Sediment Budgets (Proceedings of the Porto Alegre Symposium,
December 1988). IAHS Publ. no. 174, 1988.

Transport of suspended sediment in ephemeral channels

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Abstract Transport rates of suspended sediment in 37 straight ephemeral channels were measured during a large number of flash flood events and compared with the transport rates calculated by two different approaches. The first approach calculates for a given discharge the suspended sediment transport rates of individual fractions, whereas the second approach calculates for the discharge the suspended transport rate for uniform sediment which is then converted to transport rates of nonuniform sediment using a multiplying corrective factor. These approaches were found to be unsatisfactory. A modification is introduced to the second approach to improve its applicability in ephemeral channels. The modification considers the characteristics of flash flood hydrographs together with the characteristics of the channel and the sediments.

Transport de sédiments en suspension dans les cours d'eau intermittents

Résumé Les taux de transport de sédiments en suspension de 37 cours d'eau rectilignes temporaires ont été mesurés au cours d'un grand nombre de crues violentes et comparés avec les mêmes taux calculés par deux méthodes différentes. La première méthode calcule pour un débit donné le taux de transport de sédiments en suspension pour des fractions individuelles. La seconde méthode calcule pour le même débit le taux de transport de sédiments en suspension supposé uniforme puis est transformé en taux de transport pour une distribution non uniforme en utilisant un facteur de correction. Il a été constaté que les deux méthodes en question n'on abouti à aucun résultat acceptable. On a apporté une modification à la seconde méthode pour améliorer ses possibilités d'application aux lits des cours d'eau temporaires. Cette modification prend en considération les caractéristiques des hydrogrammes des crues violentes avec les caractéristiques des lits et des sédiments.

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INTRODUCTION

Sediment is transported in suspension, as bed load rolling or sliding along the bed and interchangeably by suspension and bed load. The nature of movement depends on the particle size, shape, and specific gravity in respect to associated velocity and turbulence. Under some conditions of high velocity and turbulence; e.g. high flows in steep-gradient streams, cobbles can be carried in suspension. On the other hand, silt size particles may move as bed load in low-gradient, low-velocity channels.

In Saudi Arabia, whose ephemeral channels (which carry water only during storms) are characterized by steep slopes (Nouh, 1988a), the amounts of transported sediment are large and cause serious deposition problems in surface reservoirs built primarily for water conservation (Nouh & Jamjoom, 1981). The suspended sediment, especially that transported during flash flood events, is of high concentrations and is larger in amount than that transported as bed load. Flash flood hydrographs are characterized by a steep rise and a rapid recession (Nouh, 1988b), and their flow is extremely unsteady and nonuniform (Nouh, 1988c). Due to such high variability in the flows and their velocity in these channels, the distribution of the particle size of sediment in suspension is nonuniform, with a geometric standard deviation reaching a value of 6.32 during flood peaks (Nouh, 1986).

Application of general suspended sediment transport theory, the balance equations of suspended-sediment transport, the theory of turbulent sediment transport, the gravitational theory of suspended-sediment transport, and the recent theories developed by Frankl, Ananyan, Nagy and Sanoyan, to these ephemeral streams provided unsatisfactory results (Nouh & Jamjoom, 1981). Review of these theories is outside the scope of this paper and reported elsewhere (Bogardi, 1974). Thus, a programme of monitoring water and sediment discharges has been initiated by the Ministry of Agriculture and Water in Riyadh, Saudi Arabia, for the main purpose of providing reliable information regarding the behaviour of transported sediment in the ephemeral channels of Saudi Arabia. In this paper the results of this programme concerning the measurement of suspended sediment discharges in some ephemeral channels are reported and compared with the corresponding suspended sediment discharges computed with two recently developed different approaches. Other results concerning measurements of bed load transport and bed profiles of the same channels are given elsewhere (Nouh, 1988d). The main objectives of these comparisons have been to examine the accuracy of the current state of knowledge (represented by these two recent approaches) in predicting suspended sediment discharges in ephemeral channels, and to introduce modifications to the most accurate approach to improve its applicability in ephemeral streams.

FIELD MEASUREMENTS

A number of ephemeral channels located in the southwest region of Saudi Arabia were selected for the study. The channels vary in bed slope, size and distribution of bed materials, and characteristics of the flash flood flow hydrographs. The main characteristics of these channels are summarized in Table 1. The general features of the flood hydrographs, and the behaviour of sediment discharges in respect to water discharges are almost the same in all channels. A typical example of such general features and behaviour is shown in Fig. 1.

Table 1 *Main characteristics of the ephemeral channels utilized for the study*

Characteristics of channel					Characteristics of flood flow hydrograph			
Number	Name	Bed slope	Bed material		Number of events	Average time to peak discharge	Average peak discharge	Average duration
			Median diameter	Geometric standard deviation				
		(10^{-4})	(mm)			(h)	(m^3/s)	(h)
1	Rabha	12.7	1.35	4.16	13	1.20	589.70	9.45
2	Naiefa	13.8	1.07	5.43	9	2.14	793.25	12.34
3	Jizan 1	17.3	1.55	5.01	4	0.92	377.14	10.77
4	Jizan 2	27.8	1.21	6.14	3	1.22	918.00	18.33
5	Nagran	18.6	1.45	4.85	10	2.05	644.19	22.07
6	Salha W.	17.4	0.92	6.20	2	1.15	817.40	15.35
7	Salha E.	28.3	1.75	4.19	3	2.25	988.35	31.77
8	Souda	9.1	0.85	3.55	1	4.15	217.90	29.55
9	Nawasy	5.4	0.59	4.02	2	1.00	195.33	6.18
10	Hada	15.5	1.25	5.17	12	1.25	566.00	9.45
11	Ashran	37.1	2.05	6.21	3	2.15	989.30	17.44
12	Tubalah	21.1	1.65	4.85	3	1.92	758.60	12.45
13	Bissal	15.35	1.50	5.18	4	2.12	815.00	27.33
14	Liyah	20.4	1.90	5.27	2	1.05	652.70	17.30
15	Khulah	23.3	1.55	6.02	2	1.85	935.80	35.45
16	Doqah	15.4	2.01	6.12	3	1.50	877.50	24.35
17	Awali	19.4	1.52	4.33	1	1.15	552.90	9.44
18	Aqiq	32.14	2.27	6.18	2	1.84	889.50	28.50
19	Bishah	24.8	1.07	4.55	3	1.45	755.31	29.45
20	Kulab	42.1	2.13	5.09	2	2.05	955.16	37.60
21	Aqul	5.8	0.65	3.18	3	0.82	412.20	12.45
22	Rabigh	6.2	0.71	2.05	2	1.05	212.70	9.55
23	Tathahab	5.1	0.55	2.17	2	0.85	193.14	8.50
24	Hani	11.8	0.95	1.93	2	0.55	930.11	32.45
25	Rimah I	13.5	1.25	3.44	3	1.33	552.70	14.00
26	Rimah II	41.1	1.93	6.21	7	1.94	905.30	45.18
27	Radwan	23.4	2.45	5.59	3	2.45	850.90	35.65
28	Safra W	17.2	1.50	4.92	2	2.05	558.40	24.17
29	Damad E	23.4	1.93	5.01	10	2.50	835.46	40.18
30	Namman	24.8	1.88	6.05	4	3.02	775.90	52.80
31	Kulay W	13.7	1.05	4.18	3	1.12	418.19	9.44
32	Kulay E	21.4	1.88	5.10	3	1.55	635.25	17.36
33	Hashbal I	37.4	2.17	5.67	4	1.85	847.40	27.13
34	Hashbal II	41.1	2.17	5.93	11	1.22	915.80	30.05
35	Sada N	12.0	1.31	5.27	5	1.33	882.75	25.18
36	Wajj E	44.3	3.18	6.08	9	1.92	959.27	29.44
37	Wajj W	31.6	2.72	6.11	6	1.26	902.95	37.05

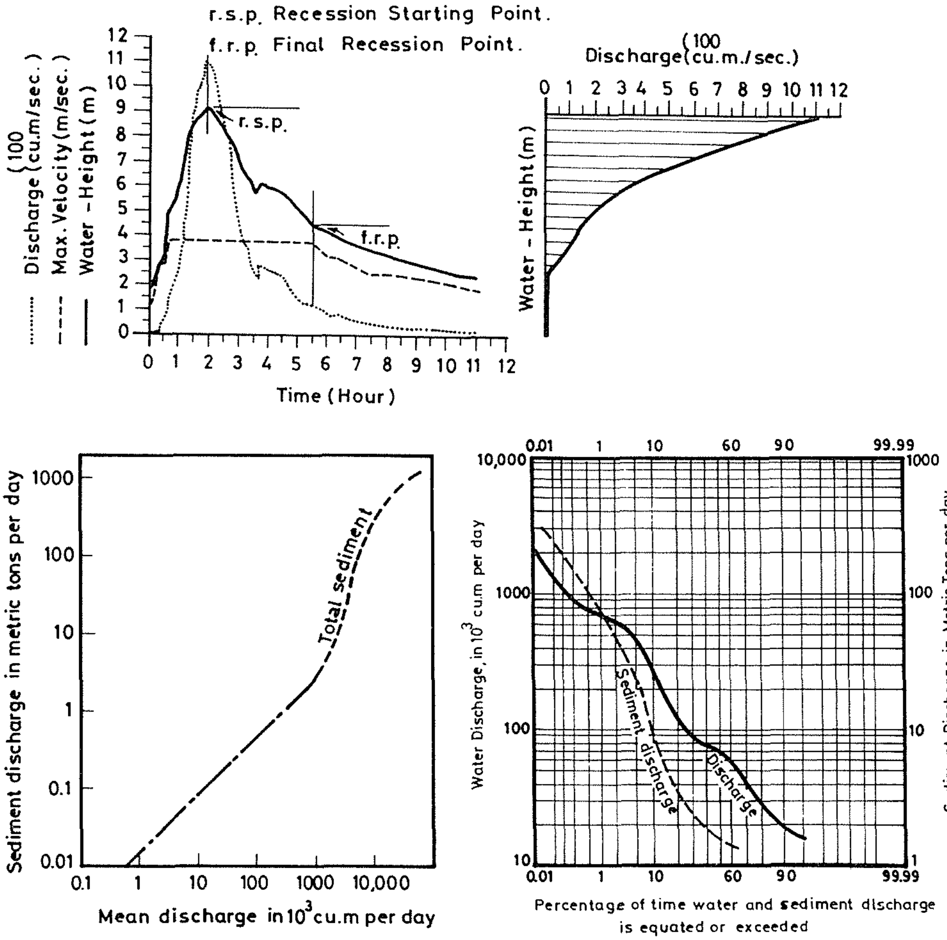

Fig. 1 Typical characteristics of hydrographs (top) and transported sediments (bottom) in the investigated ephemeral channels.

During each flood, measurements of mean concentration, particle size, specific gravity of the suspended sediment, temperature of the water-sediment mixture, water discharge, distribution of flow in the stream cross section, bed materials, and water surface elevation were made. Sediment concentrations were determined from pump samples collected from nozzles fixed to two masts and positioned at various heights above the stream bed. The concentrations of sediment determined by this method were compared with those determined using calibrated automatic sampling equipment at selected verticals. The comparison resulted in a correction factor which should be applied to the concentrations from the pump samples to obtain corrected concentrations for the samples. Water discharge and flow distribution in the cross section were determined from velocity and depth observations at properly spaced stream verticals. Data on particle-size distribution were obtained from samples selected to be representative of a range of sediment discharge and runoff conditions. The average bed material size grading was

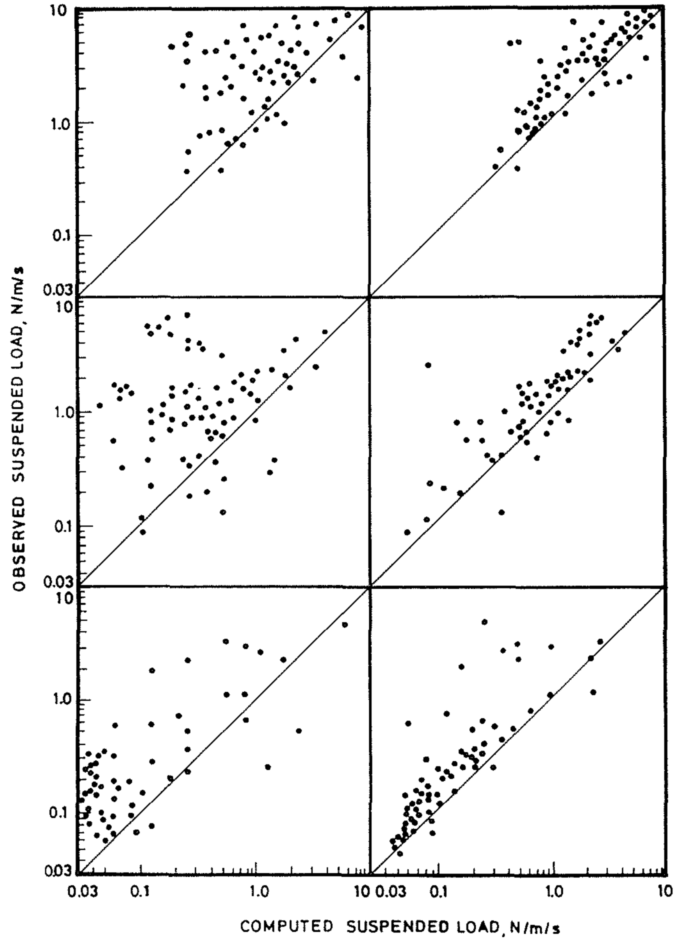

Fig. 2 Suspended sediment transport rates computed using the approach of Holtroff (left) and the approach of Samaga et al. (right) during the passing of full hydrographs (top), and during the rising (middle) and descending (bottom) limbs of hydrographs, plotted against the corresponding observed rates for $d_{50} = 0.91\text{–}1.32$ *mm, geometric standard deviation of sediment* $\sigma_g = 2.11\text{–}3.04$, *and* $\lambda \leq 0.01$.

derived from nine surface layer samples collected near the bed. Water levels were measured at 600 s intervals and used to compute water surface slopes. Velocity of flow was measured by releasing standard floats in three to five segments at approximately 120 s intervals and the measurements were repeated every 600 s. Details of the measurements techniques are reported elsewhere (Nouh & Jamjoom, 1981).

The above measurements are used to determine the suspended sediment discharge for each flood in each channel. As mentioned above. this measured suspended sediment discharge has been compared with the corresponding suspended sediment discharge computed using two different approaches. A brief description of these approaches is given in the following.

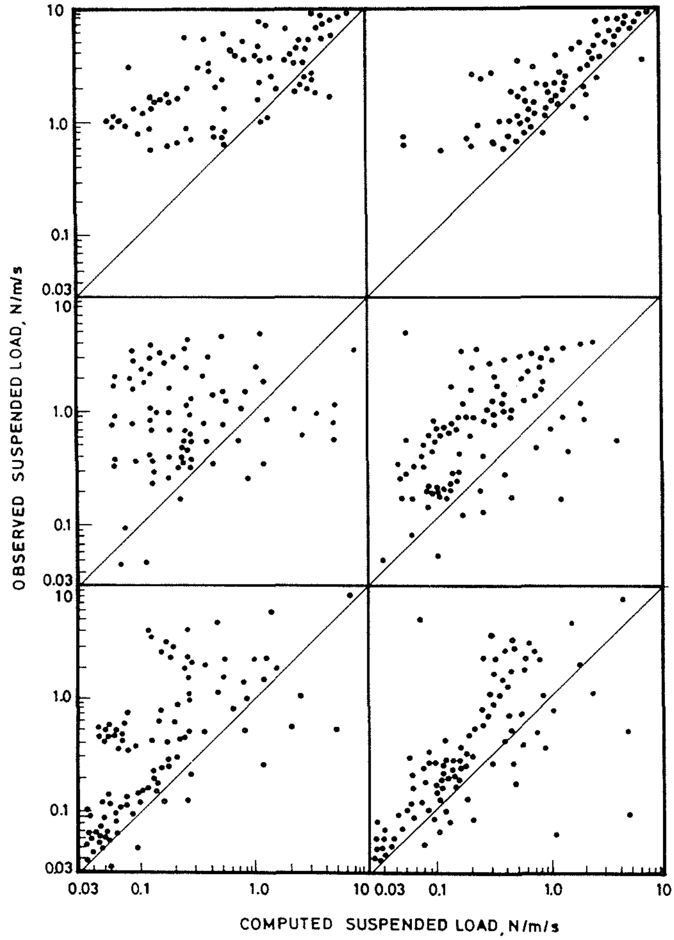

Fig. 3 Suspended sediment transport rates computed with the approach of Holtroff (left) and with the approach of Samaga et al. (right) during the passing of full hydrographs (top), and during the rising (middle) and descending (bottom) limbs of hydrographs plotted against the corresponding observed rates for $d_{50} = 0.92-1.20$ *mm, geometric standard deviation of sediment* $\sigma_g = 2.38-2.91$*, and* $\lambda \leq 0.10$*.*

APPROACHES FOR COMPUTING SUSPENDED SEDIMENT DISCHARGE

As indicated previously, suspended sediment transport rates were computed with two different recent approaches. These approaches were developed by Holtroff (1983) and Samaga *et al.* (1986).

The approach of Holtroff (1983) calculates for a given discharge the suspended sediment transport rates of individual fractions using the following equation:

$$q_s \Delta \gamma_s / \tau_0 U = 0.055 \, \Sigma i_b \, (\tau_s / \tau_0)_i \, (U/\omega_{oi}) \qquad (1)$$

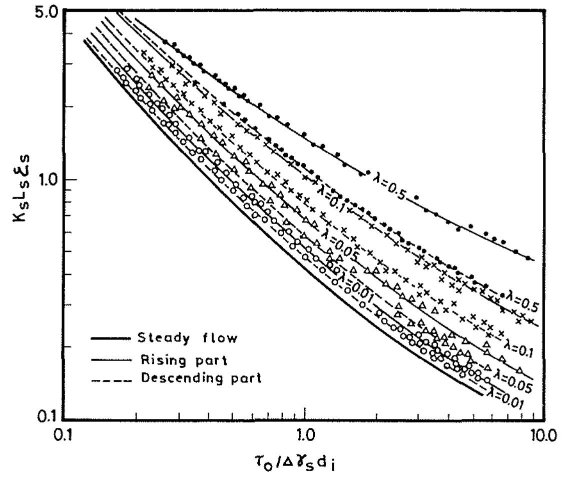

Fig. 4 Modified relation between $K_sL_s\xi_s$ *and* $\tau_0/\Delta\gamma_s d_i$

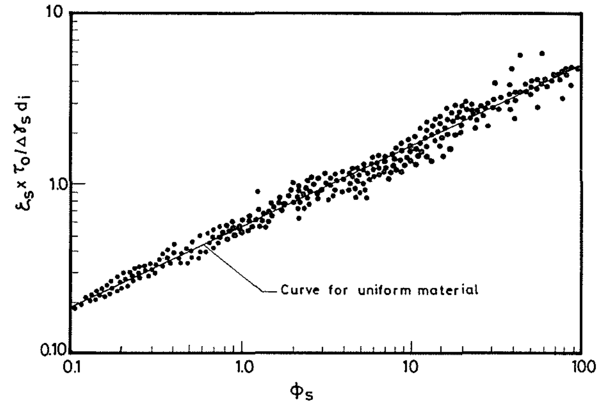

Fig. 5 Modified suspended sediment transport law for individual fractions.

in which q_s = suspended sediment transport rate of the mixture in weight per unit width; $\Delta\gamma_s = \gamma_s - \gamma_f$, where: γ_s = specific weight of the sediment, γ_f = the specific weight of the fluid; τ_0 = average shear stress; c = average velocity of flow; i_b = fraction by weight of any size d_i in the bed of sediment; τ_s = shear stress responsible for suspended load as defined by Holtroff; and ω_{oi} = the fall velocity corresponding to the maximum size that can be thrown into suspension.

The other approach of Samaga *et al.* (1986) calculates for a given discharge the suspended sediment transport rate for uniform sediment which is then converted to a transport rate of nonuniform sediment using a multiplying corrective factor. They found a unique relation between the dimensionless shear stress τ_* (defined as $\tau_* = \tau_0/\Delta\gamma_s d$, where d is the diameter of uniform sediment) and the dimensionless suspended load transport parameter Φ_s (defined as $\Phi_s = (q_s/\gamma_s d)[(\gamma_f/\Delta\gamma_s)(1/gd)]^{0.5}$, where g is the acceleration due to gravity). They recommended the use of this relation to predict the transport rate of individual fractions in a mixture by introducing a correction factor ξ_s, which was related to $\tau_0/\Delta\gamma_s d_i$, τ_0/τ_{0c}, and M. Here d_i = diameter of individual fractions in a mixture, τ_{0c} = critical shear stress for the arithmetic mean diameter size calculated on the basis of Shield's criterion, and M = Kramer's uniformity coefficient..

The computation of suspended load transport rates of different fractions in a mixture is performed as follows:

(a) Bed material is divided into various size fractions and i_b for each fraction is determined:

(b) The values of τ_0 and τ_{0c} are determined and then the ratio τ_0/τ_{0c} is computed. Based on the value of this ratio, a constant K_s is determined from a graph developed by the authors.

(c) Based on the value of M a constant L_s is determined from a graph prepared by the authors.

(d) Based on the value of $\tau_0/\Delta\gamma_s d_i$ corresponding to any desired size a value of $L_s K_s \xi_s$ is determined from a graph developed by the authors, and then used to compute ξ_s knowing the values of L_s and K_s.

(e) The value of $\xi_s \tau_0/\Delta\gamma_s d_i$ is computed and used to read Φ_s from a graph developed by the authors.

(f) The transport rate is calculated from the following equation:

$$\Phi_s = (i_s q_s / i_b \gamma_s d_i)[(\gamma_f/\Delta\gamma_s)(1/g d_i)]^{0.5} \qquad (2)$$

where i_s = fraction by weight of any size d_i in suspended load.

(g) The above steps are repeated for other sizes, and the total suspended transport rate q_s is computed as the sum of the rates for individual fractions, i.e. $q_s = \Sigma i_s q_s$

RESULTS AND DISCUSSIONS

Previous investigations (Suszka & Graf, 1987) indicated that if the measured sediment volume "V_s" during unsteady flow has to be predicted with the sediment volume "V_{so}" calculated for an equivalent steady flow, the resulting error $E = (V_s - V_{so})/V_{so}$ is a function of λ, where $\lambda = (\Delta h/\Delta t)(1/u)$; in which $\Delta h/\Delta t$ is the depth variation, Δh, over a time interval, Δt, and u_* is the shear velocity. Based on this result, one can argue that the accuracy of one of the above approaches to predicting suspended sediment transport rates during flash floods depends on the value of λ.

Thus, the available measurements of suspended transport rates have been separated into groups according to the value of λ, and for the rising and the descending limbs of the hydrographs. The measured suspended transport rates are plotted against the corresponding computed rates and shown in Fig. 2 and Fig. 3. It can be seen that the approaches considered are not accurate in predicting suspended sediment transport rates during flash flood events in ephemeral channels. The calculated sediment rates are always less than the measured rates. In addition, the accuracy of the approaches decreases as λ

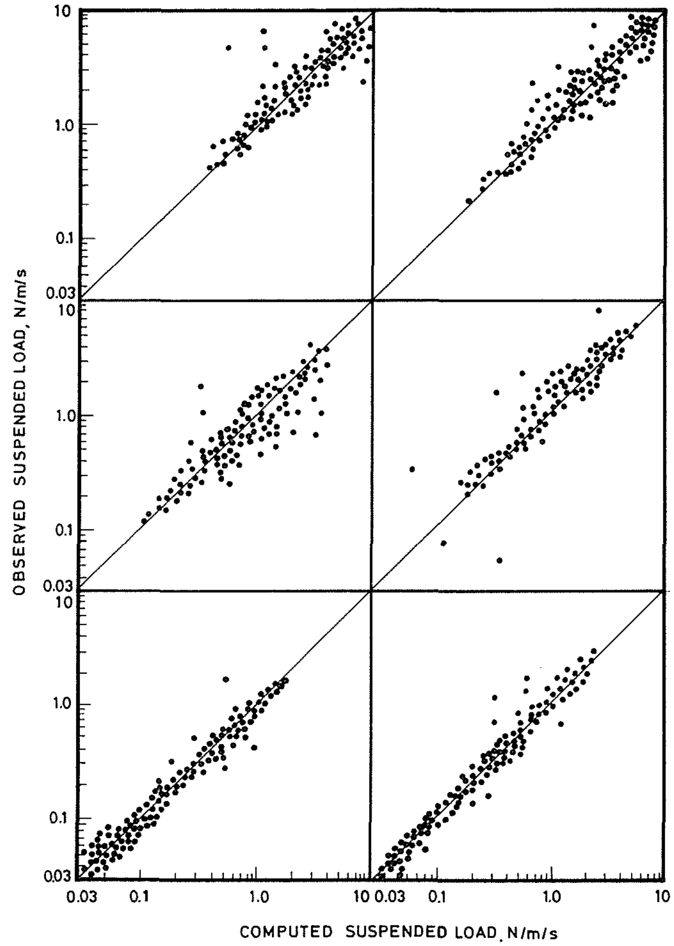

Fig. 6 Suspended sediment transport rates computed with the modified approach for d_{50} = 0.91–1.32 mm, standard deviation of sediment σ_g = 2.11–3.04, and for $\lambda \leq 0.01$ (left) and $\lambda \leq 0.10$ (right) during the passing of full hydrographs (top), and during the rising (middle) and descending (bottom) limbs of hydrographs plotted against the corresponding observed rates.

increases, and is less during the rising limbs of hydrographs than during the descending limbs of the hydrographs. Generally, the approach developed by Samaga *et al.* (1986) produced results more accurate than those of the other approach of Holtroff (1983).

To improve the approach of Samaga, the measurements were used to establish relationships between $K_s L_s \gamma_s$ and $\tau_0/\Delta\gamma_s d_i$ for different values of λ. These relationships are shown in Fig. 4. The use of this figure instead of the figure developed by Samaga *et al.* (1986) and mentioned in step (d) above produced good results, as can be seen from Figs. 5 and 6. Fig. 4 and Fig. 5 can be used in steps (d) and (e) respectively, of the computational procedure recommended by Samaga *et al.* (1986) and mentioned above, to compute the suspended load transport rates of different fractions in a mixture.

CONCLUSIONS

The application of the approaches of Holtroff (1983) and Samaga *et al.* (1986) for suspended sediment transport rates of individual fractions in a mixture provides unsatisfactory results in the investigated ephemeral channel that have steep slopes and are subject to flash floods.

As found by Samaga *et al.* (1986), a unique relation is found to exist between τ_* and Φ_s for suspended load transport of uniform sediment. This relation can be used to predict the transport rate of individual fractions in a mixture during a flood flow by introducing a correction factor ξ_s, which is found to depend on λ in addition to $\tau_0/\Delta\gamma_s d_i$, $\tau\tau_0/\tau_{0c}$ and *M*. The accuracy of the modified method in the ephemeral channels may be seen to be better than that of the methods of Holtroff (1983) and Samaga *et al.* (1986) by comparing Fig. 6 with Figs. 2 and 3.

Acknowledgements This study was supported by King Abdulaziz City for Science and Technology, Riyadh, Saudi Arabia; Saudi National Water Research Number AR-5-62. The help received from the Deputy Minister of Agriculture in Riyadh in supplying data used in this study is very much appreciated.

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