2 and Figure 6 for three of the sediment transport relationships. The maximum stable time interval is greatly dependent on the transport relationship.

The water temperature during the October 1983 flood was estimated to be 60°F. No stage-discharge data was available at the downstream boundary of this study. Therefore, the HEC-6 default critical depth option was used to generate the downstream boundary discharge rating curve. Four dummy cross sections were added to the study reach to minimize the significance of the critical depth assumption.

The final HEC-6 simulation for Rillito Creek, shown in Table 3, was evaluated with program STAP for each subreach. The subreach or reach increment is the sum of one-half the distance between the specified cross section and each of the adjacent cross sections.
CASE STUDY #2: AGUA FRIA RIVER

The Agua Fria River is located approximately twenty miles from Phoenix. Flow in the river is controlled by flood gates in Waddell Dam which impounds Lake Pleasant. The drainage area of the irrigation-storage lake is 1460 square miles. The 6.8 mile study reach is braided; and bed armoring with gravels and fine cobbles is evident. Serial photographs show that the banks migrate during flood flows. The surface layer of the bed material is approximately nine inches thick and consists of poorly-graded sands with a maximum of 6% gravel and less than 1% silt and clay. The surface material is underlain by a fairly well-graded sand with 35% gravel and negligible silt and clay. $D_{50} = 2.2$ mm and $D_{90} = 25.0$ mm. Three data sets were generated for the study periods:

<table>
<thead>
<tr>
<th>Transport Relationship</th>
<th>Discharge (cfs)</th>
<th>Maximum Time Interval (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yang</td>
<td>20,000</td>
<td>$0.05$</td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>$0.10$</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>$0.40$</td>
</tr>
<tr>
<td>Engelund and Mennin</td>
<td>20,000</td>
<td>$0.01$</td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>$0.08$</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>$0.40$</td>
</tr>
<tr>
<td>Shields</td>
<td>20,000</td>
<td>$0.002$</td>
</tr>
<tr>
<td></td>
<td>10,000</td>
<td>$0.02$</td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>$0.04$</td>
</tr>
</tbody>
</table>

*Each time interval, $\tau_m$ is composed of 5 equal time steps, i.e., $\tau_m = \Delta t_5$.*
Figure 6. Impact on the HEC-6 calculated bed change stability, for one cross section (22.706) of discharge, sediment transport relation, and the maximum stable time step ($t_m$). Note that the scales are not the same for all figures.

(a) Q = 30,000 cfs
(b) Q = 30,000 cfs
(c) Q = 30,000 cfs
(d) Q = 10,000 cfs
(e) Q = 10,000 cfs
(f) Q = 10,000 cfs

Table 3 (a) Rillito Creek: Actual change in volume and the HEC-6 predicted change in volume for each sub-reach. Yang relationship.

<table>
<thead>
<tr>
<th>X Sect.</th>
<th>Actual Volume Change (Cubic Ft)</th>
<th>Computed Volume Change (Cubic Ft)</th>
<th>% Error in Volume Change</th>
<th>Prediction Error</th>
<th>Cumulative Volume Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.76</td>
<td>6672.81</td>
<td>6672.81</td>
<td>0.00</td>
<td>0.00</td>
<td>6672.81</td>
</tr>
<tr>
<td>22.12</td>
<td>2093.20</td>
<td>2093.20</td>
<td>0.00</td>
<td>0.00</td>
<td>2093.20</td>
</tr>
<tr>
<td>22.40</td>
<td>1311.04</td>
<td>1311.04</td>
<td>0.00</td>
<td>0.00</td>
<td>1311.04</td>
</tr>
<tr>
<td>24.36</td>
<td>800.15</td>
<td>800.15</td>
<td>0.00</td>
<td>0.00</td>
<td>800.15</td>
</tr>
<tr>
<td>24.90</td>
<td>23294.17</td>
<td>23294.17</td>
<td>0.00</td>
<td>0.00</td>
<td>23294.17</td>
</tr>
<tr>
<td>24.76</td>
<td>255890.00</td>
<td>255890.00</td>
<td>0.00</td>
<td>0.00</td>
<td>255890.00</td>
</tr>
<tr>
<td>26.00</td>
<td>357624.00</td>
<td>357624.00</td>
<td>0.00</td>
<td>0.00</td>
<td>357624.00</td>
</tr>
<tr>
<td>26.82</td>
<td>537966.00</td>
<td>537966.00</td>
<td>0.00</td>
<td>0.00</td>
<td>537966.00</td>
</tr>
<tr>
<td>27.72</td>
<td>678656.00</td>
<td>678656.00</td>
<td>0.00</td>
<td>0.00</td>
<td>678656.00</td>
</tr>
<tr>
<td>28.64</td>
<td>448126.00</td>
<td>448126.00</td>
<td>0.00</td>
<td>0.00</td>
<td>448126.00</td>
</tr>
<tr>
<td>29.24</td>
<td>673282.00</td>
<td>673282.00</td>
<td>0.00</td>
<td>0.00</td>
<td>673282.00</td>
</tr>
<tr>
<td>30.36</td>
<td>105416.00</td>
<td>105416.00</td>
<td>0.00</td>
<td>0.00</td>
<td>105416.00</td>
</tr>
<tr>
<td>30.88</td>
<td>-98816.00</td>
<td>-98816.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-98816.00</td>
</tr>
<tr>
<td>31.46</td>
<td>197712.00</td>
<td>197712.00</td>
<td>0.00</td>
<td>0.00</td>
<td>197712.00</td>
</tr>
<tr>
<td>31.96</td>
<td>-180866.00</td>
<td>-180866.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-180866.00</td>
</tr>
<tr>
<td>32.44</td>
<td>-286200.00</td>
<td>-286200.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-286200.00</td>
</tr>
<tr>
<td>32.84</td>
<td>-16830.00</td>
<td>-16830.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-16830.00</td>
</tr>
<tr>
<td>33.50</td>
<td>41904.00</td>
<td>41904.00</td>
<td>0.00</td>
<td>0.00</td>
<td>41904.00</td>
</tr>
</tbody>
</table>

Table 3 (b) Rillito Creek: Actual change in bed elevation and the HEC-6 calculated change in bed elevation. Yang relationship.

<table>
<thead>
<tr>
<th>X Sect.</th>
<th>Actual Depth Change (ft)</th>
<th>Predicted Depth Change (ft)</th>
<th>% Error in Depth Change</th>
<th>Predicted Error</th>
<th>Cumulative Depth Change (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.76</td>
<td>-2.21</td>
<td>-2.21</td>
<td>0.00</td>
<td>0.00</td>
<td>-2.21</td>
</tr>
<tr>
<td>22.12</td>
<td>-0.76</td>
<td>-0.76</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.76</td>
</tr>
<tr>
<td>22.40</td>
<td>0.67</td>
<td>0.67</td>
<td>0.00</td>
<td>0.00</td>
<td>0.67</td>
</tr>
<tr>
<td>24.36</td>
<td>0.33</td>
<td>0.33</td>
<td>0.00</td>
<td>0.00</td>
<td>0.33</td>
</tr>
<tr>
<td>24.90</td>
<td>1.03</td>
<td>1.03</td>
<td>0.00</td>
<td>0.00</td>
<td>1.03</td>
</tr>
<tr>
<td>24.76</td>
<td>1.28</td>
<td>1.28</td>
<td>0.00</td>
<td>0.00</td>
<td>1.28</td>
</tr>
<tr>
<td>26.00</td>
<td>0.86</td>
<td>0.86</td>
<td>0.00</td>
<td>0.00</td>
<td>0.86</td>
</tr>
<tr>
<td>26.82</td>
<td>0.66</td>
<td>0.66</td>
<td>0.00</td>
<td>0.00</td>
<td>0.66</td>
</tr>
<tr>
<td>27.72</td>
<td>0.76</td>
<td>0.76</td>
<td>0.00</td>
<td>0.00</td>
<td>0.76</td>
</tr>
<tr>
<td>28.64</td>
<td>0.20</td>
<td>0.20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.20</td>
</tr>
<tr>
<td>29.24</td>
<td>0.27</td>
<td>0.27</td>
<td>0.00</td>
<td>0.00</td>
<td>0.27</td>
</tr>
<tr>
<td>30.36</td>
<td>-0.35</td>
<td>-0.35</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.35</td>
</tr>
<tr>
<td>30.88</td>
<td>-0.55</td>
<td>-0.55</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.55</td>
</tr>
<tr>
<td>31.46</td>
<td>0.15</td>
<td>0.15</td>
<td>0.00</td>
<td>0.00</td>
<td>0.15</td>
</tr>
<tr>
<td>31.96</td>
<td>-0.37</td>
<td>-0.37</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.37</td>
</tr>
<tr>
<td>32.44</td>
<td>-0.71</td>
<td>-0.71</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.71</td>
</tr>
<tr>
<td>32.84</td>
<td>-0.97</td>
<td>-0.97</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.97</td>
</tr>
<tr>
<td>33.50</td>
<td>0.29</td>
<td>0.29</td>
<td>0.00</td>
<td>0.00</td>
<td>0.29</td>
</tr>
</tbody>
</table>

The percentage of the reach increments where Depth-Difference (DF) is:

- $|DF| < 0.1$: 84.45%
- $|DF| < 0.3$: 94.45%
- $|DF| < 0.5$: 94.45%
- $|DF| < 0.7$: 94.45%
- $|DF| < 0.9$: 94.45%
- $|DF| < 1.0$: 94.45%

The statistics of Depth-Difference are as follows:

- Mean = -0.0000
- Standard Dev. = 0.0000
- Median = 0.0000
- Mode = 0.0000
- Range = 2.00
- Skewness = 0.00
- Kurtosis = 0.00

The percentage of the reach increments where Volume Change Ratio (VCR) is:

- $|VCR| < 0.1$: 84.45%
- $|VCR| < 0.3$: 94.45%
- $|VCR| < 0.5$: 94.45%
- $|VCR| < 0.7$: 94.45%
- $|VCR| < 0.9$: 94.45%
- $|VCR| < 1.0$: 94.45%

The statistics of Volume Change Ratio are as follows:

- Mean = 0.2753
- Standard Dev. = 1.1959
- Median = 0.2753
- Mode = 0.2753
- Range = 2.00
- Skewness = 0.00
- Kurtosis = 0.00

NOTE: negative volume changes indicate scour. The percentage of the reach increments where "Volume Change Ratio (VCR)" is:

- $|VCR| < 0.1$: 84.45%
- $|VCR| < 0.3$: 94.45%
- $|VCR| < 0.5$: 94.45%
- $|VCR| < 0.7$: 94.45%
- $|VCR| < 0.9$: 94.45%
- $|VCR| < 1.0$: 94.45%

Statistics of "Volume Change Ratio": Mean = 0.2753
- Standard Dev. = 1.1959
- Median = 0.2753
- Mode = 0.2753
- Range = 2.00
- Skewness = 0.00
- Kurtosis = 0.00
1964 to 1979: 3 flood flows with a total duration of 10 days; 
Q = 2,000 to 57,000 cfs.

1979 to 1983: 1 flood flow with a duration of 8 days; 
Q = 900 to 65,000 cfs.

1964 to 1983: 4 flood flows with a duration of 18 days; 
Q = 900 to 65,000 cfs.

A partial presentation of the results is shown in Table 4 for the 1979 to 1983 study period. This period has the most accurate geometric data.

CASE STUDY #3: SALT RIVER

The Salt River flows through metropolitan Phoenix, where the channel is usually dry. River flows are controlled by a series of dams with a watershed of more than 6,000 square miles. The 2.0 mile study reach channel is slightly braided and with overbanks occupied by industry, agriculture and housing developments. The upper 1.5 to 2.0 feet of the river bed material is composed primarily of sandy gravel and well rounded cobbles with a maximum particle diameter of 3 inches. However, there are locations where the surface material consists of fine to medium sand. A well developed armor layer exists throughout most of the channel with material sizes of 6 to 9 inches. D50 = 39.0 mm and D90 = 240.0 mm.

The 1977 to 1983 study period experienced 4 major flood flows of 82,000, 100,000, 79,000, and 118,000 cfs; with a total duration of 181 days. Computational stability tests were made for 10,000, 25,000, 75,000, 100,000 and 125,000 cfs.

A partial presentation of the results is shown in Table 5.

RESULTS

A summary of the analyses to determine the applicability of HEC-6 to quantify sediment transport in ephemeral stream channels is presented in Table 6. The results of the study unquestionably demonstrate that the assumptions, upon which HEC-6 was devised, must be rigorously observed, namely, well defined stream channel with stable banks, maximum bed material diameter less than 64 mm; and the discretized flood hydrographs has segments of fairly long,
constant duration. The Rillito Creek study most closely adhered to the HEC-6 assumptions and gave the most satisfactory prediction of sediment transport quantities.

The inability of HEC-6 to simulate the movement of bed material in the Salt River, with sediments greater than 64 mm diameter, is primarily due to the numerical techniques used in the equilibrium depth and armor formation/stability part of the program. The inferior results of the Agua Fria River study are, to a large degree, due to the inaccuracies in defining the geometric boundaries of the channel.

**ACKNOWLEDGEMENTS**

The investigation was sponsored by the Arizona Department of Transportation Research Center, Arizona Department of Transportation.

**REFERENCES**


DMA Civil Engineers and Geologists, "Review and Analysis of HEC-6: Scour and Deposition in Rivers and Reservoirs." Hydrologic Engineering Center, USACE, Davis, California, January 1983.


