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Methods of estimating bed load transport rates applied to ephemeral streams

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Abstract Bed load transport rates were calculated with different methods and measured in 37 straight ephemeral channels varying in width, slope, surface roughness, and flood flow characteristics. The methods of Diplas (1987), Samaga *et al.* (1986), Misri *et al.* (1984), and Proffitt & Sutherland (1983) are considered. None of the methods were satisfactory although the first methods proved relatively the best for the investigated channels. To improve the applicability of these methods in ephemeral channels, a modification which considers the effect of unsteady flow during flash floods is introduced. The modified methods produced satisfactory results in most of the investigated channels.

Application des méthodes de calcul des moyennes de transport de fond dans les cours d'eau intermittents

Résumé Le calcul des moyennes de charriage de fond a été fait utilisant différentes méthodes et leurs mesures ont été faites sur 37 lits de cours d'eau temporaires rectilignes et différents quant à la largeur, l'inclinaison et la rugosité des surfaces ainsi que les caractéristique de écoulement de crue. Les méthodes de Diplas (1987), Samaga *et al.* (1986), Misri *et al.* (1984), et Proffitt & Sutherland (1983) ont été prises en considération. Il été constaté ainsi, que tous les moyens utilisés n'ont abouti à aucun resúltat acceptable. Les deux premieres méthodes ont abouti à un meilleur résultat quant à leurs applications sur les lits étudies. Pour une meilleure application de ces procédés sur les lits de cours d'eau temporaires on a procédé à une modification de ces procédés en tenant compte de la variabilité très grande du débit pendant les crues violentes. Cette dernière modification a contribué à donner des résultats acceptables pour la plupart des cours d'eau étudiés.

INTRODUCTION

Ephemeral streams differ from perennial streams. They are generally characterized by steep slopes and high sediment transport rates (Nouh, 1988a). The flow of these streams is unsteady and nonuniform. Their

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hydrographs are characterized by a steep rise and a rapid recession. Due phenomena to the high variability of flow conditions during a flash flood, the sediment transported with the flow is nonuniform, and covers a wide range of size and standard deviation. Boulders, cobbles, gravel, sand and silt occur in a mixture that is normally transported as suspended load or as bed load (Nouh & Jamjoon, 1981). The amount of sediment transported in suspension during a flash flood hydrograph is normally larger than that transported as bed load during the flood, and both amounts follow the rise-recession pattern of the hydrograph (Nouh, 1988b).

Although there are several methods suitable for the computation of sediment transport rates under steady flow conditions, it must be emphasized that there is a lack of information concerning suitable methods for computing transport rates of nonuniform sediments under unsteady flow condition as occur in ephemeral channels. Methods developed to compute sediment transport rates at steady flow conditions generally underestimate the sediment rates transported at unsteady flow conditions (Graf & Suska, 1985). Recently, Nouh (1988a) used field measurements to develop a procedure for the computation of transport rates of nonuniform suspended sediments in ephemeral channels.

This paper is concerned with the transport rates of nonuniform bed load in ephemeral streams. Its main objectives have been to examine the applicability to ephemeral channels of some methods developed for the computation of bed load transport rates of nonuniform sediments, and to develop a procedure suitable for the computation of such rates in these channels. Field measurements of flow and sediment transport in a number of ephemeral channels located in the southwest region of Saudi Arabia were used to achieve these objectives. A brief description of the study region, the measurements techniques, and the methods of computation is given in the following.

THE STUDY REGION

The study region is a typical arid area of the world. Its channels are characterized by steep slopes (0.0005–0.0069) and carry water only during storms. The dry period between two successive storms varies from 14 days to five months. Flood flow hydrographs in these channels are due to short duration-high intensity-rainstorm events. They are characterized by a steep rise and a rapid recession. Field observations indicate that it takes about 25 min, on average, to reach a flow of 100 m^3s^{-1}. The region is subject to climatic conditions evidencing high fluctuations in temperature, low diurnal humidity, and violent solar action which causes chemical changes in the region's soils, frequently resulting in disintegration of soils. These climatic conditions furnish the violent rainfall and torrents with large amounts of sediment to carry downstream. For more details about the characteristics of rainfall, flood flow hydrographs, and ephemeral channels in this region the reader may be referred to the previous investigations of Nouh (1986, 1987, 1988c, 1988d).

MEASUREMENTS TECHNIQUES

Measurement of discharge and sediment concentration were made during 163 flash flood hydrographs in 37 straight ephemeral channels. The flood hydrographs vary in the time to peak discharge (0.32–6.16 h), peak discharge (218.15–1179.35 m^3 s^{-1}), and duration (6.25–54.93 h). The channels vary in bed slope (0.0005–0.0044), bed material median size (0.55–3.18 mm) and geometric standard deviation (1.93–6.21). More details about the flow and channel characteristics is reported elsewhere (Nouh, 1988a).

A straight reach in each channel was selected for the measurements, and three cross sections in this reach were identified. The distance between the upstream and downstream sections was about 500 m. The middle cross section, which was approximately at equal distances from the upstream and downstream cross sections, was used in calculating the various parameters needed for the computation.

During each flood in each channel reach, water levels were measured at 600 s intervals and used to compute water surface slopes. Velocity of flow was measured by releasing standard surface floats in three to five segments at approximately 120 s interval and the measurements were repeated every 600 s. Sediment concentrations were determined from calibrated pump samples collected from nozzles fixed to two masts and positioned at various heights from the stream bed. Bed material size grading was derived from nine samples collected as close as possible to the bed level. Sediment concentration and bed material samples were collected at 30 min intervals. Details of the measurements techniques are reported elsewhere (Nouh & Jamjoom, 1981).

The above measurements were used to determine the bed load transport rates of nonuniform sediment. These rates are compared with the corresponding rates computed with the following methods.

METHODS FOR COMPUTING BED LOAD TRANSPORT RATES

Bed load transport rates of sediment mixtures were computed with several methods and compared with the corresponding measured rates in the investigated channels. The methods of Diplas (1987), Samaga *et al.* (1986), Misri *et al.* (1984), and Proffitt & Sutherland (1983) are considered.

The method of Diplas (1987) is based on a similarity approach and requires a knowledge of the subsurface material size distribution. The bed load transport rate computed by this method depends on the ratio of the mean grain size the transported bed material to the subsurface geometric mean grain size. Based on comparisons between measured and computed bed load rates, Diplas (1987) suggested the use of his method for low to moderate, and high normalized Shields stress.

Samaga *et al.* (1986) used the relationships between the dimensionless grain shear stress and the dimensionless bed load transport rate developed by Misri et al. (1984) for uniform sediment to compute the bed load transport rate of nonuniform sediment by introducing a multiplying correction factor. They found that this correction factor is a a function of τ_0'/τ_{0c}, $\tau_0/\Delta\gamma_s d_i$, and M; where τ_0' = shear stress calculated on the basis of grain roughness, τ_{0c} = critical shear stress for arithmetic mean diameter size of mixture based on Shield's criterion, $\Delta\gamma_s = \gamma_s - \gamma_f$, γ_s = specific weight of sediment, γ_f = specific weight of fluid, d_i = particle diameter of the particular diameter, and M = Kramer's uniformity coefficient. Their method improves the method of Misro *et al.* (1984) in which the above correction factor is considered as a function of τ_0'/τ_{0c} and $\tau_0'/\Delta\gamma_s d_i$ only.

Proffitt & Sutherland (1983) used the total shear stress on the bed instead of the shear stress due to grain resistance in their method of computation. They used experimental data to derive a relationship for the computation of the bed load transport rates for individual fractions. This relationship is based on the bed load transport laws suggested by Paintal (1971) and Ackers *et al.* (1973).

RESULTS AND DISCUSSIONS

Previous results (Nouh, 1988a) indicated that the accuracy of prediction of sediment transport rates during flash flood events using methods developed for prediction under steady flow conditions depends on the value of the parameters $\lambda = (\Delta h/\Delta t)(1/u_*)$; in which $\Delta h/\Delta t$ is the depth variation, Δh, of a hydrograph over a time interval, Δt, and u_* is the shear velocity, and that such accuracy varies according to the part of hydrograph during which the prediction is made. Based on these results, the measurements of bed load transport rates are separated into groups according to the value of λ, and for the rising and the descending limb of hydrographs. The separated measurements are then compared with the corresponding rates computed using the above methods. Some statistical measures were used to gauge the adequacy of each method. These statistical measures are:

$$\text{standard error} = SE = [\Sigma\,(q_{so} - q_{sc})^2/N]^{0.5} \tag{1}$$

$$\text{correlation coefficient} = R = [\Sigma\,(q_{so} - \bar{q}_{so})(q_{sc} - \bar{q}_{sc})]/(N-1)\,s_o\,s_c \tag{2}$$

in which q_{so} = measured bed load transport rate, q_{sc} = calculated bed load transport rate, $\bar{q}_{so}$ = mean measured bed load transport rate, $\bar{q}_{sc}$ = mean computed bed load transport rate, s_o = standard deviation of the measured rates, s_c = standard deviation of the computed rates, and N = number of hydrographs.

The above statistical measures were computed, and are given in Table 1 and Table 2.

Inspection of Table 1 and Table 2 indicates that the method of Diplas, followed by that of Samaga et al. are the best to apply in the investigated channels. The methods of Misri *et al.* and Proffitt & Sutherland provided poor results. Generally the accuracy of the methods decreases as λ increases. In addition, the prediction during the descending period is more accurate than that during the rising period of hydrographs.

Table 1 *Performance of bed load transport rate computation methods ($\lambda \leqslant 0.001$)*

Part of hydrograph	*Diplas*		*Samaga et al.*		*Misri et al.*		*Proffitt & Sutherland*	
	SE	*R*	*SE*	*R*	*SE*	*R*	*SE*	*R*
Full	3.72	0.72	4.88	0.61	6.17	0.43	9,45	0.40
Rising	4.05	0.68	5.18	0.55	8.69	0.35	9.69	0.30
Descending	2.68	0.79	4.31	0.67	5.80	0.48	8.15	0.42

Table 2 *Performance of bed load transport rate computation methods ($\lambda \geqslant 0.10$)*

Part of hydrograph	*Diplas*		*Samaga et al.*		*Misri et al.*		*Proffitt & Sutherland*	
	SE	*R*	*SE*	*R*	*SE*	*R*	*SE*	*R*
Full	6.23	0.54	8.52	0.42	10.14	0.35	12.36	0.21
Rising	8.38	0.50	9.44	0.40	13.27	0.22	17.05	0.15
Descending	6.02	0.59	7.59	0.48	9.72	0.45	10.05	0.42

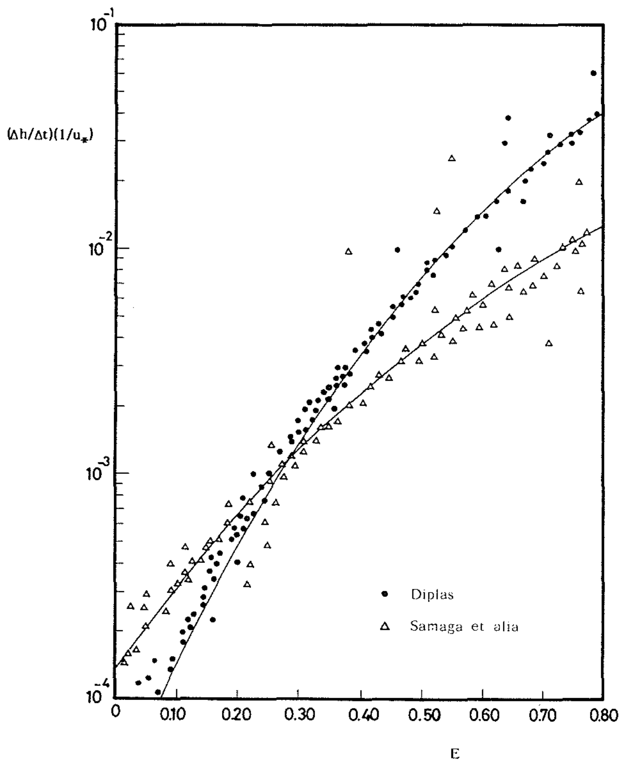

Fig. 1 Variation of E with $(\Delta h/\Delta t)(1/u_*)$ during full hydrographs.

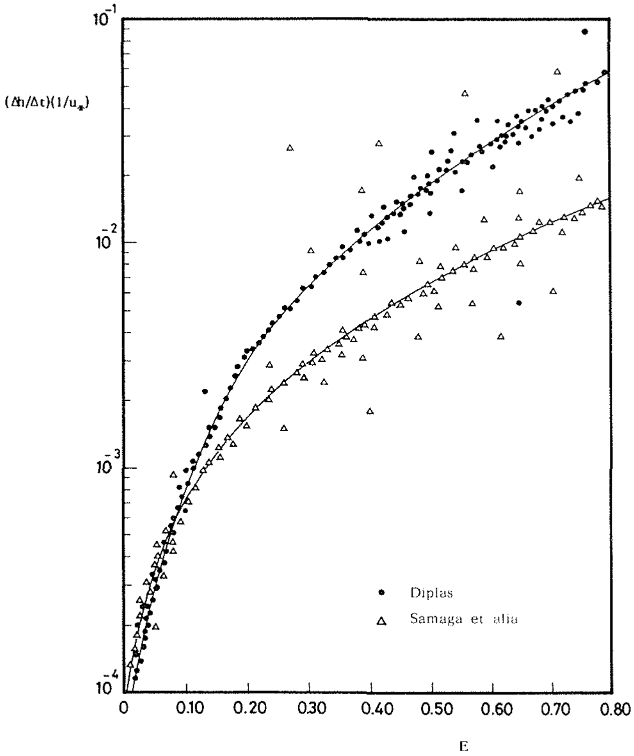

Fig. 2 Variation of E with $(\Delta h/\Delta t)(1/u_*)$ *during rising limbs.*

decreases as λ increases. In addition, the prediction during the descending period is more accurate than that during the rising period of hydrographs. Based on these results, the methods of Diplas and Samaga *et al.* are retained for further investigation.

Previous investigations (Graf & Suszka, 1985) indicated that the error $E = (q_{so} - q_{sc})/q_{sc}$ is not only a function of λ but also a function of the median grain size of the bed load (d_{50}) and the channel bed slope (S_o). Thus, the separated data were used to develop regression relationships between E (in which q_{sc} is the bed load transport rate computed by a given method) and the above parameters. The following relationships were obtained:

During the full hydrographs:

$$E = 20000\ (\lambda)^{0.21}\ (d_{50}\ S_o/\Delta h)^{0.5} - 0.21\ ; \qquad r = 0.83 \tag{3}$$

$$E = 34400\ (\lambda)^{0.25}\ (d_{50}\ S_o/\Delta h)^{0.5} - 0.36\ ; \qquad r = 0.76 \tag{4}$$

During the rise limbs:

$$E = 500\ (\lambda)^{0.25}\ (d_{50}\ S_o/\Delta h)^{0.31} - 0.27\ ; \qquad r = 0.81 \tag{5}$$

$$E = 370\ (\lambda)^{0.31}\ (d_{50}\ S_o/\Delta h)^{023} - 0.39\ ; \qquad r = 0.71 \tag{6}$$

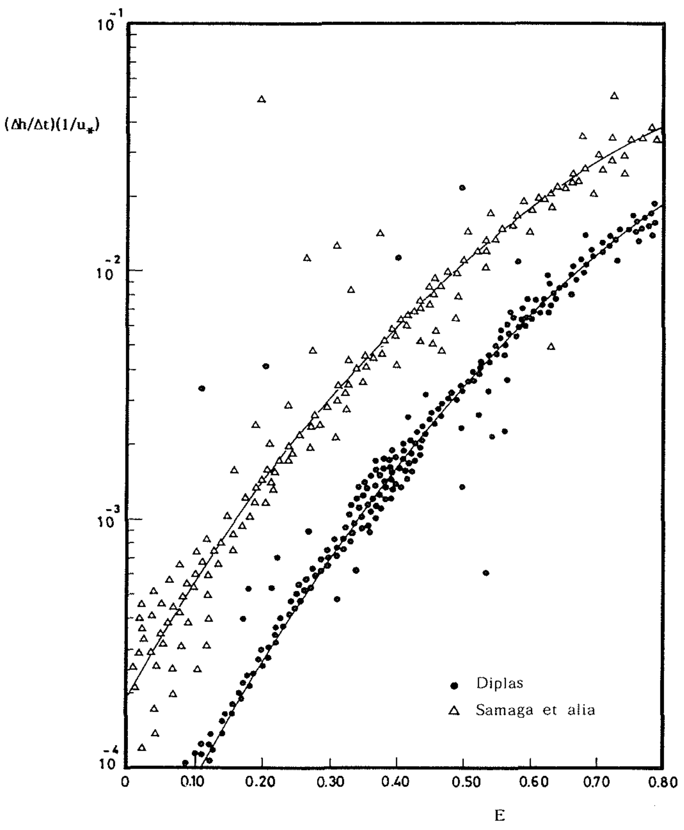

Fig. 3 Variation of E with $(\Delta h/\Delta t)(1/u_*)$ *during descending limbs.*

During the descending limbs:

$$E = 22500\ (\lambda)^{0.18}\ (d_{50}\ S_d/\Delta h)^{0.53} - 0.32\ ; \qquad r = 0.87 \qquad (7)$$

$$E = 40100\ (\lambda)^{0.20}\ (d_{50}\ S_d/\Delta h)^{0.55} - 0.31\ ; \qquad r = 0.80 \qquad (8)$$

in which r is the correlation coefficient, and q_{sc} is computed in equations (3), (5) and (7) using the Diplas method, and in equations (4), (6) and (8) using the method of Samaga *et al.*

Figures 1, 2 and 3 show the data fitted to equations (3) to (8). As can be seen from the plots, a reasonable fit is obtained. Thus, to compute bed load transport rate during a flash flood, the value q_{sc} may be predicted using the methods of either Diplas or Samaga *et al.* This predicted value of q_{sc} can be modified according to the channel and flood flow characterisitcs by using the proper equation from the above (equations (3) to (6)) to evaluate E. The value of q_{so} (at unsteady flow conditions) can then be predicted, knowing the value of q_{sc}. Figures 4 and 5 show comparisons between q_{sc} computed with the above procedure and the actual measured q_{so} values. As can be seen, satisfactory results

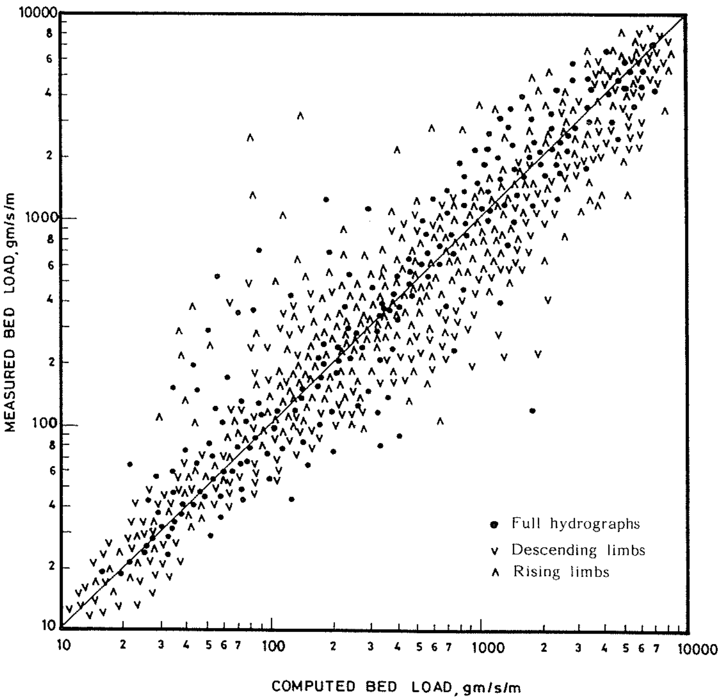

Fig. 4 Measured bed load transport rates against the corresponding rates computed with modified Samaga et al. method.

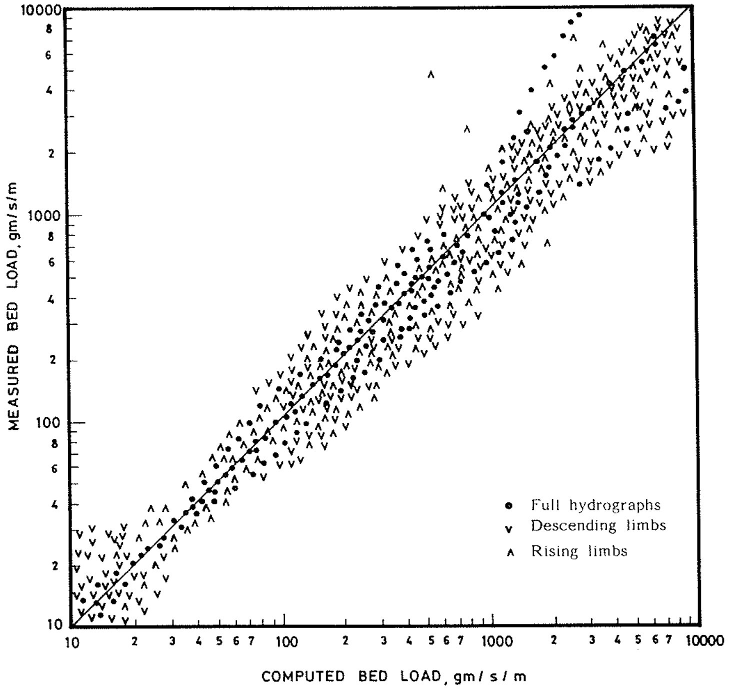

Fig. 5 Measured bed load transport rates against the corresponding rates computed with modified Diplas method.

are obtained. This recommends the use of the above procedure in ephemeral streams.

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