Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium, July 1982). IAHS Publ. no. 137.

Development of a procedure to estimate runoff and sediment transport in ephemeral streams

L. J. LANE*
USDA-ARS, Southwest Rangeland Watershed Research Center, 442 East Seventh Street, Tucson, Arizona 85705, USA

ABSTRACT A hydrological model for application on small semiarid watersheds is developed. The model incorporates simplified routing schemes to include the influence of transmission losses on runoff. A sediment transport model, by sediment size fractions, is developed to compute transport capacity and sediment yield in noncohesive, alluvial channels. Based on available information published in soils and topographic maps and on channel and bed sediment characteristics, the procedure is used to estimate runoff rates and amounts together with sediment yields from semiarid watersheds. Example applications include flood frequency analysis and sediment yield. The procedure requires a minimum of observed data for calibration and is designed for practical applications.

INTRODUCTION

Competition for water resources in semiarid regions is becoming more severe each year as increasing urban, industrial and agricultural demands put more pressure on existing water supplies. Flood prevention and control and sedimentation problems add to the need to develop practical methods of estimating water yield, flood frequency, and sediment transport and yield.

Transmission losses can have a significant influence on water yield (e.g. Babcock & Cushing, 1941; Burkham, 1970a, 1970b; Renard, 1970) and on the shape and size of the runoff hydrograph (e.g. Smith, 1972; Jordan, 1977; Thornes, 1977). At any section in the stream channel the flow is unsteady (stage changing with time) and because of channel changes in the downstream direction, lateral inflow, and transmission losses the flow is spatially varied.

The rate of sediment transportation in alluvial channels, composed of noncohesive sediments, is related to the morphologic properties of the channel, the velocity and depth of flow, the temperature, the size distribution and physical characteristics of the bed sediments, and the dynamic interaction of the fluid and channel boundary conditions. Parker (1978, p. 109) summarized the problem and further elaboration is given in a recent Task Committee Report of the American Society of Civil Engineers (ASCE, 1982).

* *On temporary assignment to the Los Alamos National Laboratory, Mail Stop K495, PO Box 1663, Los Alamos, New Mexico 87545, USA.*

A procedure is needed that mimics the stream's ability to transport sediment; it must include the total transport rate as well as the composition of the transported sediment. The composition of the transported sediments is of particular importance in transport of contaminants strongly associated with sediment (e.g. Hakonson *et al.*, 1976; Lewin *et al.*, 1977; Menzel, 1980).

RUNOFF FROM SEMIARID WATERSHEDS

As described earlier, runoff from small watersheds of interest herein is often in response to thunderstorm rainfall. Because of the storm type and transmission losses, hydrographs are often sharply peaked and streamflows are often of short duration. These, and other characteristics of runoff from these areas are described by Branson *et al.* (1981) and Renard (1970).

The Soil Conservation Service (SCS) method is used to estimate runoff volume for specified antecedent moisture conditions and rainfall depth. A National Engineering Handbook (NEH-4, 1972) is available to aid in selecting parameters and improved estimates are available for semiarid watersheds (e.g. Simanton *et al.*, 1973; Zeller, 1979; Hanson *et al.*, 1980).

Mean duration of flow is estimated using basin characteristics following procedures developed by Murphey *et al.* (1977). Given a volume of runoff and a flow duration, peak discharge and hydrograph shape are estimated using a double-triangle hydrograph approximation (Ardis, 1972, 1973; Diskin & Lane, 1976).

Transmission losses

Based on the work of Lane *et al.* (1971) and Jordan (1977), Lane (1980) approximated the rate of change in runoff volume with distance in a channel as

$$dQ/dx = -wc - wk\ Q(x) + Q_L/x \tag{1}$$

where

$Q(x)$ runoff volume (L^3),
Q_L lateral inflow volume (L^3),
c parameter (L),
k parameter (L^{-2}),
w width of the channel reach (L), and
x length of the channel reach (L).

The parameters c and k are functions of the effective hydraulic conductivity of the channel alluvium and the mean duration of flow in the channel reach. The solution to equation (1) is $Q(x)$, the runoff volume at the end of a channel reach of length x and width w (Lane, 1980). Each channel reach can receive upstream input from an upland area or from one or two upstream tributary channels and uniform lateral inflow along its length. The channel network is constructed of any number of channel reaches, each described by equation (1). Through the use of the mean flow duration and the double-triangle hydrograph approximation, peak discharge of the outflow hydrograph is estimated as

$$Q_p = C\ Q/\bar{D} \tag{2}$$

where

Q_p peak discharge (L^3/T),
Q runoff volume (L^3),
$\bar{D}$ mean flow duration (T), and
C peak discharge coefficient.
The coefficient C is a function of the hydrograph shape assumed, which in turn is a function of the drainage basin characteristics (Murphey *et al.*, 1977; Diskin & Lane, 1976).

Piece-wise normal approximation

If the approximating double-triangle hydrograph is broken into N intervals for the period $[0,D]$, where D is the flow duration, and normal flow is assumed within each of the N time intervals, the result is the piece-wise normal approximation (Lane *et al.*, 1982). By changing the piece-wise approximating hydrograph in the downstream direction the result is an approximation to the spatial variability. By assuming normal flow within each time interval, but changing the flow rate between intervals to approximate the hydrograph, the result is an approximation to the unsteady flow. Moreover, the assumption of normal flow allows calculation of depth, hydraulic radius, and velocity, throughout the hydrograph, to be used in the sediment transport equations.

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

Following Einstein (1950) and others, a distinction is made between bed load and suspended load. If we assume that the sediment transport rate is proportional to the water flow rate, then this distinction is somewhat arbitrary. This is because particles that travel as bed load at one flow rate may be suspended at another. The relationship between mode of transport and flow rate is a dynamically complex one and represents a continuous rather than distinct transition.

Nevertheless, it is reasonable to assume that the "larger" particles travel as bed load and that the "smaller" particles more easily enter suspension. Moreover, it is computationally convenient to assume a sharp distinction based on particle size. Therefore, we arbitrarily assume that all sediment larger than 0.062 mm in diameter is transported as bed load and that finer material is transported as suspended load. Separate transport equations were derived for bed load transport and suspended load transport based on this assumption (Lane *et al.*, 1982).

Using a modification of the Duboys-Straub formula (see Graf (1971) for a complete description) Lane *et al.* (1982) computed transport capacity for bed load-sized particles as

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

where

$g_{sb}(d_i)$ transport capacity per unit width for particles of size d_i

(M/T-L),
α a weighting factor to insure that the sum of the individual transport capacities equals the total transport capacity computed using the median particle size,
f_i proportion of particles in size class i,
d_i diameter of particles in size class i,
$B_s(d_i)$ sediment transport coefficient (L^3/M-T),
T shear stress (F/L^2), and
$T_c(d_i)$ critical shear stress for particles in size class i (F/L^2).

Values of B_s and T_c were determined by Straub (1935) in English units and presented in metric units by Zeller (1963). The total bed load transport capacity is then found by summing the results from equation (3) over all the size fractions.

Bagnold (1956, 1966) proposed a sediment transport model based on the concept of stream power as

$$i_s = P \frac{e_s u_s}{v_s} (1 - e_b) \tag{4}$$

where
i_s suspended sediment transport rate per unit width (M/T-L),
$P = TV$ = available stream power per unit area of the bed (F/T-L),
e_s suspended load efficiency factor,
e_b bed load efficiency factor,
u_s transport velocity of suspended load (L/T), and
v_s settling velocity of the particles (L/T).

Now, if u_s is assumed equal to the mean velocity of the fluid, V, then equation (4) is of the form

$$g_{sus} = k\ T\ V^2 \tag{5}$$

where the coefficient k includes the efficiency parameters, the settling velocity for the representative particles, and the proportion of particles smaller than 0.062 mm in the channel bed material. The total load is then computed as the sum of the bed load from equation (3), and the suspended load from equation (5).

APPLICATIONS

Typical applications of the hydrological model include simulating flood frequencies using observed rainfall data and simulating flood frequencies using rainfall frequency distributions. The procedures described above were applied to Watershed 63.011 on the Walnut Gulch Experimental Watershed in southeastern Arizona (see Renard, 1970). Observed rainfall data for the maximum annual floods from 1963 to 1975 were used to simulate runoff volumes and peak rates on this 8.2 km^2 semiarid basin. Observed and simulated flood peaks are shown in Fig.1(a). The observed and simulated values agree quite well for return periods up to about 25 years. However, the coefficient of determination between observed and predicted peak rates was $R^2 = 0.78$. This suggests that the hydrological model predicted the distribution of flood peaks better than it predicted for individual events.

Based on soils and vegetation data and a topographic map,

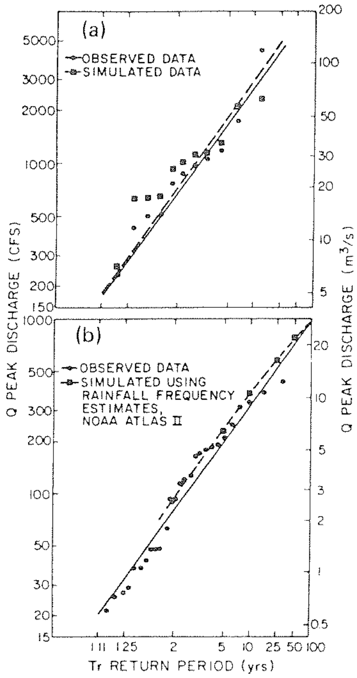

FIG.1 Observed and computed flood frequency curves for (a) Watershed 63.011 and (b) Watershed 45.001.

parameters were estimated for a small semiarid basin near Safford, Arizona. Watershed 45.001 is a 210 ha basin with sparse vegetation (USDA, 1965). Approximately 85% of the area is bare and the basin is classified as sparsely vegetated rangeland. Maximum 1-h depths of rainfall for return periods of 2, 5, 10, 25, 50, and 100 years were estimated using a rainfall frequency atlas (Miller *et al.*, 1973). These rainfall data were then used to simulate flood events for the given return period. As a comparison, annual flood flows for the period 1939-1968 were tabulated and used to derive a flood frequency curve. Observed and simulated flood peaks are shown in Fig.1(b). The approximations to the observed flood series are quite close, as differences of this magnitude could result from selecting a different distribution (e.g. extreme value rather than log-normal) for the observed data.

Typical applications of the sediment transport component of the model include predicting sediment discharge rates for steady flow and predicting sediment yields using the piece-wise normal hydrograph approximation. The sediment transport model was fitted to data representing 27 observations at the Niobrara River in Nebraska, USA (Colby & Hembree, 1955). These data represent nearly steady state conditions. Observed and computed sediment discharge rates are shown in Fig.2(a). The fitted and measured sediment discharge rates agree very well.

The sediment yield model, using the piece-wise normal approximation, was used to predict sediment yields for 47 runoff events from five small basins in southern and southeastern Arizona. These small (1.6-4.0 ha) watersheds are described in detail by

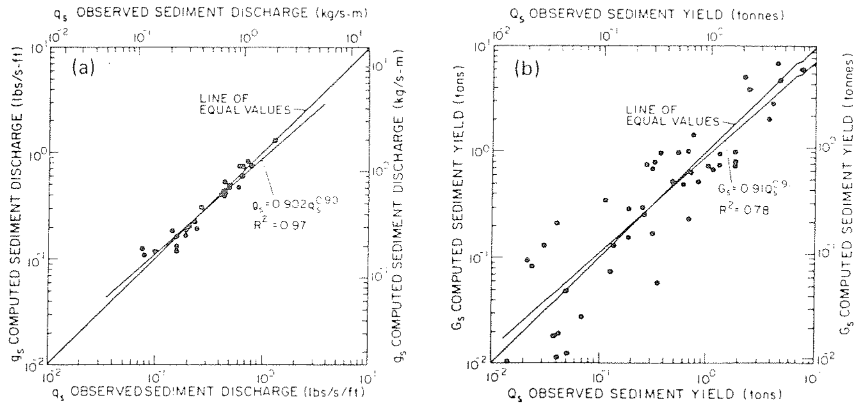

FIG.2 Observed and computed sediment data for (a) Niobrara River and (b) the Arizona basins.

Lane *et al.* (1982). Predicted and observed sediment yields for these watersheds are shown in Fig.2(b). Notice that there is more variation in the sediment yield data (Fig.2(b)) than in the sediment discharge data (Fig.2(a)) and that the observed and computed data are in closer agreement when the model was calibrated (Fig.2(a)) than when it was used to predict (Fig.2(b)).

The discussion of these example applications in brief, however, additional details of the hydrological model are given by Lane (1980). Additional details on the sediment yield model are given by Lane *et al.* (1982). These examples do illustrate intended or typical applications of the hydrological, sediment transport, and sediment yield models described herein.

REFERENCES

Ardis, C.V. (1972) A storm hydrograph model for the response and variation of small rural watersheds. PhD Dissertation, Univ. of Wisconsin, Madison, Wisconsin, USA.

Ardis, C.V. (1973) A double triangular model for generating storm hydrographs. *Proc. First World Congress on Water Resources*, vol. 4, 350-360.

ASCE (1982) Relations between morphology of small streams and sediment yield. Progress report of the Task Committee, L.J.Lane, Chairman, *J. Hydraul. Div. ASCE* (in press).

Babcock, H.M. & Cushing, E.M. (1941) Recharge to ground water from floods in a typical desert wash, Pinal County, Arizona. *Trans. AGU* 23(1), 49-56.

Bagnold, R.A. (1956) The flow of cohesionless grains in fluids. *Phil. Trans. Royal Soc. Lond.* A246(964), 235-297.

Bagnold, R.A. (1966) An approach to the sediment transport problem from general physics. *USGS Prof. Pap.* 422-J.

Branson, F.A., Gifford, G.F., Renard, K.G., & Hadley, R.F. (1981) *Rangeland Hydrology* (2nd edn.). Soc. for Range Mgt, Denver, Colorado, USA, Kendall/Hunt Pub. Co., Dubuque, Iowa, USA.

Burkham, D.E. (1970a) A method for relating infiltration rates to streamflow rates in perched streams. *USGS Prof. Pap.* 700-D, D266-D271.

Burkham, D.E. (1970b) Depletion of streamflow by infiltration in the main channels of the Tucson basin, southeastern Arizona. *USGS Water Supp. Pap.* 1939-B.

Colby, B.R. & Hembree, C.H. (1955) Computation of total sediment discharge Niobrara River near Cody, Nebraska. *USGS Water Supp. Pap.* 1357.

Diskin, M.H. & Lane, L.J. (1976) Application of a double triangle unit hydrograph to a small semiarid watershed. *Hydrol. and Water Res. in Arizona and the Southwest* 6, 125-135.

Einstein, H.A. (1950) The bed-load function for sediment transportation in open channel flow. *USDA Tech. Bull.* no. 1026, USDA, Washington, DC.

Graf, W.H. (1971) *Hydraulics of Sediment Transport.* McGraw-Hill, New York, NY.

Hakonson, T.E., Nyhan, J.W. & Purtymun, W.D. (1976) Accumulation and transport of soil plutonium in liquid waste discharge areas at Los Alamos. In: *Transuranic Nuclides in the Environment*, 175-189. Int. Atomic Energy Agency, Vienna, Austria.

Hanson, C.L., Neff, E.L. & Nicks, A.D. (1980) Estimating SCS runoff curve numbers on native grazing land. In: *CREAMS, A field scale model for chemicals, runoff, and erosion from agricultural management systems* vol. 3, ch. 3, 398-404. USDA Conserv. Res. Report no. 26.

Jordan, P.R. (1977) Streamflow transmission losses in western Kansas. *J. Hydraul. Div. ASCE* 103(HY8), 905-919.

Lane, L.J. (1980) Transmission losses. In: *National Engineering Handbook,* ch. 19, sec-4, Hydrology. USDA Soil Conservation Service, Washington, DC.

Lane, L.J., Diskin, M.H. & Renard, K.G. (1971) Input-output relationships for an ephemeral stream channel system. *J. Hydrol.* 13, 22-40.

Lane, L.J., White, G.C. & Hakonson, T.E. (1982) Simulation of sediment transport in alluvial channels and special applications. Joint report of the Los Alamos National Laboratory and USDA-ARS Southwest Rangeland Watershed Research Center, Los Alamos, New Mexico, USA (in press).

Lewin, J., Davies, B.E. & Wolfenden, P.J. (1977) Interaction between channel change and historic mining sediments. In: *River Channel Changes* (ed. by K.J.Gregory), 353-367. John Wiley & Sons, Chichester.

Menzel, R.G. (1980) Enrichment ratios for water quality modeling. In: *CREAMS, A field scale model for chemicals, runoff, and erosion from agricultural management systems,* vol. 3, ch. 12, 486-492. USDA Conserv. Res. Report no. 26.

Miller, J.F., Frederick, R.H. & Tracey, R.J. (1973) *Precipitation-Frequency Atlas of the Western United States* vol. VIII - Arizona. NOAA Atlas 2, US Dept of Commerce, Nat. Oceanic and Atmos. Admin., Nat. Weather Service, Silver Spring, Maryland, USA.

Murphey, J.B., Wallace, D.E. & Lane, L.J. (1977) Geomorphic parameters predict hydrograph characteristics in the Southwest. *Wat. Resour. Bull.* 13(1), 25-38.

NEH-4 (1972) Section-4, Hydrology, *National Engineering Handbook.*

USDA Soil Conservation Service, Washington, DC.
Parker, G. (1978) Self-formed straight rivers with equilibrium banks and mobile bed. Part 1: The sand-silt rivers. *J. Fluid Mech.* 89(1), 109-125.
Renard, K.G. (1970) The hydrology of semiarid rangeland watersheds. *USDA-ARS, ARS 41-162.*
Simanton, J.R., Renard, K.G. & Sutter, N.G. (1973) Procedures for identifying parameters affecting storm runoff volumes in a semiarid environment. USDA, ARS, *ARS-W-1,* Washington, DC.
Smith, R.E. (1972) Border irrigation advance and ephemeral flood waves. *J. Irrig. Drain. Div. ASCE* 98(IR2), 289-307.
Straub, L.G. (1935) Missouri River report, Appendix XV, US Serial no. 9829, *House Document no. 238*, 73rd Congress, 2nd Session, Washington, DC.
Thornes, J.B. (1977) Channel changes in ephemeral streams: observations, problems, and models. In: *River Channel Changes*, (ed. by K.J.Gregory), 317-335. John Wiley & Sons, Chichester.
USDA (1965) Hydrologic data for experimental agricultural watersheds in the United States, 1960-61. *USDA Misc. Publ. 994,* USDA-ARS, Washington, DC.
Zeller, J. (1963) Einfuhrung in den sedimenttransport offener gerinne. *Schweiz. Bauzeitung*, Jgg. 81.
Zeller, M.E. (1979) *Hydrology Manual for Engineering Design and Flood Plain Management within Pima County, Arizona*. Pima Co. Dept of Trans. and Flood Control Dist., Tucson, Arizona, USA.