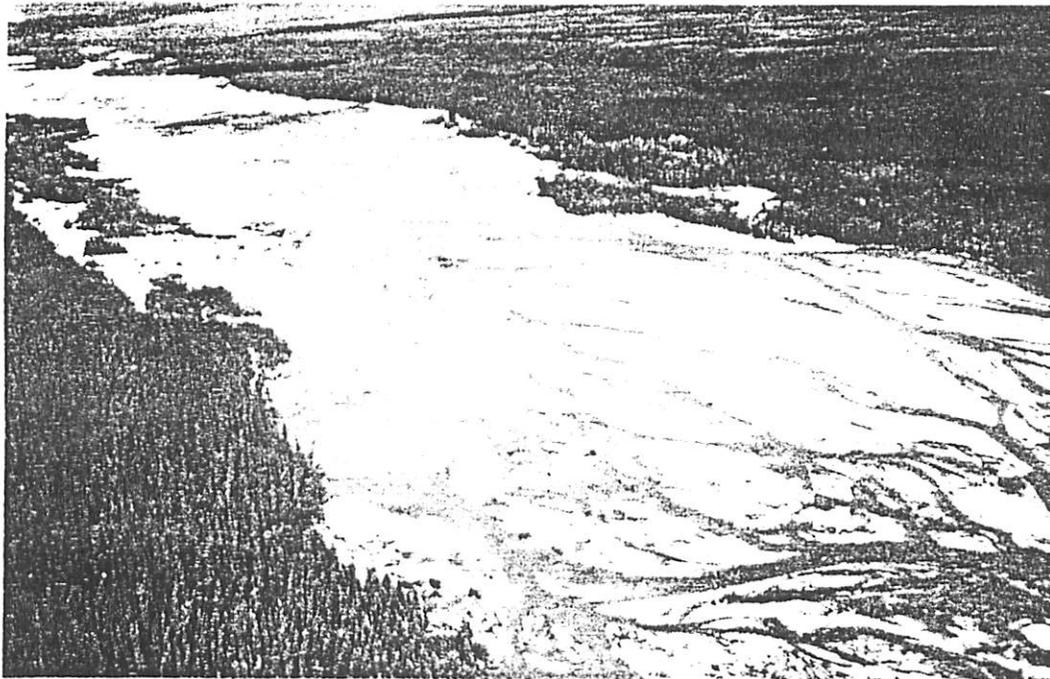


505

**Proceedings
of the
Fourth Federal Interagency
Sedimentation Conference
1986**

Volume 2



Subcommittee on Sedimentation
of the
Interagency Advisory Committee
on Water Data

#505

PROCEEDINGS
OF THE
FOURTH FEDERAL INTERAGENCY
SEDIMENTATION CONFERENCE

MARCH 24-27, 1986

LAS VEGAS, NEVADA

Subcommittee on Sedimentation
Interagency Advisory Committee on Water Data

Agricultural Research Service
Bureau of Land Management
Bureau of Mines
Bureau of Reclamation
Corps of Engineers
Department of Energy
Department of Housing and Urban Development
Environmental Protection Agency
Federal Energy Regulatory Commission
Federal Highway Administration
Forest Service
Geological Survey
National Oceanic and Atmospheric Administration
Office of Surface Mining
Soil Conservation Service
Tennessee Valley Authority

VOLUME II

A RUNOFF-SEDIMENT YIELD MODEL FOR SEMIARID REGIONS

By J.J. Stone and L.J. Lane, hydrologists, E.D. Shirley, mathematician, and K.G. Renard, hydraulic engineer, USDA-ARS Southwest Rangeland Watershed Research Center, 2000 E. Allen Rd., Tucson, AZ 85719.

ABSTRACT

Watershed or basin-scale models are distributed to account for spatial variations in rainfall, soils, vegetation, and land use, and to accurately represent complex channel networks. A distributed model, ARDBSN (Arid Basin), based on simplified equations approximating infiltration, runoff, erosion, and sediment transport is described. The development and structure of the model is briefly reviewed. Three extensive analyses are described and interpreted: (1) sensitivity analysis for the major model parameters, (2) model validation, and (3) example applications. Theoretical shortcomings are used to illustrate the need for research on specific processes and model components. Strengths of the present model are used to show the necessity of including hydrologic simulation in the development of scientifically defensible range management research. A final manuscript section describes the need for development of expert systems for "front end" or parameter estimation/input file development in support of complex simulation models, and the need for output interpretation to summarize detailed simulation results.

INTRODUCTION

Land use planners and engineers in semiarid regions are commonly faced with evaluating the impacts of a project on water yield and quality or designing a hydraulic structure on watersheds where insufficient data are available. Empirical methods, such as the Soil Conservation Service (SCS) runoff and peak flow equations (SCS, 1972), and Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) are relatively simple to use, but sacrifice accuracy for simplicity when applied to nonhomogenous or large drainage areas. Computer simulation models, such as CREAMS (Knisel, 1980), incorporate some of the above methods with more sophisticated procedures (e.g., daily soil water accounting) to estimate the impact of agricultural management systems on water, sediment, and plant yields. Extending the concepts developed for these models for application on semiarid uncultivated basin-scale drainage areas requires that the special features of these watersheds be taken into account. Spatial variability of rainfall and watershed physical characteristics, such as soil types and vegetation density, influence the upland processes of infiltration, runoff, erosion and plant productivity. As drainage area increases, the channel network characteristics become more important in affecting runoff rates and amounts as well as sediment yield. Streamflow will vary in the downstream direction as a result of channel geometry, delivery of water and sediment to the channel network, infiltration into the channel alluvium, and erosion, transport, and deposition in the channel.

In addition to approximating the upland and channel processes, a model should be able to reflect changes in watershed response due to land use changes, be applicable to ungauged areas, and be cost effective, both in data requirements and computer time. SPUR (Simulation of Production and Utilization of Rangeland) (Wight, 1983) is a comprehensive rangeland model, under development by the USDA Agricultural Research Service and cooperating universities, which

attempts to approximate the above processes. SPUR is composed of seven major components, including climate, hydrology, plant, livestock, wildlife, insect, and economics. This paper discusses a simplified version of the SPUR hydrology component which will be referred to hereafter as the ARDBSN (short for Arid Basin) model.

The objectives of this paper are to: (1) present and document a distributed runoff/sediment yield model; (2) discuss an analysis of simulation and prototype data agreement from experimental watersheds in southeastern Arizona; (3) demonstrate strengths and weaknesses of the model in relation to potential applications and simplifying assumptions made in the model structure; and (4) offer suggestions for future research and study.

MODEL DESCRIPTION AND DEVELOPMENT

ARDBSN is a quasi physically based, distributed runoff and sediment yield model based on a continuous simulation of a daily time step water balance, the SCS runoff and transmission loss equations, Modified Universal Soil Loss Equation (MUSLE), and modified DuBoys-Bagnold sediment transport equations.

ARDBSN contains an upland or field component, and a channel component. The field component maintains the daily water balance and calculates surface runoff, field erosion and sediment yield. The channel component assumes surface runoff delivered from the fields is input to the channel network, and routes the water from the watershed upper reaches to the outlet. Flow volume reductions and peak discharge attenuation resulting from losses in alluvial stream beds are accounted for by the model. Sediment discharge is calculated as a function of the channel's sediment transport capacity.

The model is distributed in that a watershed can be subdivided into as many as 27 subbasins consisting of upland (no well defined channels) and lateral or interchannel basins. The channel network can be represented by one to nine channel segments; the 1st order channel segment receives input from one or more upland and two lateral subbasins, while higher order segments receive input from one or two lower order channel segments and lateral subbasins (Fig. 1).

Model input variables include daily rainfall totals, mean monthly temperature and solar radiation, and seasonal leaf area index. Model parameters can be estimated from field data, topographic maps and readily available handbooks so that it is possible to apply the model to unaged watersheds.

Field Component: The field component of ARDBSN maintains a daily water balance and calculates sediment yield for each of the user chosen subbasins on the watershed. Most of the field component calculations are from the model SWRRB (Williams et al., 1985). Surface runoff is calculated using the SCS Curve Number equation,

$$Q = (P - .2S)^2 / (P + .8S) \quad (1)$$

where Q is surface runoff (in), P is storm rainfall (in), and S is a retention parameter (in). The influence of soil moisture on infiltration rate is approximated by updating the retention parameter, S, as a weighted average unused storage in the soil from 0 to the maximum retention parameter, S_{max} .

which is calculated by,

$$S_{\max} = 1000/\text{CNI} - 10 \quad (2)$$

where CNI is the dry antecedent moisture condition Curve Number.

Field erosion and sediment yield, E, is calculated with MUSLE (Williams, 1977) using the equation,

$$E = 95.14(Q*Q_p) \quad \text{KLSCP} \quad (3)$$

where Q(ac-ft) and Q_p (cfs) are the runoff volume and peak rate respectively, and K, LS, C, and P are the factors in the USLE equation (Wischmeier and Smith, 1978).

Both the Curve Number and MUSLE factors are simplifications of the upland runoff and erosion and sediment yield processes. Because the Curve Number is a storm total rainfall-runoff relationship, it does not account for variability in rainfall intensity which, in semiarid regions, can be a dominant factor in the runoff amount produced (Osborn and Lane, 1969). MUSLE does not simulate the rill and interrill detachment and deposition rates as individual processes but in a lumped manner incorporated in the runoff variables and USLE parameters. However, in spite of these drawbacks, both methods have the advantages of being extensively tested and documented (albeit less so for semiarid rangelands), and parameter values are easily estimated from physical watershed characteristics.

Channel Component: The channel component computes runoff rates and volume, sediment transport and yield, and flood flow reductions caused by channel abstraction (transmission losses). Many semiarid watersheds have broad alluvial channels which can abstract large quantities of streamflow. These abstractions, or transmission losses, are important not only because the runoff volume is reduced and flow peak is attenuated as the flood wave travels downstream, but also because they can be an important source of groundwater recharge. The transmission loss calculations used in ARDBSN were developed by Lane et al. (1983), and represent a compromise between simple loss-rate equations (SCS, 1972) and complex kinematic wave models incorporating an infiltration function.

Transmission loss equations developed by Lane use an ordinary differential equation to approximate rate of runoff volume change with distance. Transmission loss amount is a non-linear function of channel length and average width, upstream and lateral inflow, and mean duration and volume runoff. The transmission loss model parameterization was based on analyses of 139 events from 14 channel reaches in Arizona, Texas and Nebraska.

Ephemeral streamflow in semiarid regions usually results from individual thunderstorm rainfall events and the hydrograph is characterized by a rapid rise, a sharp peak, and a slower recession. A double triangle hydrograph approximation, applied to semiarid watersheds by Diskin and Lane (1976), can be estimated if the peak discharge, time to peak, runoff volume and flow duration are known. The peak discharge equation was derived from the SCS method (SCS, 1972), and is calculated as

$$Q_p = C5 V/D \quad (4)$$

where V is runoff volume (in), D is runoff duration (hr), and C5 is a parameter expressing hydrograph shape. Mean runoff volume (\bar{V}) and flow duration (\bar{D}) were related to drainage area using data from semiarid watersheds by Murphey et al. (1977), and are calculated from the equations

$$\bar{D} = C1 A^{C2} \quad (5)$$

$$\bar{V} = C3 A^{C4} \quad (6)$$

where A is area (mi²) and C1-C4 are parameters estimated as a function of the watershed Curve Number, channel slope and watershed length to width ratio.

Sediment transport is assumed equal to sediment transport capacity and is calculated as a function of flow hydraulics and particle size distribution of the channel sediment. Sediment particles larger than 0.062 mm are assumed to travel as bed load. A modification of the DuBoys-Straub formula is used to calculate bed load transport capacity as

$$g_{sb}(d_i) = \alpha f_i B_s(d_i) \tau [\tau - \tau_c(d_i)] \quad (7)$$

where $g_{sb}(d_i)$ is the transport capacity (lb/s-ft) per unit width for particles of size d_i (mm), α is a weighting factor, f_i and d_i are the proportion and diameter (mm) of particles in size class i , $B_s(d_i)$ is the sediment transport coefficient (ft³/lb-s) and τ and τ_c are the effective and critical shear stress (lb/ft²), respectively. Lane (1982) derived estimates for $B_s(d_i)$, τ , and $\tau_c(d_i)$ based on d_{50} , or median particle size, and calibrated the model with data from the Niobrara River in Nebraska. The largest particle size in the calibration was 2.0 mm and the largest d_{50} was 1.0 mm.

The suspended load transport equation is a modified Bagnold (1956) equation based on stream power in the form

$$g_{sus} = f_{sc} CAS \tau V^2 \quad (8)$$

where g_{sus} is the suspended transport capacity (lb/s-ft), CAS is the suspended transport coefficient (s/ft), f_{sc} is the proportion of particles smaller than 0.062 mm in the channel bed, and V is the average velocity (ft/s).

The hydraulic variables needed to solve equations 7 and 8 are estimated at 9 time intervals by a piecewise normal flow approximation of the double triangle hydrograph (Lane, 1982). The piecewise normal approximation allows for the discharge rate to vary in time as runoff moves down the channel segment, transmission loss equations account for runoff changes in the downstream direction, and variations in channel geometry and particle size allow for deposition or scour along channel reaches.

In summary, the upland runoff and erosion processes are approximated by the SCS curve number relationship and MUSLE. Stream flow is routed based on surface runoff delivery to the channel system. Runoff volume and flow rate are reduced by transmission losses which are functions of basin characteristic mean runoff volume and duration, and channel characteristics. Sediment transport is assumed to equal transport capacity and calculated as a function of hydrograph characteristics, hydraulic geometry, and channel particle size.

The hydrograph approximates spatially varied unsteady flow and allows the model to account for variability of channel geometry, transmission losses, and lateral inflow and their influence on water and sediment yield.

Applications: ARDBSN is intended to be applied to watersheds from about .01 to 10 mi² having alluvial channel systems which contain non-cohesive sediments. Stream flow should be ephemeral and occur as a result of individual storm events. The model should not be applied to watersheds where base flow or snowmelt dominate the streamflow. Because average events were used to derive the water and sediment yield equations, simulated individual events may be in error, especially for events associated with abnormally high or low intensity storms or unusual antecedent moisture conditions. Typical applications of ARDBSN include simulating flood frequency, predicting water and sediment yields from semiarid watersheds, and deriving sediment delivery ratios and sediment rating curves. An important model application is evaluating the influence of land use and conservation measures upon water and sediment yield. The model field component contains parameters, such as the Curve Number and MUSLE factors, which are affected by land use changes. Given changes in these parameters, the model can be used to estimate the channel network response to these changes.

ANALYSIS

The hydrology component has been previously verified with data from 3 small watersheds, ranging from 3.2 - 108 acres, on the Walnut Gulch Experimental Watershed at Tombstone, AZ (Wight, 1983). The model was found to explain 88 - 94% of the variance of observed annual runoff and sediment yield, but tended to overpredict runoff and basin sediment yield during those years in which winter rainfall was greater than normal, indicating that the model will not provide realistic results for meteorologic conditions differing from those used in the development of the runoff and peak flow calculations. However, the model did reproduce the phenomena of decreasing water yield and discharge rate per unit area with increasing drainage area observed in semi-arid regions.

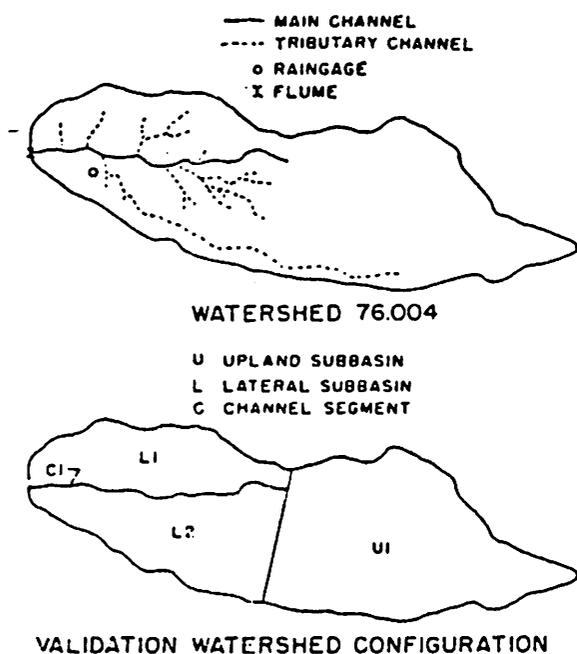
Sensitivity Analysis: Those parameters which are important in the water and sediment yield and peak flow calculations were varied from the specified or optimal values to test the model's response to parameter changes and to evaluate the sensitivity in model output due to errors in estimating parameter values. Table 1 is a list of the parameters used in the analysis and their relative significance on the various types of model output for a 108-acre watershed. The Curve Number is the most sensitive parameter, significantly affecting all the outputs. Sediment yield is the most sensitive output, affected by Curve Number, Manning's n, the suspended transport capacity coefficient, channel slope and sediment particle size distribution. Manning's n does not affect peak flow or runoff because of the approximations used in developing the equations used to calculate transmission losses. The C1 and C5 parameters affect peak flow and, because peak flow is used in MUSLE, sediment yield from the fields. Transmission losses are sensitive to changes in channel hydraulic conductivity, but because the amount of losses relative to the amount of runoff is small, runoff is not as sensitive to this parameter. The result of the sensitivity analysis is that care must be taken to subdivide the watershed into homogeneous subbasins as dictated by data availability and application of the model. Errors in estimating the subbasin Curve

Number can cause significant errors in the model output. Channel geometry and particle size significantly affect simulated sediment yield so that the number of channel segments defined by the user should depend on the variability of channel geometry and sediment characteristics along the channel reach.

Table 1. Summary of sensitivity analysis parameters and relative significance to model output.

Parameter	Runoff	Transmission losses	Peak discharge	Field erosion	Sediment yield
Curve Number	A ¹	A	A	A	A
C1	C	C	B	B	C
C3	C	C	D	D	C
C5	D	D	B	B	C
CAS	D	D	D	D	B
Channel Characteristics					
Width	C	C	C	D	C
Length	C	C	C	D	C
Slope	D	D	D	D	A
d ₅₀	D	D	D	D	A
Manning's n	D	D	D	D	A
Hydraulic Conductivity	C	A	C	D	C

¹Explanation of Symbols: A = output change greater than parameter change; B = output change in between 1/2 and equal to parameter change; C = output change less than 1/2 parameter change; D = no change in output.



Validation: Santa Rita Experimental Range watersheds, 76.004 (4.9 acres) and 76.003 (6.8 acres), were chosen to validate the model and test the transferability of parameter estimation techniques to ungaged watersheds. The hydrologic regime of the Santa Rita watersheds is similar to that of Walnut Gulch in that runoff occurs as a result of intense summer thunderstorms. Both watersheds have a gently sloping upland area with up to 30% desert brush and grass cover and an active channel area covering the lower 1/2 of the watershed. Both watersheds were divided into one upland, two lateral subbasins and one channel segment for the simulation runs. Fig. 1 shows watershed 76.004 and the simulation configuration. Parameters were estimated using field data, topographic maps, and procedures outlined in the SPUR User's Manual.

Fig. 1. Santa Rita Watershed 76.004 near Tucson, AZ and equivalent watershed configuration validation simulation.

Fig. 2 is a comparison of observed and simulated annual values of runoff volume, maximum peak discharge,

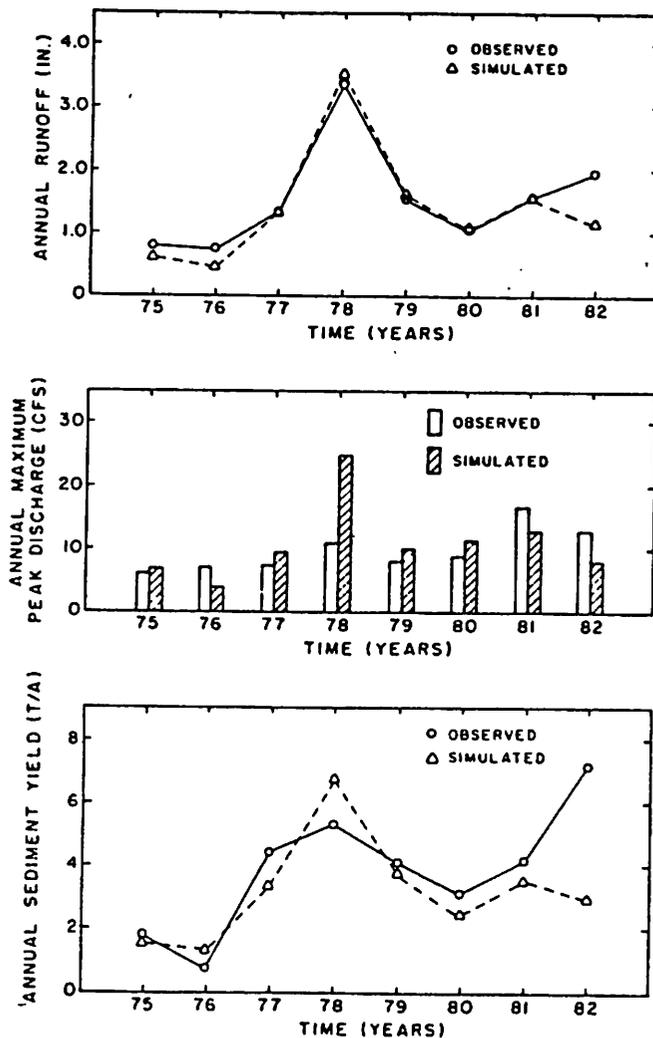


Fig. 2. Observed and simulated annual runoff volume, maximum peak discharge, and sediment yield for the period of simulation, validation, Watershed 76.004.

maximum peak discharge and water and sediment yield and (2) to evaluate a range management plan.

For the first example, simulated annual peak discharge, runoff volume, and sediment yield were ranked, plotted on log normal probability paper, and the 2, 10, and 100 year return period events were estimated. Fig. 3 is a plot of watershed drainage area and the 2, 10, and 100 year frequency maximum annual peak discharge. The solid lines are least squares regression fits to observed data from 8 watersheds in southeast Arizona (Lane, 1985). The circles are simulated peak flows for the 2, 10, and 100 year return periods for 3 watersheds on the Walnut Gulch Experimental Watershed and 2 watersheds on the Santa Rita Experimental Range. Notice that the points agree with the data based relationship and follow the trend of decreasing peak discharge with increasing area for the return periods.

and sediment yield for watershed 76.004 (watershed 76.003 showed the same trends). Considering that parameters were not optimized, the simulated annual values are in good agreement with the observed data, with the exception of peak discharge. Notice that in 1978, the simulated peak is almost 2.5 times greater than the observed peak. The simulated peak is a result of a 23 hour, 2.2 inch storm which occurred in December. Overestimation of runoff and peak flow results from the use of the single parameter SCS Curve Number model and the peak/volume relationship (eq. 4), which was developed from analysis of short duration thunderstorm events. Thus, large volume, but low intensity, storms which occur in winter will be misinterpreted by the model. However, if used as a first approximation, the model can reproduce annual series of runoff and sediment yield. In addition, the parameter estimation techniques developed from Walnut Gulch data appear to be transferable to areas with similar hydrologic regimes.

Example Applications: Two examples are presented demonstrating use of the model (1) to develop an annual series for

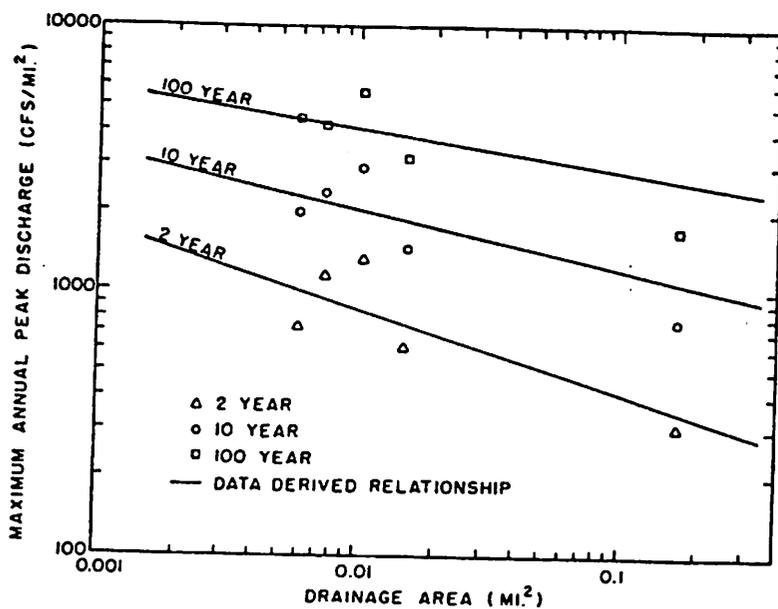


Fig. 3. Comparison of simulated 2, 10, and 100 year return period annual maximum peak discharge (cfs/sq. mi) with data derived relationship.

In the second example, three rangeland conditions were simulated by varying the Curve Number and the C factor of MUSLE. These somewhat representative range conditions are: sparse vegetation or desert brush, poor condition grass cover, and fair condition grass cover. Table 2 is a summary of the mean annual results of a 17 year simulation for the three rangeland conditions for watershed 63.103 on the Walnut Gulch Experimental Watershed; the last row is the magnitude of the output change resulting from changing from sparse vegetation to fair grass. Notice that as the watershed condition is improved, the magnitude of change is between 2 and

3.5 for sediment yield, runoff and peak flow rate, but that field sediment yield changes by a factor of 19. The last column in Table 2 is the percentage of the basin sediment yield contributed by the channel. As field sediment yield decreases, the relative amount that the channel contributes to the total yield increases by a factor of almost 2. There are two important implications of Table 2. One, the results suggest that the channel becomes more

Table 2. Simulated average annual runoff, erosion, sediment yield, and maximum peak discharge for three range conditions for 63.103.

Range conditions	Runoff (in)	Maximum discharge (cfs)	Field sediment yield (t/a)	Sediment yield (t/a)	Channel contribution (%)
Sparse vegetation (SV)	1.27	13.7	1.33	2.34	43
Poor grass (PG)	.67	9.2	.30	1.19	75
Fair grass (FG)	.40	6.6	.07	.69	90
Ratio of SV to FG	3.2	2.0	19.0	3.4	.5

dominant in sediment production as the amount of field sediment delivered to the channel network decreases. It is important to point out that, while a natural channel will adjust its geometry in response to changes in water and sediment delivery to the channel system, ARDBSN assumes constant channel geometry and sediment particle-size distribution for a given simulation period. Therefore, some caution must be used in interpreting sediment yield results, particularly results of long simulations. Two, a significant decrease in field erosion and sediment delivery to the channels may not immediately bring about a correspondingly significant decrease in sediment yield (in this case, a 19 fold versus 3 fold reduction). These results indicate that a program to monitor the effects of a watershed treatment should consider both the upland and channel processes. Evaluating upland improvement treatments by measuring

water and sediment yield at the watershed outlet could result in an incorrect decision on the effects of a particular treatment.

EXPERT SYSTEMS

As hydrologic models grow more complex and incorporate a wide spectrum of the processes active within the hydrologic cycle, it becomes difficult for a user to have the necessary expertise to both estimate input parameters and interpret model output. For example, to evaluate the parameters for all of the components of SPUR requires expertise or knowledge of hydrology, engineering, range management, plant physiology, animal science, and economics. It is incumbent upon the model developer to facilitate use of the model by action agencies if a model is to be more than a research tool. The use of expert systems or knowledge engineering could significantly aid in this process.

An expert system is defined by Bramer (1982) as ". . . a computing system which embodies organized knowledge concerning some specific area of human expertise, sufficient to perform as a skillful and cost effective consultant." Potential applications of expert systems in hydrologic modeling could include (1) determining if the model chosen is appropriate to the given problem, (2) selecting the parameters for model input, (3) summarizing and interpreting model output, and 4) suggesting management alternatives. The first category above would determine from an interactive dialogue with the user or an analysis of input data if the model is applicable to the user supplied conditions, the type of data available, and user needs. The second category would accept input parameters from the user, check their accuracy, given both the watershed physical description and other parameters, and estimate parameter values which the user is unable to evaluate. This is an important category because, as models become more complex, errors in input or parameter estimation become more probable, particularly by users not familiar with a model's structure. The last two categories are interdependent; interpretation of results will lead to simulating alternative management plans. Given a set of conditions and needs, the results can be interpreted in various ways; the system would decide, based on the user's needs, which type of summary will be presented, and interpret that summary. The fourth category would use the initial watershed condition and the results of the interpretation to suggest management schemes. By simulating the alternative plans, and giving the user both a choice of scenarios and the implications of each on the user's needs, the system could act as a cost effective consultant.

DISCUSSION AND CONCLUSIONS

The structure of ARDBSN includes simplifications and lumping of parameters in both the field component (Curve Number, MUSLE) and the channel component (average channel geometry, sediment transport equations) which simplify operation of the model, but potentially decrease its accuracy. As shown in the analysis, the model poorly represents extreme events or events caused by low intensity but high depth rainfall. However, considering that parameters were not optimized, the simulated annual series for runoff, peak discharge, and sediment yield are in good agreement with observed data. Parameter estimation techniques appear to be transferable to hydrologically similar areas, but more testing should be done on watersheds composed of a wider range of soil types and vegetation. The model duplicates the phenomena of decreasing yields with increasing areas, suggesting that the processes causing the

decrease are being approximated by the model structure. The model results also suggest that as drainage area increases, channel processes become more dominant in determining water and sediment yields, consistent with observations in the field. As a management tool, it indicates that significant changes on the watershed to reduce erosion might have little immediate effect on the channel system. Finally, it underscores the idea that to model semi-arid watersheds accurately, the channel processes controlling water and sediment yields must be represented in a manner which allows for spatial variability.

REFERENCES

- Bagnold, R. A., 1956, The Flow of Cohesionless Grains in Fluids. Philosophical Transactions, Royal Society of London, Series A 246(964); 235-297.
- Bramer, M. A., 1982, A Survey and Critical Review of Expert Systems Research, Chapter 1 In: Introductory Readings in Expert Systems, D. Michie, Editor, Gordon and Breach, Science Publishers, Inc., New York.
- 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, 6:125-135.
- Knisel, W. G., Editor, 1980, CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, U.S. Department of Agriculture, Conservation Research Report No. 26, 640 p.
- Lane, L. J., 1982, Development of a Procedure to Estimate Runoff and Sediment Transport in Ephemeral Streams, In: Proceedings, Symposium of the International Association of Hydrological Sciences, Exeter, England, Publication No. 137, pp. 275-282.
- _____, 1983, Transmission Losses, In: National Engineering Handbook, Chapter 19, Section 4, Hydrology, USDA Soil Conservation Service, Washington, D.C., pp. 191-194.
- _____, 1985, Estimating Transmission Losses, Proceedings of the American Society of Civil Engineers, Irrigation and Drainage Div., Engineering Specialty Conference, San Antonio, TX, pp. 106-113.
- Osborn, H. B., and Lane, L. J., 1969, Precipitation Runoff Relationships for Very Small Semiarid Rangeland Watersheds, Water Resources Research, American Geophysical Union 5(2):419-425.
- Murphey, J. B., Wallace, D. E., and Lane, L. J., 1977, Geomorphic Parameters Predict Hydrograph Characteristics in the Southwest, Water Resources Bulletin 13(1):25-38.
- Soil Conservation Service, U.S. Department of Agriculture, 1972, National Engineering Handbook, Section-4, Hydrology, Washington, D.C.
- Wight, J. R., Editor, 1983; SPUR--Simulation of Production and Utilization of Rangelands: A Rangeland Model for Management and Research, U.S. Department of Agriculture Miscellaneous Publication No. 1431, 120 p.
- Williams, J. R., and Berndt, H. D., 1977, Sediment Yield Prediction Based on Watershed Hydrology, Transactions of the American Society of Agricultural Engineers, 20(6):1100-1104.
- Williams, J. R., Nicks, A. D., and Arnold, J. G., 1985, Simulator for Water Resources in Rural Basins, Journal of Hydraulic Engineering, American Society of Civil Engineers, 111(6):970-986.
- Wischmeier, W. H., and D. D. Smith, 1978, Predicting Rainfall Erosion Losses--A Guide to Conservation Planning, U.S. Department of Agriculture Handbook No. 537, 58 p.