1152

Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision, 1997
S.S.Y. Wang, E.J. Langendoen and F.D. Shields, Jr. (eds.) *ISBN 0-937099-05-8*

A HYDROLOGIC METHOD FOR SEDIMENT TRANSPORT AND YIELD

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ABSTRACT

Sediment transport equations are coupled with a runoff hydrograph approximation to produce a sediment transport and yield estimation procedure called the hydrologic method. The procedure was developed and calibrated using data from the Niobrara River in Nebraska and small watersheds in Arizona. Validation studies were conducted for steady and uniform flow conditions at Muddy Creek in Wyoming and the Rio Grande in New Mexico. The sediment transport equations computed bed material sediment discharge rates comparable to those measured and to those computed using several well accepted sediment transport formulae. The procedure was applied to unsteady, nonuniform flow events in ephemeral stream channels on the Walnut Gulch Watershed in Arizona using a piecewise normal hydrograph approximation technique. Computed sediment yields explained about 99% of the variance in observed sediment yields. This good fit was obtained by the hydrologic method accurately simulating the 10 runoff hydrographs and the mean suspended sediment concentration. However, temporal variations in observed suspended sediment concentration during the runoff event were not well simulated by the hydrologic method.

INTRODUCTION

Sediment transport equations developed for steady, uniform flow conditions (called normal flow) are commonly used in engineering design and analysis. Discussions of assumptions, limitations, and applications of the most commonly used sediment transport equations have been presented by, for example, Graf (1971) and Pye (1994). Erosion and sediment yield models often incorporate normal flow sediment transport equations to compute sediment transport capacity for runoff hydrographs. However, runoff hydrographs can represent highly unsteady and nonuniform flow, thereby severely violating the assumptions under which the sediment transport equations were derived.

Several methods have been developed to improve the applicability of normal flow sediment transport equations to unsteady, nonuniform flow conditions. One method of application is based on using a "characteristic" steady discharge, such as the peak discharge, for the sediment transport calculations and then applying the runoff and sediment discharge rates over an equivalent period of time to preserve, or match, the runoff volume (e.g. see Foster, et al., 1981). Although this meets the steady flow assumptions, this approach severely distorts the runoff hydrograph. The effects of these hydrograph distortions are unknown as validated sediment transport equations for unsteady and nonuniform flow do not exist.

An alternative method of applying sediment transport equations applicable for normal flow to unsteady and nonuniform flow involves approximating the runoff hydrograph by a series of step functions wherein normal flow is assumed for each time interval but rates of flow vary from one time interval to the next (Lane, 1982 and Lane, 1987). The equations used in this method have been calibrated with data from the Niobrara River near Cody, NE (Colby and Hembree, 1955) under normal flow conditions and for runoff hydrographs from small watersheds in Arizona (Lane, 1982), but it has not been validated with independent analyses or data and its degree of applicability remains unknown.

The sediment yield procedure is based on a hydrograph approximation technique developed for small semiarid watersheds. Thus, runoff and streamflow are assumed ephemeral and in direct response to rainfall. The purposes of this paper are to: 1) describe a hydrologic method (sediment transport equations coupled with a runoff hydrograph approximation) of estimating sediment transport rates and yields for alluvial channels where sediment supply is not limiting and the bed sediments are noncohesive, and 2) describe the evaluation of the hydrologic method with field data not used in its original development.

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METHODS AND PROCEDURES

Runoff hydrograph approximation

A typical hydrograph in an initially dry stream bed starts from zero, rises to the peak, and then recedes to a condition of no flow again. Usually the time to peak is much less than the recession time and typically, the recession is rapid following the peak and then decreases more gradually near the end of the runoff.

Runoff hydrographs of this type have been found to be well described by a double triangle approximation. The double triangle hydrograph can further be approximated by a series of step functions over the duration of flow. This step function approximation, called the piecewise normal approximation, matches the original runoff volume and flow duration exactly and assumes normal flow during each interval representing the hydrograph. Within each time interval flow is assumed steady and uniform (normal), thus meeting the assumptions of the sediment transport equations described later.

Development of sediment transport equations

Normal flow is described by the Manning equation,

$$V = 1/n \, s^{1/2} R^{2/3} \tag{1}$$

where:

V = average velocity (L/T),
n = Manning resistance coefficient ($T/L^{1/3}$),
s = slope of energy grade line equal to the slope of the channel bed, and
R = hydraulic radius, cross sectional area divided by wetted perimeter (L)

Following the logic and derivation of Einstein (1950), flow resistance due to the channel banks does not directly contribute to sediment transport on the channel bed. The total cross-sectional area can be divided into an area "pertaining" to the banks or channel side walls and an area "pertaining" to the bed. Relationships then can be developed relating the shear stress on the bed to the hydraulic radius of the bed, the unit weight of water, and the slope of the bed channel. Of the shear stress acting on the bed, some acts on bedforms (form roughness) and some acts on the sediment particles (grain roughness). An equation relating a representative grain size to its Manning's n value is of the form

$$n_g = a \, (d_{50})^{1/6} \tag{2}$$

where d_{50} is the median particle diameter (L). Values of a in Eq. 2 generally range from 0.013 to 0.016 if d_{50} is in mm (Simons and Senturk, 1992, pp. 281-286). Relationships then can be developed relating the shear stress on sediment particles to the hydraulic radius of the bed, the unit weight of water, and the slope of the channel bed.

Einstein (1950) distinguished between bed load and suspended load. The sediment particles larger than the finest 10% of the bed material were said to constitute bed material transported. Material finer than this and thus not originating from the bed material was termed wash load and was not considered in the calculations.

Even though bed material may travel on or near the bed at one flow rate and be suspended in the flow at a higher flow rate, it is computationally convenient to assume the larger particles travel near the bed, i.e. bed load, and the smaller particles travel in suspension, i.e. suspended load. Lane (1982) made an arbitrary distinction based on particle size rather than percentage composition of the bed material. The distinction was for particles larger and smaller than 0.062 mm with the larger particles traveling as bed load and the smaller ones traveling as suspended load. Bed material was said to consist of all particles in the bed down to 1% or even less of the cumulative size distribution. As before, wash load is not directly computed from open channel flow hydraulics as it originates in upland areas and is controlled by soil erosion processes.

The Duboys-Straub formula (see Graf, 1971, pp. 124-127) was modified to incorporate grain shear stress and to account for a distribution of particle sizes. The modified equation for bed load sediment transport is

$$g_{sb} = \alpha \, f_i \, B_s(d_i) \, T_g \, [\, T_g - T_c(d_i) \,] \tag{3}$$

where:

$g_{sb}(d_i)$= transport capacity per unit width for particles of size d_i (M/TL),
α = a dimensionless weighting factor to ensure that the sum of the individual transport capacities is equal to the transport capacity computed using d_{50},
f_i= fraction of particles in size class i,
d_i = representative diameter of particles in size class i,
$B_s(d_i)$ = a sediment transport coefficient (LT^3/M),
T_g = effective shear stress, bed shear acting on sediment particles (F/L^2), and

$T_c(d_i)$= a critical shear stress for particles in size class i (F/L^2).

Transport of particles smaller than 0.062 mm is computed based on a modification of Bagnold's Equation (Bagnold, 1966). The modification is of the form

$$g_{ss} = CAS\, f_{sc}\, T_g\, V^2 \tag{4}$$

where:

g_{ss} = suspended sediment (<= 0.062 mm) transport rate per unit width (M/LT),
CAS = suspended sediment transport coefficient (T^3/L^2),
f_{sc} = fraction of particles smaller than 0.062 mm in the bed material,
T_g= effective shear stress (F/L^2), and
V = mean velocity of flow (L/T).

Calibration of Sediment Transport Equations

Data collected under near normal flow conditions from the Niobrara River near Cody, NE by Colby and Hembree (1955) were used to calibrate Eqs. 3 and 4. Data from 27 observations on the Niobrara River resulted in a relationship between observed (q_s) and fitted sediment transport rates (g_s) as

$$g_s = 0.90\, q_s^{0.90} \qquad R^2 = 0.97 \tag{5}$$

Eqs. 3 and 4 together with the piecewise normal hydrograph approximation were used with 47 runoff events from 4 small watersheds (less than 10 ha) on the Santa Rita Experimental Range near Tucson, AZ and from one small (3.68 ha) watershed on the Walnut Gulch Experimental Watershed near Tombstone, AZ. The relationship between the observed (Qs) and fitted sediment yields (Gs) was

$$G_s = 0.91\, Q_s^{0.91} \qquad R^2 = 0.78 \tag{6}$$

TESTING, EVALUATION, AND VALIDATION

The sediment transport equations were applied to data collected at 3 sites: 1) Muddy Creek, Wyoming, 2) Rio Grande near Bernalillo, New Mexico, and 3) Walnut Gulch, Arizona. Characteristics of the datasets are presented in Table 1.

Table 1. Summary of dataset characteristics

				sediment transport		
Site	sampling dates	# events	discharge (cm/s)	suspended (kg/s)	bed load (kg/s)	sampler
Muddy Creek[1]	4/6 - 8/31/75	35	0.15 - 1.57	--	0.0039 - 0.82	Helly-Smith bedload sampler
Rio Grande[2]	4/25/52 - 5/19/61	21	35 - 286	42 - 870	45 - 840[4]	US D-49
Walnut Gulch[3]	8/19/63 - 9/12/64	10	0 - 187	0 - 5930	--	US P61 and US DH48

[1] details sampling, measurements, and transport rates given by Andrews (1981)
[2] details given by Nordin (1964)
[3] details given by Renard and Laursen (1975)
[4] calculated using modified Einstein method for 2 events (Nordin, 1964)

Application of sediment transport calculation procedures

Normal flow assumptions approximated flow conditions very well at Muddy Creek and Rio Grande and values for Manning's n were computed to match mean depths, velocities and discharges. The sediment transport procedures described earlier were applied to both data sets and discrepancy ratios (defined as the ratio of simulated to measured sediment discharge rates) were calculated.

For all 35 bedload measurements at Muddy Creek, 74% of the discrepancy ratios were within the range 0.5 to

2.0. Andrews (1981) reported that the percentage of discrepancy ratios in the range 0.5 to 2.0 for several sediment transport formulae were as follows: Engelund and Hansen (1967) 77% without including samples for ripple bedforms, Yang (1973) 60% for all data; Shen and Hung (1972) 71% for all data; and Ackers and White (1973) 66% for all dat Therefore, for the Muddy Creek data, we conclude that the proposed sediment transport procedure produces simulate sediment transport rates comparable in accuracy with several transport equations from the literature.

The sediment transport procedure was applied to the Rio Grande data and the simulated bed material discharges for material coarser than 0.062 mm were compared to measured values of suspended sediment coarser tha 0.062 mm. Discrepancy ratios ranged from 0.56 to 2.18 with only one of 21 values outside of the 0.5 to 2.0 range. From these analyses, we conclude that the proposed sediment transport calculation procedure produces reasonable results.

Runoff and measured and simulated suspended sediment yield data for 10 unsteady, nonuniform flow events 1963 and 1964 on the USDA-ARS Walnut Gulch Experimental Watershed are summarized in Table 2. The sedimen transport procedure was applied using values for Manning's n from 0.020 to 0.022. Figure 1 shows the piecewise approximation to the measured hydrograph for the event of Sept. 11, 1964 at Flume 1 and Figure 2 shows the resultin measured and simulated suspended sediment concentrations in percent by weight.

Table 2. Runoff and measured and simulated suspended sediment yield data for Walnut Gulch

event date	runoff (mm)	measured sediment yield (Mg)	simulated sediment yield (Mg)	discrepancy ratio
7/31/64 FL1[1]	0.28	1100	890	.81
8/2/64 FL1	0.28	1410	910	.65
8/8-9/64 FL1	0.08	270	150	.56
9/8/64 FL1	0.91	3440	3260	.95
9/9/64 FL1	0.38	1710	1310	.77
9/10/64 FL1	4.68	20310	20760	1.02
9/11/64 FL1	1.98	8840	8780	.99
8/19/63 FL6[2]	2.97	5490	5410	.99
7/22/64 FL6	5.38	11940	13220	1.11
9/11/64 FL6	3.83	7440	7560	1.02

[1] Flume1 (FL1) supercritical depth flume measuring runoff from 149 km^2 watershed 63.001

[2] Flume6 (FL6) supercritical depth flume measuring runoff from 95 km^2 watershed 63.006

Application of the hydrologic procedure resulted in an excellent degree of correspondence (discrepancy ratio varied from 0.56 to 1.11 and simulated sediment yields explained about 99% of the variance in observed sediment yields). However, sediment yield data are often dominated by total runoff volume such that if measured runoff volume are used to compute sediment yields then the simulated and measured values will agree very well if mean sediment concentration is well estimated (the case herein). These results suggest that while mean sediment concentration (and thus total sediment yield) were accurately simulated by the proposed procedure, the temporal variability of instantaneous suspended sediment concentration was underestimated by the procedure (e.g. the range in measured suspended sediment concentration at FL1 for the event of 9/11/64 was 1.34 to 5.00 % by weight while the corresponding range of the simulated concentrations was 1.39 to 3.53 % although the means were comparable, 2.99% and 2.97%, respectively). This is particularly true for the high values of concentration measured on the rising hydrograph shortly after the beginning of flow. In nature, the slope of the energy gradeline exceeds the channel slope on the rising hydrograph while the modeling procedure assumes normal flow throughout. This difference is hypothesized as a main factor resulting in underestimation of instantaneous suspended sediment concentration during the early portions of runoff and corresponding overestimation during the flow recession.

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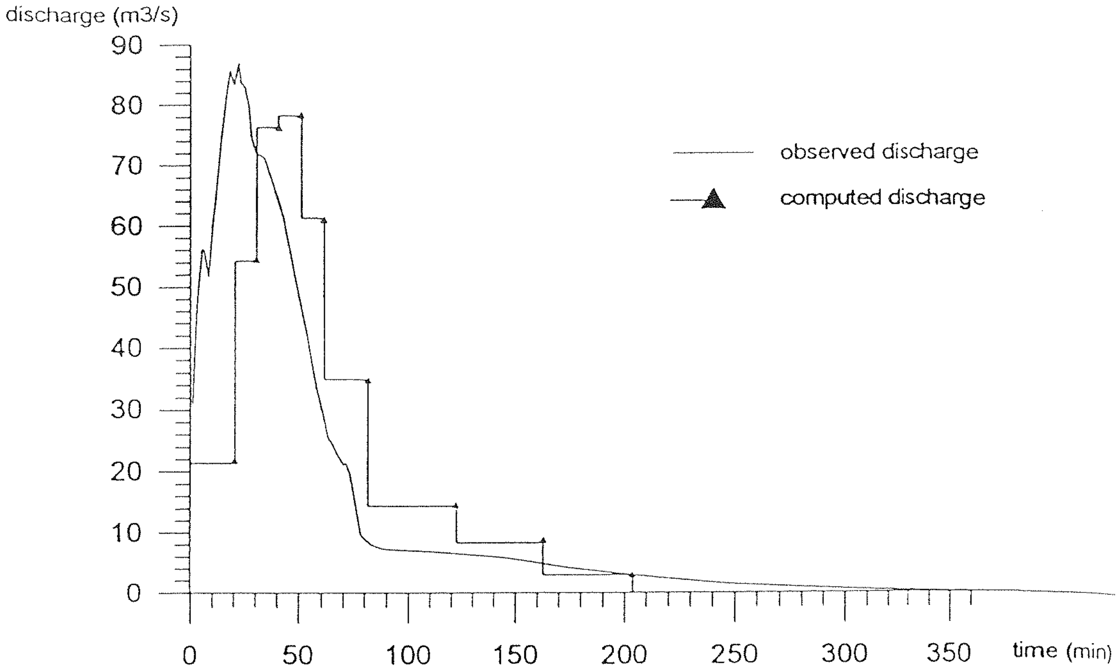

Figure 1 Observed and computed discharge at Walnut Gulch Flume1 on 9/11/64

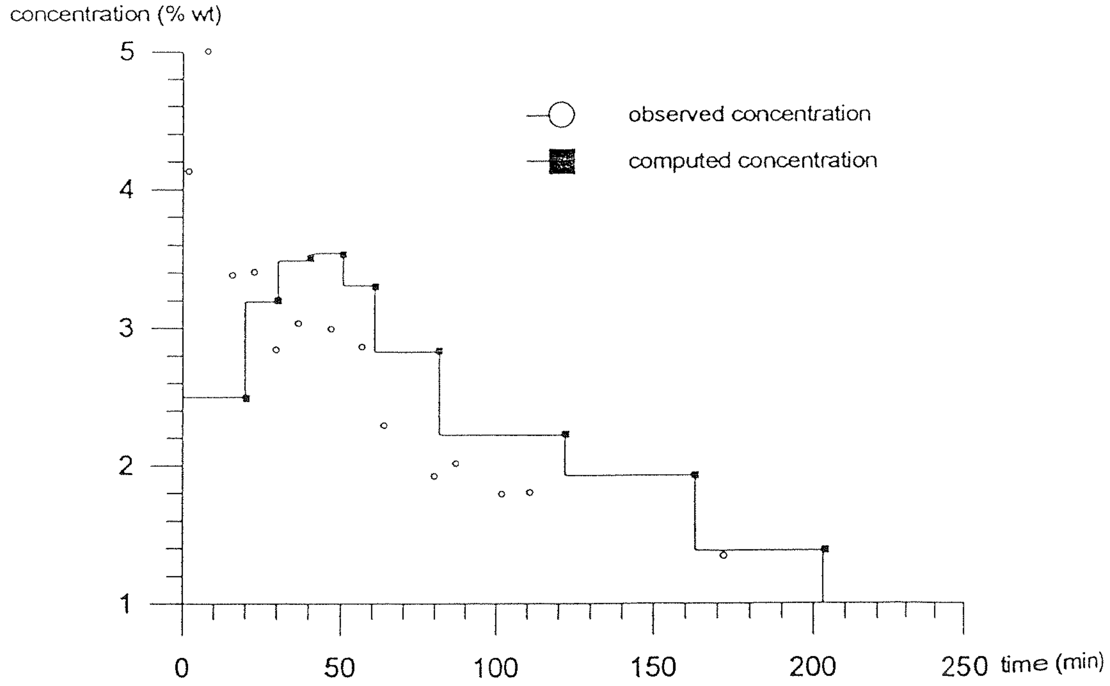

Figure 2 Observed and computed sediment concentration at Walnut Gulch Flume 1 on 9/11/64

Management of Landscapes Disturbed by Channel Incision

Stabilization • Rehabilitation • Restoration

Proceedings of the Conference on Management of Landscapes
Disturbed by Channel Incision

Oxford Campus, The University of Mississippi

May 19-23, 1997

Edited By:

Sam S. Y. Wang
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F. Douglas Shields, Jr.

Published By:

The Center for Computational Hydroscience and Engineering
The University of Mississippi

Management of Landscapes Disturbed by Channel Incision

Proceedings of the Conference on Management
of Landscapes Disturbed by Channel Incision
held at The University of Mississippi, May 1997

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ISBN 0-937099-05-8

First published in May 1997, by:

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University, MS 38677
USA