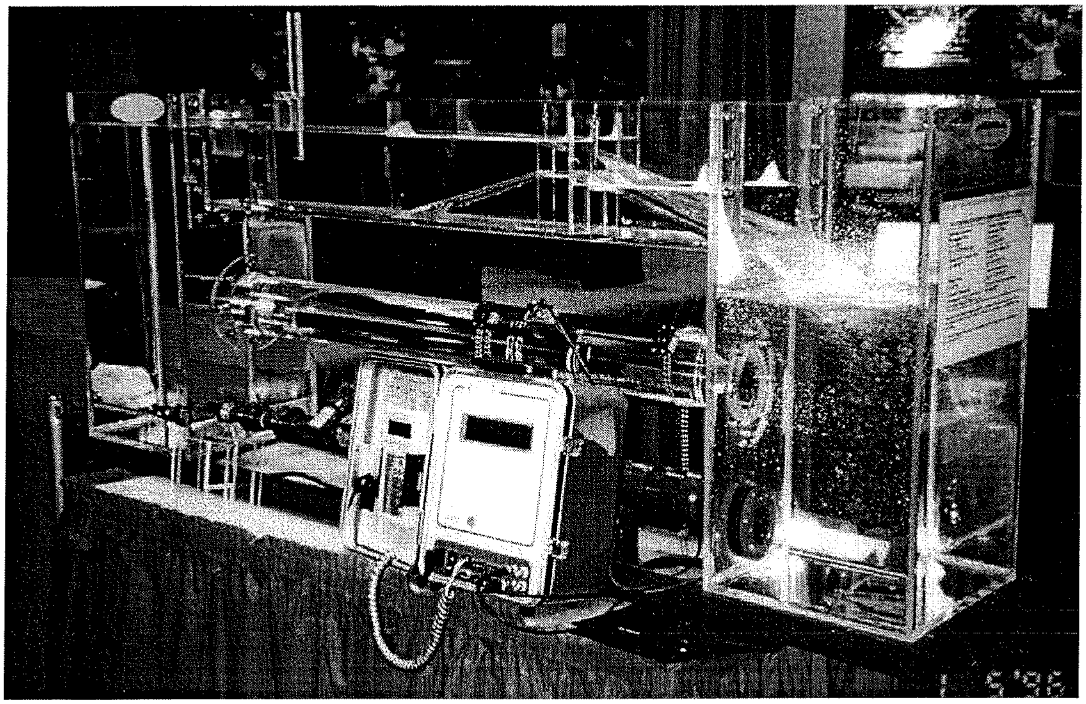
#1323

Volume 1

I. Sediment and Flow Modeling



I. Sediment and Flow Modeling

TABLE OF CONTENTS

A SEDIMENT TRANSPORT AND YIELD MODEL FOR ALLUVIAL STREAMS

Leonard J. Lane, Hydrologist, USDA-ARS, Tucson, Arizona

Abstract: We have developed a sediment transport and yield model over the last 20 years. It is based on a hydrograph approximation technique, sediment transport equations for bed-load and suspend load, and the assumption that sediment transport rates are not limited by sediment supply. The model fits observed sediment transport and yield data from a variety of situations when sediment supply in the channels is non-limiting. The calibration and validation studies include data with varying discharge, varying proportions of bed load and suspended sediment, and varying stream channel and bed material characteristics. Validation studies in Arizona and New Mexico suggest the model is appropriate for the situations studied and can be used to predict sediment transport and sediment yield under similar circumstances as existed for the calibration and validation experiments.

INTRODUCTION

Sediment transport equations have been developed for steady, uniform flow conditions, or normal flow. For a comprehensive discussion of assumptions, limitations, and applications of the most commonly used sediment transport equations see Graf (1971). Erosion and sediment yield models usually incorporate normal flow-based sediment transport equations to compute sediment transport capacity for runoff hydrographs. However, runoff hydrographs exhibit unsteady and non-uniform flow, and thus, violate the normal flow assumption.

A method of applying sediment transport equations applicable for normal flow to unsteady and non-uniform flow involves approximating the runoff hydrograph. The approximation method herein uses a double triangle hydrograph. This in turn is approximated 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; Lane et al., 1985; and Lane, 1987). The effects of these hydrograph distortions are unknown because validated sediment transport equations for unsteady and non-uniform flow do not exist.

The purpose of this paper is to describe development, calibration, and validation studies for a sediment transport and yield model based on the above hydrograph approximation technique and the assumption that sediment transport rates are not limited by sediment supply.

THE SEDIMENT TRANSPORT AND YIELD MODEL

Runoff hydrographs characteristic of many small watersheds can be well described by a double triangle approximation (e.g. Diskin and Lane, 1976). The double triangle hydrograph can further be approximated by a series of step functions over the duration of flow. This step function approximation matches the original runoff volume and flow duration exactly and assumes normal flow during each interval representing the hydrograph.

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 often equal to the slope of the channel bed, and
R = hydraulic radius as the flow area divided by the wetted perimeter (L).

Einstein (1950) asserted that 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 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 channel bed. Of the shear stress acting on the bed, a portion acts on cobbles, vegetation, other roughness elements and bedforms and the remainder is available to act upon the sediment particles (grain roughness).

An equation relating a representative grain size to its Manning's n value is of the form

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

with d_{50} as the median particle diameter (L). Values of a in Eq. 2 generally range from 0.013 to 0.016 when d_{50} is in mm (see Simons and Senturk, 1992, pp. 281-286). With this information, the shear stress on sediment particles can be related to the hydraulic radius of the bed, the unit weight of water, and the slope of the channel bed.

An arbitrary distinction based on particle size rather than composition of the bed material was made by Lane (1982). 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 may travel on or near the bed at one flow rate and be suspended in the flow at a higher flow rate. Even so, it is convenient to assume the larger particles travel near the bed (i.e. as bed load). The bed load is modeled with one sediment transport equation. The smaller particles travel in suspension, i.e. suspended load, and are modeled with a second sediment transport equation. As described by Einstein (1950), 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) 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

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

with:

$g_{sb}(d_i)$= 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). In equation form, the modification is

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

with:

g_{ss} = suspended sediment (<0.062 mm) transport rate per unit width (M/TL),
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 cross-sectional velocity of flow (L/T).

The total sediment yield, G_s, in units of mass flowing past a stream cross-section is then computed as the sum of the sediment < 0.062 mm from Eq. 4 and the summation of bed material transport from Eq. 3 summed over all size fractions, that is

$$G_s = g_{ss} + \sum [g_{sb}(d_i)] \tag{5}$$

where the summation is over the index i, from i = 1 to i = the number of particle size classes used to characterize the bed sediment material. The resulting model calculates total sediment transport capacity and yield at a point on a stream channel. The model was last modified in 1998, therefore it is called APOINT98 hereafter.

Model Development and Applications: 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 (Lane, 1982). Data from 27 observations on the Niobrara River resulted in a relationship between observed (q_s) and fitted sediment transport rates (g_s) as

$$g_s = 0.90\, q_s^{0.90}, \text{ with } R^2 = 0.97 \qquad (6)$$

Equation 5 and the 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 watershed (3.7 ha) on the Walnut Gulch Experimental Watershed near Tombstone, AZ (Lane, 1982). The relationship between the observed (Qs) and fitted sediment yields (Gs) was

$$G_s = 0.91\, Q_s^{0.91}, \text{ with } R^2 = 0.78 \qquad (7)$$

In a subsequent study (Lane and Nichols, 1997) the sediment transport equations and the APOINT model were applied to data collected at 3 sites: 1) Muddy Creek, Wyoming, 2) Rio Grande near Bernalillo, New Mexico, and 3) Flumes 1 and 6 at Walnut Gulch, Arizona. Characteristics of the data are presented in Table 1.

Table 1. Summary of database characteristics from Lane and Nichols (1997).

				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] detailed 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)

Lane and Nichols (1997) found that for all 35 bedload measurements at Muddy Creek, 74% of the discrepancy ratios (defined as the ratio of computed to measured sediment transport rates) 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 equations 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 data. Therefore, for the Muddy Creek data, Lane and Nichols (1997) concluded that the proposed sediment transport procedure produces simulated sediment transport rates comparable in accuracy to several transport equations from the literature.

The sediment transport procedure was also 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 than 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, Lane and Nichols (1997) again concluded 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 in 1963 and 1964 on the USDA-ARS Walnut Gulch Experimental Watershed were also modeled by Lane and Nichols (1997) using APOINT. The model was applied using values for Manning's n from 0.020 to 0.022. Application of the model resulted in an excellent degree of correspondence (discrepancy ratios varied from 0.56 to 1.11 and simulated sediment yields explained about 99% of the variance in observed sediment yields).

The Need for Additional Validation Studies: An important step in application of physically based models to determine sediment transport rates and yields is to conduct validation studies. These studies are tests of model performance to demonstrate the appropriateness/inappropriateness of a particular model for a specific application (e.g. see Sharika, et al., 2000). Thus, there is a critical need to perform validation studies on APOINT98, the model proposed herein. Additional validation studies are needed at data rich locations such as Walnut Gulch and at other locations where bed load transport is not as large a component of the total sediment load.

EXPERIMENTAL WATERSHEDS USED FOR VALIDATION STUDIES

The Walnut Gulch Experimental Watershed: The 149 sq. km Walnut Gulch Experimental Watershed (or Walnut Gulch) is a rangeland watershed located in southeastern Arizona, at approximately 31 degrees 45 minutes north latitude and 110 degrees west longitude. Elevations range from 1,250 m to about 1,900 m above MSL (Fig. 1). The climate in the Walnut Gulch area is classified as semiarid or steppe. Mean annual precipitation is about 320 mm with about 70% of the annual precipitation occurring from thunderstorms during the summer months. The remainder of the precipitation is usually associated with winter frontal storms with more general rains and less convective activity.

Walnut Gulch is located in the Basin and Range Province of the Southwest and is bounded on the southwest, south, and east by mountain blocks separated by broad alluvium filled basins. The northern 50 to 70% of the 149 sq. km drainage area consists of Quaternary and Tertiary alluvium, derived from the Dragoon Mountains. The remaining southern part of the watershed is composed of more complex geologic structures and composition including limestone, quartzite, and granite.

Soils on Walnut Gulch are mostly well drained, calcareous, gravelly to cobbly loams and are closely associated with the geologic features described above. Shrub vegetation, such as creosote bush, acacia, tarbush, and small mesquite trees, dominates (30 to 40% canopy cover) the lower two thirds of the watershed. The major grass species (10 to 80% canopy cover) on the upper third of the watershed are the grama grasses, bush muhley, and lovegrass, with some invasion of the shrub species and mesquite (Renard et al., 1993). Land use consists primarily of grazing, recreation, mining, and some urbanization. Sediment yield-watershed scale relationships for Walnut Gulch were described by Lane et al., (1997).

The Alamogordo Creek Experimental Watershed: The 174 sq. km Alamogordo Creek Watershed is located in east central New Mexico at approximately 34 degrees 53 minutes north latitude and 104 degrees 7 minutes west longitude (Fig. 1). The watershed is in a relatively flat, recessed basin with a steep escarpment surrounding most of the basin. Elevations range from 1420 m at the outlet to over 1680 m MSL at the upper end of the watershed. Sandstone formations underlie the basin and isolated outcrops in the main stream channels control local grades and gradients. Small areas of the watershed located on the mesa above the escarpment have shallow limestone layers overlying sandstone formations.

The climate at Alamogordo Creek is semiarid with mean annual precipitation of just over 350 mm. Soils are generally heavy in clay: clay to clayloams, to loamy soils, and are less well drained and cobbly than on Walnut Gulch. The central, relatively flat basin areas of Alamogordo Creek are grasslands dominated by grama grasses while juniper trees dominate the steeper escarpment area. Land use is primarily domestic livestock grazing. Additional information on the Alamogordo Creek Watershed is given in Drissel and Osborn (1968) and Renard et al. (1970).

The mean slope of the main stream channel on Alamorgodo Creek is about 0.58% compared with 1.2% at Walnut Gulch. Stream channels on both watersheds are classified as ephemeral. The steeper channels on Walnut Gulch contain coarser material (sands and gravels with up to a few percent silt and clay) in comparison with the finer material (mostly sands with a few percent up to as much as 30% silt and clay) at Alamogordo Creek. Thus, transmission losses (infiltration of streamflow to stream channel beds and banks) are less significant and transported sediment is much finer at Alamogordo Creek than at Walnut Gulch.

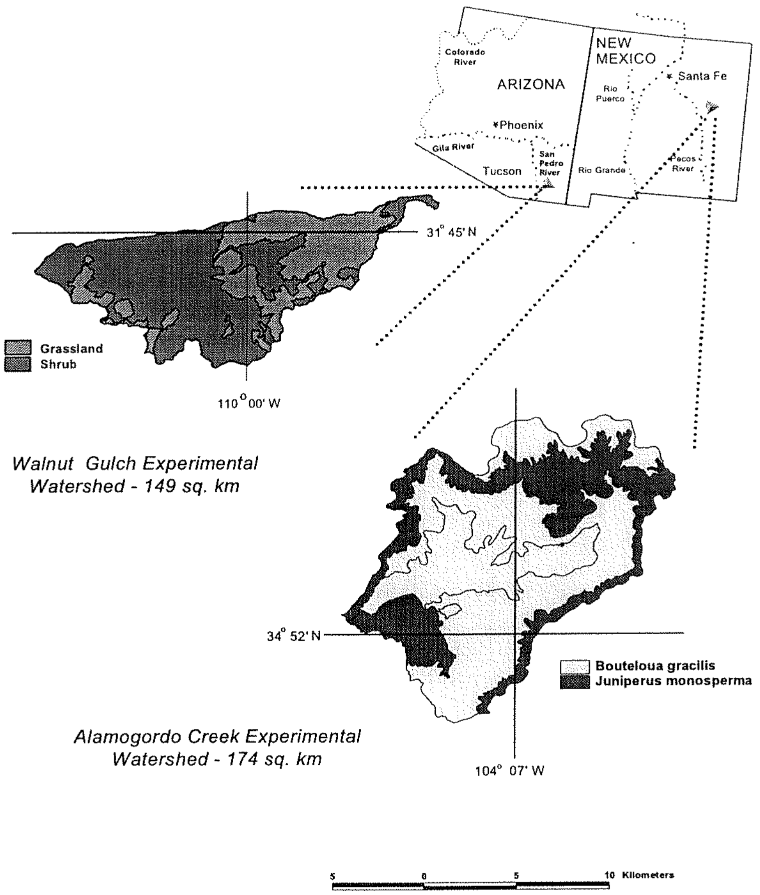


Figure 1. Location map of the Walnut Gulch Experimental Watershed in southeastern Arizona and the Alamogordo Creek Experimental Watershed in eastern New Mexico.

CALIBRATION AND VALIDATION STUDIES

Additional Analyses at Walnut Gulch: Nichols and Lane (2000) applied APOINT98 to data from a small watershed within Walnut Gulch. The APOINT model was calibrated and validated based on data collected during 49 runoff events at Flume 63.103 (Table 2). The flume is located in the main channel that drains the small, 3.68 ha watershed. Calibration was accomplished by varying Manning's n until a maximum R^2 value was obtained and the sum of squared errors was minimized. An optimal value of 0.021 was found for Manning's n.

Table 2. Summary of APOINT calibration and validation at Walnut Gulch Watershed 63.103, 3.68 ha.

Item	Total Sediment Yield (t/ha)			
	Calibration		Validation	
	Observed	Simulated	Observed	Simulated
Number Of Events	24	24	25	25
MEAN	0.404	0.342	0.355	0.355
SD	0.538	0.527	0.652	0.829
Regression Equation	Y= -0.024 + 0.90X		Y = -0.087 + 1.23X	
R^2		0.85		0.98

where Y = simulated sediment yield (t/ha) and X = observed sediment yield (t/ha)

Both the calibration and validation simulations matched the observed means and standard deviations well within the 95% confidence limits. The calibration simulations explained 85% of the variation in observed sediment yield data and the validation simulations explained 98% of the variance.

Analyses at Alamogordo Creek: The APOINT98 model was calibrated to 11 runoff events with measured sediment concentration data. Calibration consisted of varying Manning's n until the value of R^2 was maximized and the sum of squared errors was minimized. A value of n= 0.031 was found to be optimal. The model with n=0.031 was then applied to the 12 validation events, also with measured sediment concentration data, which were not used in the calibration. The results are summarized in Table 3.

Table 3. Summary of APOINT calibration and validation at Alamogordo Creek Watershed, 17,400 ha.

Item	Total Sediment Yield (t/ha)			
	Calibration		Validation	
	Observed	Simulated	Observed	Simulated
Number Of Events	11	11	12	12
MEAN	0.189	0.189	0.081	0.101
SD	0.473	0.457	0.171	0.174
Regression Equation	Y= 0.0065 + 0.97X		Y = 0.022 + 0.97X	
R^2		0.998		0.915

where Y = simulated sediment yield (t/ha) and X = observed sediment yield (t/ha)

Both the calibration and validation simulations matched the observed means and standard deviations well within the 95% confidence limits. The calibration simulations explained over 99% of the variation in observed sediment yield data and the validation simulations explained 92% of the variance.

CONCLUDING REMARKS

The APOINT98 model has evolved over the last 20 years and has been shown to fit observed sediment transport and yield data from a variety of calibration and validation studies, when sediment supply in the channels was non-limiting. The calibration and validation studies included data with varying discharge, varying proportions of bed load and suspended sediment, and varying stream channel and bed material characteristics. Validation studies in Arizona and New Mexico suggest the model is valid for the situations studied and can be used to predict sediment transport and sediment yield under similar circumstances as observed in the calibration and validation experiments. However, it should be noted that sediment yield data are often dominated by total runoff volume. If measured runoff volumes are used to compute sediment yields then the simulated and measured values will agree very well if mean sediment concentration is accurately estimated. This was the case for the validation studies reported herein.

ACKNOWLEDGMENTS

I gratefully acknowledge the USDA-ARS employees who have operated and maintained the Walnut Gulch and Alamogordo Creek Experimental Watersheds over the years, making this research possible. I also acknowledge funding and support provided by the USDA-ARS Southwest Watershed Research Center, Tucson, AZ. Finally, the reviewers of this manuscript helped to improve it significantly.

REFERENCES

Ackers, P. and White, W. R., 1973, Sediment Transport; New approach and analysis. Journal of the Hydraulics Division, ASCE, Vol. 99, (No. HY11), 2041-2060.

Andrews, E. D.,1981, Measurement and Computation of Bed-Material Discharge in a Shallow Sand-Bed Stream, Muddy Creek, Wyoming. Water Resources Research, Vol. 17, (No. 1), 131-141.

Bagnold, R. A.,1966, An Approach to the Sediment Transport Problem from General Physics. U. S. Geological Survey Professional Paper 422-I.

Colby, B. R., and Hembree, C. H., 1955, Computation of Total Sediment Discharge Niobrara River near Cody, Nebraska. U. S. Geological Survey Water Supply Paper No. 1357.

Diskin, M. H., and Lane, L. J., 1976, Application of a Double Triangle Unit Hydrograph to a Small Semiarid Watershed. Hydrology and Water Resources in Arizona and the Southwest, Office of Arid Land Studies, Univ. Of Arizona, Vol. 6, 125-135.

Drissel, J. C. and Osborn, H. B., 1968, Variability in Rainfall Producing Runoff from a Semiarid Rangeland Watershed, Alamogordo Creek, New Mexico. J. of Hydrology, 6, 194-201.

Einstein, H. A., 1950, The Bed-load Function for Sediment Transportation in Open Channel Flow. U. S. Department of Agriculture, Technical Bulletin No. 1026.

Engelund, F. and Hansen, E., 1967, A Monograph on Sediment Transport in Alluvial Streams. In Teknisk Vorlag, Technical University of Denmark, Copenhagen, Denmark. 63 pp.

Graf, W. H., 1971, Hydraulics of Sediment Transport. McGraw-Hill Book Company, New York. 513 pp.

Lane, L. J., 1982, Development of a Procedure to Estimate Runoff and Sediment Transport in Ephemeral Streams. In Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield, IAHS Publ. no. 137, 275-282.

Lane, L. J., Becker, N. M., and Purtymun, W. D., 1985, New Estimating Procedures for Surface Runoff, Sediment Yield, and Contaminant Transport in Los Alamos County, New Mexico. Los Alamos Nat. Lab. Report, LA-10335-MS, 50 pp.

Lane, L. J., 1987, Hydrology Component: Water Routing and Sedimentation. Chapter 5 In: SPUR Simulation of Production and Utilization of Rangelands Documentation and User's Guide. U. S. Department of Agriculture ARS-63, 41-56.

Lane, L. J., Hernandez, M. and Nichols, M., 1997, Processes Controlling Sediment Yield from Watersheds as Functions of Spatial Scale. J. of Environ. Modelling and Software, 12(4), 355-369.

Lane, L. J. and Nichols, M. H., 1997, A Hydrologic Method for Sediment Transport and Yield. In: Management of Landscapes Disturbed by Channel Incision. Eds. S. Y. Wang, E. J. J. Langendoen, and F. D. Shields, Jr., Center for Comp. Hydrosci. And Eng., University of Mississippi, Oxford, MS, May 1997, 365-370.

Nichols, M. H. and Lane, L. J., 2000, An Integrated Systems Approach to Modeling Sediment Yield from Rangelands. Presentation and paper at the ASCE Watershed Management 2000 Conf., In: Science and Engineering Technology for the New Millennium, Colorado State Univ., Ft. Collins, CO, June 20-24, 2000, ISBN 0-7844-0499-2, 8 pp.

Nordin, C. F., 1964, Aspects of Flow Resistance and Sediment Transport Rio Grande near Bernalillo New Mexico. U. S. Geological Survey Water-Supply Paper 1498-H. 40 pp.

Renard, K. G., Drissel, J. C. and Osborn, H. B., 1970. Flood Peaks from Small Southwest Range Watershed. J. Hyd. Div., ASCE, 96(HY3), Proc. Paper 7161, 773-785.

Renard, K. G. and Laursen, E. M., 1975, Dynamic Behavior Model of Ephemeral Stream. Journal of the Hydraulics Division, ASCE, Vol. 101, No. HY5, 511-528.

Renard, K. G., Lane, L. J., Simanton, J. R., Emmerich, W. E., Stone, J. J., Weltz, M. A., Goodrich, D. C., and Yakowitz, D. S., 1993, Agricultural Impacts in an Arid Environment: Walnut Gulch Studies. Hydrol. Sci. and Tech., 9, 145-190.

Sharika, U. S., Ogden, F. L., Downer, C. W., and Sharif, H. O., 2000, On the Calibration and Verification of Two-Dimensional, Distributed, Hortonian, Continuous Watershed Models. Water Res. Research, 36 (6), 1495-1510.

Shen, H. W., and Hung, C. S., 1972, An Engineering Approach to Total Bed-material Load by Regression Analysis. In Sedimentation Symposium Proceedings, ed. H. W. Shen, 14-17.

Simons, D. B. and Senturk, F., 1992, Sediment Transport Technology, Water Resources Publications , Littleton, Co. 897 pp.

Yang, C. T., 1973, Incipient Motion and Sediment Transport. Journal of the Hydraulics Division, ASCE, Vol. 99, (No. HY10), 1679-1704.

Leonard J. Lane
USDA-ARS
Southwest Watershed Research Center,
2000 E. Allen Rd.
Tucson, AZ 85719
Tel. 520-670-6380, Fax 520-670-5550
Email: **ljlane@tucson.ars.ag.gov**