HEC-6 模式應用於河川冲刷能力之探討

On the Capability of the Hec-6 Program to Calculate River Scour

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摘　　要

HEC-6，河川與水庫冲淤模式 (Scour and Deposition in Rivers and Reservoirs, HEC-6) 爲美國陸軍工程兵團 (US Corps of Engineers) 所發展出的一種洪流與沉滓演算之數學模式，自 1976 出版以來，曾受到廣大的重視與應用。天然含滓 (Sediment-laden) 河川，由於輸砂不均勻，底床往往發生冲刷 (Scour) 或淤積 (Deposition) 現象，造成河床的不規則變化。一般工程設計，如以定床 (Fixed Bed) 模擬，有時不合實際，而必須考慮動床 (Movable Bed) 模式之應用。本短文主旨在介紹應用 HEC-6 做洪水與沉滓演算 (Water and Sediment Routing) 時，所需特別注意的原則，俾能"正確"地使用此數學模式。文中並舉二條河川爲例，以數值輸入 HEC-6 模式，比較其輸出結果之合理性。唯有更了解 HEC-6 本身之限制性及其適用性，才能更正確地掌握像 HEC-6 這種一般用途 (General-Purpose) 的大電腦模式於不敗之地。文內並提供給初學者的一些經驗或用 HEC-6 可能遭遇的困惑，及其應該修正的方向。

Introduction

The HEC-6 program, "Scour and Deposition in Rivers and Reservoirs" (Ref. 1), developed by the US Corps of Engineers was adopted to simulate the general scour evaluation for the river crossings. This report addressed the validations and limitations of HEC-6 to perform the scour or deposition simulation in natural streams.

Sediment transport in natural rivers is a very complex process, and general scour estimation within natural streams is heavily dependent upon engineering judgement and empiricism. The basic difficulty lies in the complete comprehension of the mechanics of sediment transport in natural channels. Nevertheless, mathematical models for the estimation of scour and deposition in rivers and reservoirs, such as HEC-6, have recently been developed and applied, with some degree of success, to numerous rivers throughout the North America.

Since its 1976 publication, HEC-6 was calibrated for river and reservoir scour and deposition by using both laboratory and field data. Examples and locations of its applica-

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tion include: Red River, Louisiana (Ref. 2); Fort Randall Reservoir on the Missouri River (Ref. 3); Ozark Reservoir on the Arkansas River (Ref. 3); Barber Reservoir on the Boise River, Idaho (Ref. 3); Clearwater River, Snake River and Lower Granite Reservoir, Idaho (Ref. 4); and Cottonwood Creek, Sacramento River, California (Ref. 5).

Background

Despite the reported success of HEC-6 to model scour and deposition of rivers and reservoirs (reservoir deposition estimated being the most successful of the two), application of the HEC-6 model was not found feasible to estimate scour computation on all river crossing projects. The main reasons are explained as follows:

1. Numerical Stability – The program has to satisfy the continuity of sediment material, that is, the Exner Equation. Since an explicit first-order finite difference scheme was used to advance the time domain, the computation-time interval, Δt, had to satisfy the Courant-Friedrichs-Lewy condition,

$$\Delta t \leqslant \left| \frac{(1-p)B(1-F^2)\,\Delta X}{-\dfrac{\partial G}{\partial h}} \right| \tag{1}$$

   where Δx is the reach length, G is the sediment transport capacity, B is the erodible width of channel, p is the porosity, F is the Froude number, and h is the water depth. Based on the available data, numerical stability required that the time interval be of the order of 10 minutes for small creeks, and 100 minutes for large rivers. Under these stability criteria, and for short reaches and readily erodible channels, the model became extremely expensive to operate. Violation of this stability would result in the oscillation of the computational results.

2. Armor Layer – In HEC-6, the scour depth is directly dependent upon two parameters; elevation of the model bed and elevation of the equilibrium depth. (as defined in the following section). The depth of bed material which must be removed to scour to equilibrium is determined by the following criteria: (a) If the elevation of the equilibrium depth is greater than the elevation of model bed, the depth of scour to equilibrium is equal to the difference between the elevation of the existing channel bed and the elevation of equilibrium depth. (b) If the elevation of the model bed is higher than the elevation of equilibrium depth, the depth of scour to equilibrium is equal to the difference between the elevation of the existing channel bed and the elevation of the model bed. In this case, the depth of armor layer is equal to the depth of scour to equilibrium, since when all material is removed from that layer, the channel bottom is completely armored and no more scour is allowed. A predetermined value of the elevation of model bed thus becomes crucial to the computation of scour depth in HEC-6, since the program will prohibit bed scour below this elevation if the elevation of the equilibrium depth is lower than the elevation of the model bed. This situation occurred in the cases of highly potential scouring rivers with high discharges and fine sand bed materials. To circumvent the uncertainty of the elevation of the model bed, HEC-6 sets a default of 10-feet to armor layer.

(That is, the elevation of the model bed is equal to the thalweg elevation minus 10-feet). However, in some rivers, by varying the depth of armor layer, maximum scour depths of from 0 to 120 feet were observed. It may thus be concluded that scour depth is not unique and must depend on data verification and sound engineering judgement.

3. Equilibrium Depth – The equilibrium depth is defined as the minimum water depth required for a particular grain size to be immobile on the bed surface, and is obtained by combining the Manning, Stricker, and Einstein equations, resulting in the equation:

$$D_e = \left\{ \frac{q}{10.21 d^{1/3}} \right\}^{6/7} \qquad (2)$$

where q is the water discharge per unit width, and d the grain diameter. In HEC-6, q is obtained from the total discharge, without distinguishing between main channel and overbank flows. As such there may be no problem when rivers are under bank-full flows, but validity questions arise when overbank flows occur. This problem was encountered in all types of streams, including single, split, meandering and braided channels. In most rivers under the Project Design Flood (PDF) condition, overbank flows were common, and as such and overestimation of the equilibrium depth was inevitable.

4. Transport Capacity – Three options for calculating sediment transport capacity for non-cohesive material were available: (a) Toffaleti's modification of Einstein's bed load function, (b) Laursen's relationship as modified by Madden for large rivers, and (c) a functional relationship between transport capacity and the depth-slope product. (More precisely, there were five options in total, the other two were (d) DeBoy's method, and (e) Yang's stream power method).

   It was believed that the Toffaleti's and Laursen's methods might be acceptable for the sand bed channels ($d < 2mm$), but not suitable for the gravel bed channels ($2 < d < 64mm$). As pointed out by Prasuhn and Sing (Ref. 5), the most recommended Toffaleti's transport method was found to greatly underestimate gravel movement, when Cottonwood Creek and the Sacramento River were tested. Therefore they recommended the Schoklitsch's bedload function (Ref. 6). As far as gravel transport was concerned, the Meyer-Peter and Mueller method (Ref. 7) seemed the most reliable approach.

   The selection of an appropriate transport capacity function is an important step in scour and deposition modeling. The confidence of the simulated results may only be justified by the data verification procedure.

5. Data Requirements – To run the HEC-6 program, three data categories are needed. They were geometric, sediment and hydrologic data. As emphasized before, calibration is imperative to assess the validity of the model before scour prediction may be made. In most river crossing projects, only very limited sediment and hydrologic data are available, and due to the generally inadequate, or the complete lack of data, successful calibration could not be conducted.

Tested Examples

Two alluvial streams were initially chosen to assess the performance of the HEC-6 program for the scour computation. The first one is a small creek (Hereafter will be named The Creek) with fine sand bed material. The second one is a large river (Hereafter will be named The River) also with fine sand bed material.

The Creek

The only available data for the Creek were the geometric characteristics of the channel and the bed material gradation. Hydrologic data were taken from the derived PDF hydrograph, and the sediment transport-discharge rating curve was estimated by using Colby's method (Ref. 8). There were no observed data to calibrate the model, hence HEC-6 was used directly to predict the scour and deposition processes without model verification. The Creek consists of a sand bed with d_{50} equal to 0.09 mm. Backwater computations for the PDF indicated that overbank flow occurred at all locations within the study reach. Figure 1 gives the bed material gradation curve, and Figure 2 the hypothetical PDF hydrograph. Channel cross-sectional data were taken from the HEC-2 format (Ref. 9), and transferred into the HEC-6 program. The results of simulation indicated that when the armor layer was limited to 10-feet, it took less than three days for the Creek to scour to 8.94 feet for the most critical section. However, when the armor layer was set equal to 20-feet, the most critical section of the Creek scoured to 17.88 feet within three days. The results indicate that without data calibration, scour depth estimation is directly dependent upon determination of the armor layer.

The River

The scour and deposition of the River using HEC-6 was carried out similarly. Measured water surface profiles and the sediment load rating curve were used for the model calibration.

Figure 3 shows the comparison of the measured and simulated water surface profile for the study reach using the observed discharges. The calibrated Manning coefficient was then used in the HEC-6 program. The bed material gradation is given in Figure 4, and the hypothetical PDF hydrograph together with the corresponding water temperatures given in Figure 5. Figure 6 gives the observed sediment rating curve. These geometric, sediment and hydrologic parameters were inputed into HEC-6 to test scour and deposition of the River. As indicated in Figure 6, good correlation was obtained between measured and simulated sediment transport-discharge relationship. The sediment load rating curve was obtained from the available data at the observed gaging station. Checking of correct sediment capacity for the corresponding water discharges was necessary to assure the quality of the computed scour depth. The HEC-6 predicted a net of 7 feet scour at the most critical section during the PDF event.

Conclusions and Recommendations

Two alluvial rivers were selected to test the feasibility of using HEC-6 to evaluate the scour depth. A comparison of some of the hydraulic parameters computed are given in Table 1. It may be shown from the Exner equation that, under the same sediment transport values, the rate of scour or deposition for the River was almost 65 times slower than that of the Creek. In reality, sediment transport of the Creek is far greater than that of the River, whereas it took only 3 days for the Creek to reach the specified scour depths. The scour duration of the River could last for 22 days. The high scour potential of the Creek is due to the small width of deposit, the short channel reach, high velocity, and fine bed material.

A striking difference between the two rivers lies in the fact that the River had the observed data to calibrate the model, while there were no data available to verify the Creek. This makes the estimation of scour depth of the Creek very difficult.

Caution must be taken in choosing the methodology of the sediment transport capacity. The existing options for calculating sediment transport capacity for non-cohesive material in the HEC-6 model were tested on sand bed channels. As far as gravel bed streams are concerned, some modification was recommended. Also calibration procedures to verify the simulated results are necessary to obtain a viable routing model.

In general, the model may be applicable to medium and low flow streams where scour potential is low, such as in the modeling of sediment deposition in reservoirs (see Ref. 2 to 4). In the other rivers, including the gravel bed channels, the HEC-6 model was not found satisfactory for degradation or aggradation computation.

Table 1: Comparison of the Hydraulic Characteristics of the Creek and the River computed from the HEC-6 model.

	Mean deposit width (ft)	Mean reach length (ft)	Max flow velocity (ft/sec)	Computation time interval (sec)
The Creek	187	763	11.7	600
The River	1,594	5,766	9.6	6,000

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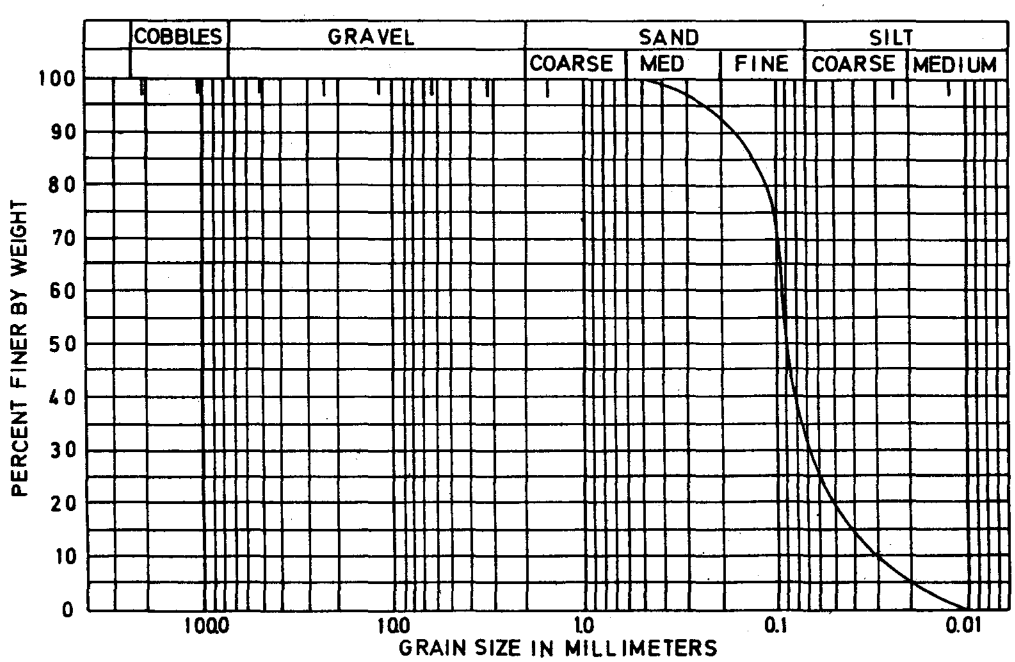

FIGURE 1 BED MATERIAL GRADATION CURVE FOR THE CREEK

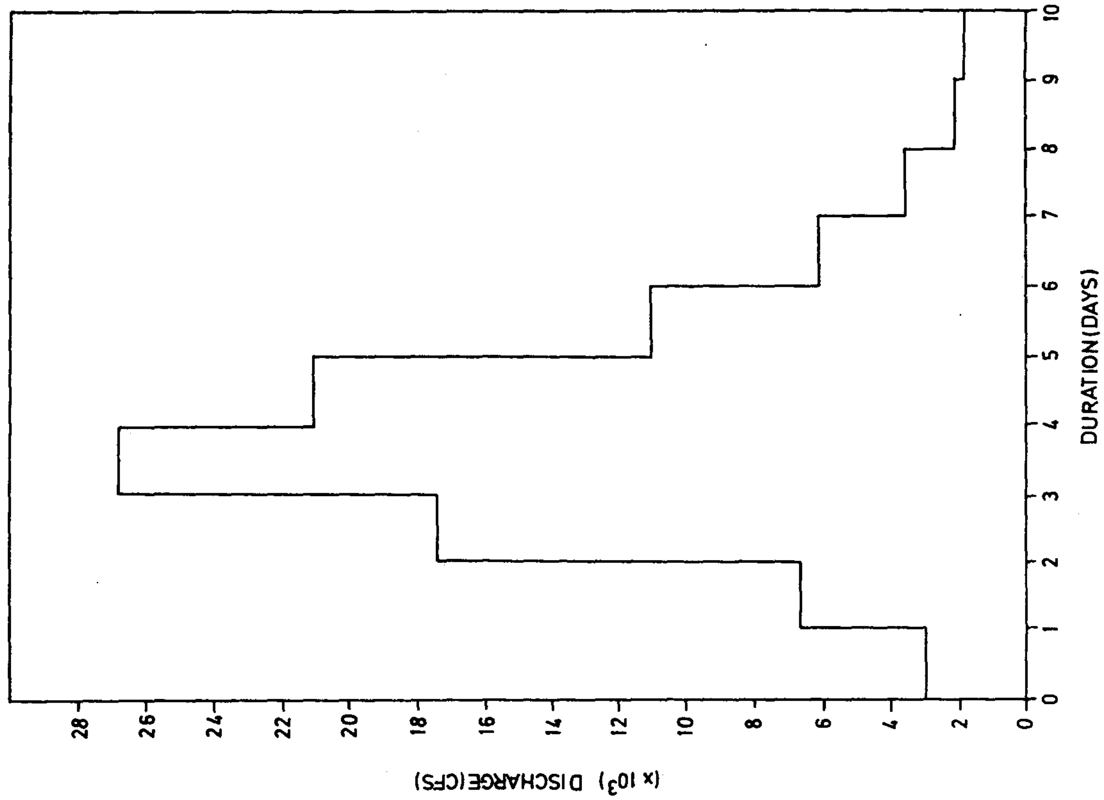

FIGURE 2 HYPOTHETICAL PDF HYDROGRAPH FOR THE CREEK

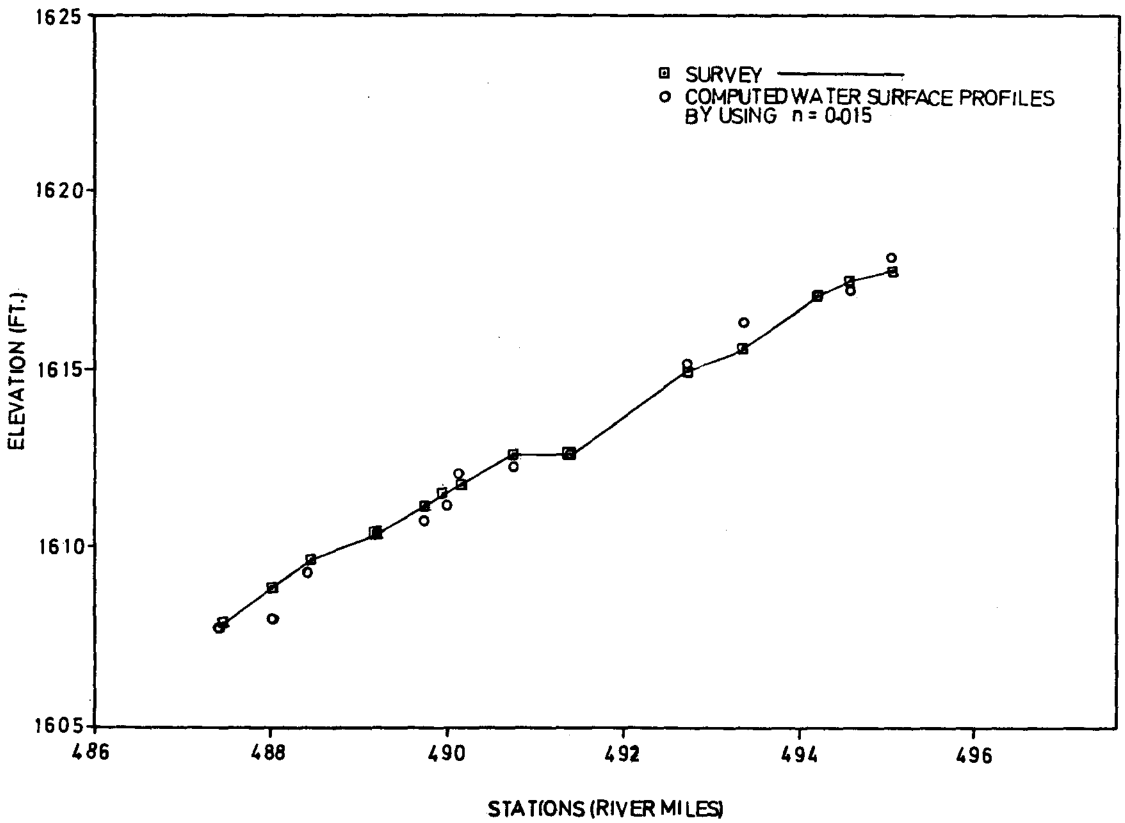

FIGURE 3 COMPARISON OF COMPUTED AND OBSERVED WATER SURFACE PROFILES FOR THE RIVER

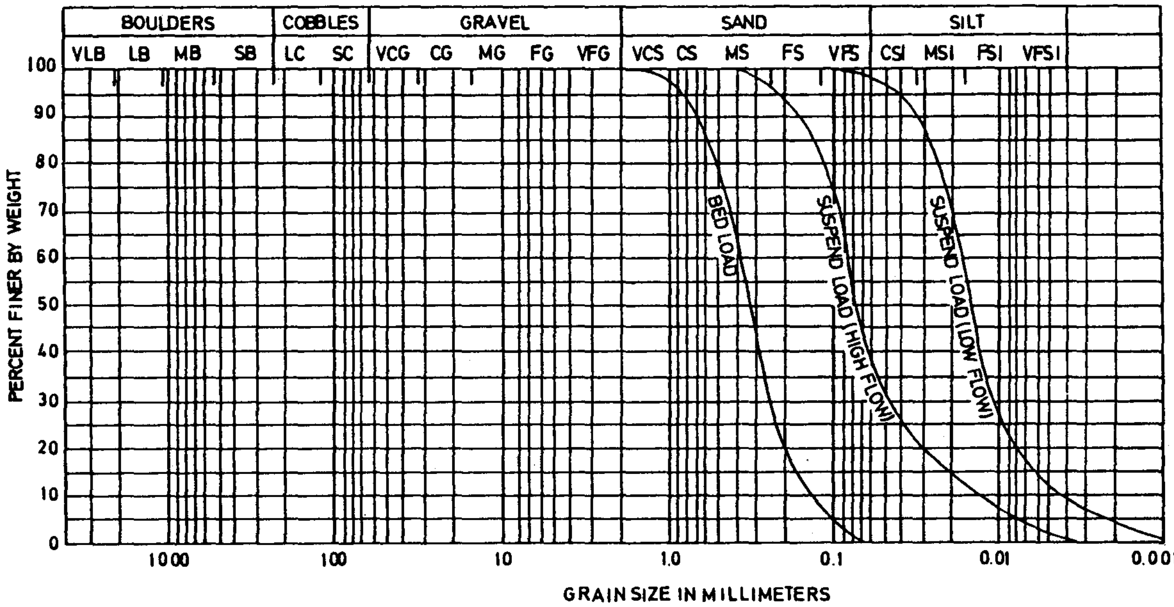

FIGURE 4 BED MATERIAL GRADATION CURVE FOR THE RIVER

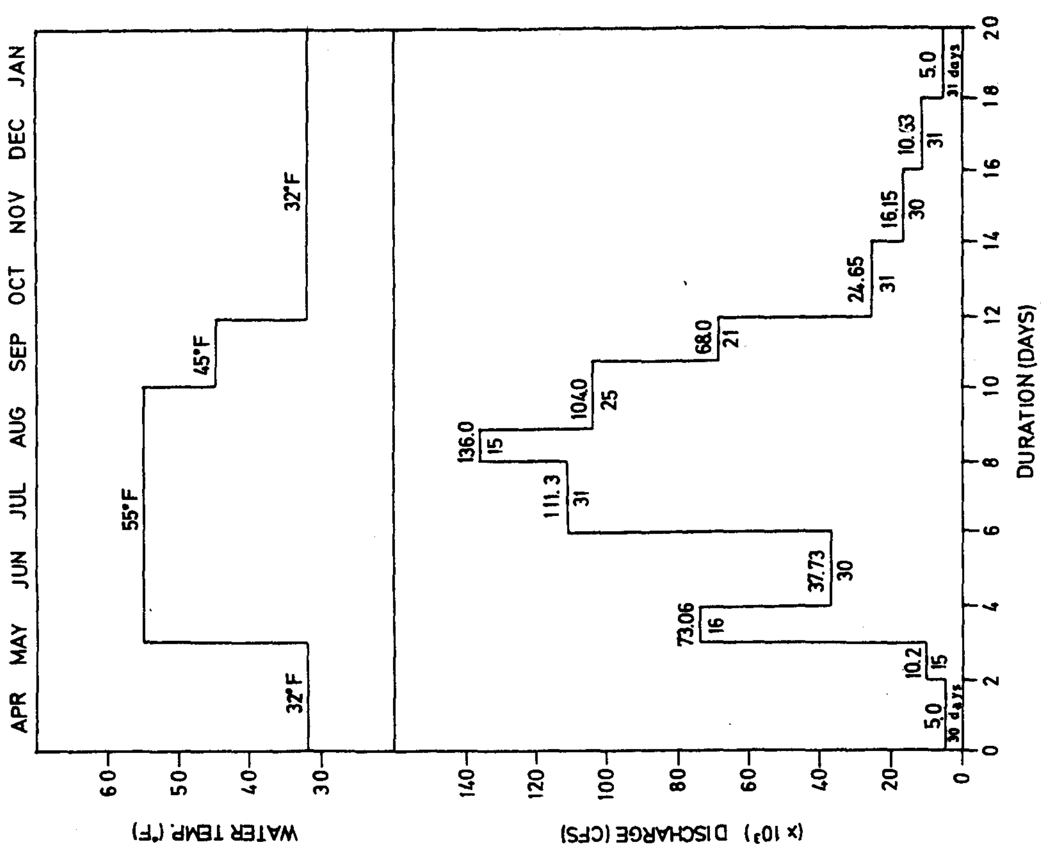

FIGURE 5 HYPOTHETICAL PDF HYDROGRAPH FOR THE RIVER

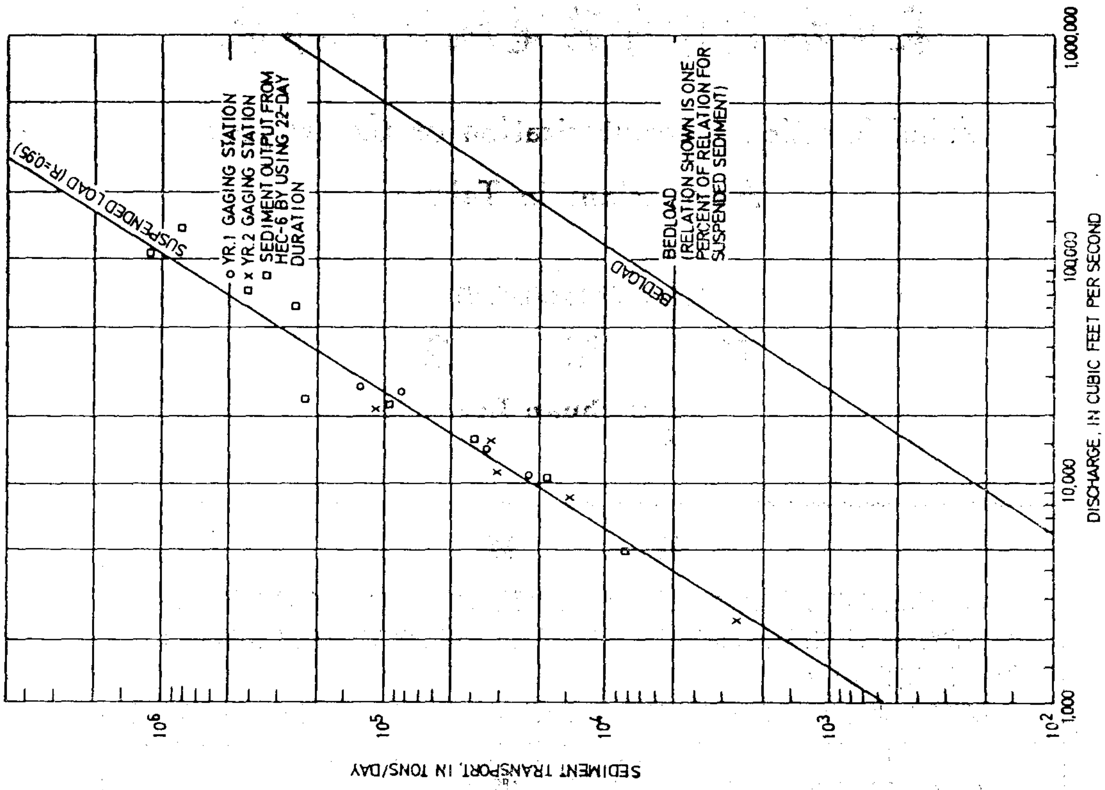

FIGURE 6 COMPARISON OF COMPUTED AND OBSERVED BED MATERIAL TRANSPORT FOR THE RIVER