THE ROLE OF LARGE STORMS IN DETERMINING MEAN ANNUAL SEDIMENT YIELD[1]

Leonard J. Lane[2]

Abstract: Erosion and sediment yield monitoring programs are often conducted over short time periods. The resulting short-term databases are used for a variety of purposes including estimation of mean annual soil erosion rates and mean annual sediment yield, simulation model parameterization and calibration, design of erosion/sediment control practices and structures, and to estimate rates of landscape evolution for geomorphic design of reclamation systems. Analyses of data from plots and small watersheds in Missouri, Iowa, and Arizona are used to examine the importance of large storm events in determining mean annual soil erosion rates and mean annual sediment yield from small watersheds. Under a wide range of climate, environmental, land use, and management factors, large storms were found to dominate mean annual sediment yield. This large-storm dominance was observed over a range of spatial scales, from experimental plots (88 sq m) to small watersheds (up to 33.5 ha), spanning the size of many reclamation projects. Storm size is determined using frequency analyses techniques for sediment yield from measured data to facilitate comparisons between humid and arid sites. Probability theory is used to determine the probability of observing a storm of a specified return period during a given length of monitoring. These results are shown to have direct application in interpreting the adequacy of monitoring data at reclamation sites and in evaluating the performance of soil erosion and sediment transport models in capturing the temporal variability of mean annual sediment yield. However, the state-of-the-science is such that process-based models need some actual calibration data to determine their parameter values. Thus, the limitations of the length of monitoring periods carry over into simulation modeling, evaluation of alternative reclamation systems based on monitoring data and simulation modeling, and ultimately, to the quality of the site reclamation.

Additional Key Words: soil erosion, sediment transport, frequency analyses, probability theory, simulation modeling, and evaluating site reclamation.

---

[1] Paper was presented at the 2007 National Meeting of the American Society of Mining and Reclamation, Gillette, WY, 30 Years of SMCRA and Beyond June 2-7, 2007. R.I. Barnhisel (Ed.) Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

[2] Leonard J. Lane, Hydrologist, L. J. Lane Consulting, Inc., 411 E. Suffolk Dr., Oro Valley, AZ 85704, email: ljlane2@msn.com

Proceedings America Society of Mining and Reclamation, 2007 pp 403-412
DOI: 10.21000/JASMR07010403
http://dx.doi.org/10.21000/JASMR07010403

Introduction

Erosion and sediment yield monitoring programs are often conducted over short time periods and the resulting short-term databases are used for a variety of purposes including estimation of mean annual soil erosion rates, mean annual sediment yield, design of erosion/sediment control practices and structures, and to estimate rates of landscape evolution. Since, by definition, large events are rare and do not occur often, a short monitoring period may or may not sample any large events. An obvious question

is:

> "How important are large events in determining mean annual soil erosion rates and mean annual sediment yield?"

A key focus of this paper and the resulting discussion will be answering this question and considering its practical implications.

Purposes

The purposes of this paper are to pose the above question, to discuss it relative to analysis and interpretation of experimental data, to summarize the interpretations, and to discuss their practical implications.

Scope and Limitations

The analyses mostly were limited to addressing the question: How important are large events in determining mean annual soil erosion rates and mean annual sediment yield?

Measured sediment yield data from plot scale and small watershed scale experiments were used to determine and illustrate the role of large storms (for example, how much of the total sediment yield measured during the monitoring period was from the largest storm, the largest 2 storms, etc.). However, the largest watershed used in the analyses was 33.5 ha so results and implications from the analyses herein should not be extrapolated to watersheds significantly larger than this value.

Review and Analyses of Experimental Data

Data and Information from the Plot to Hillslope Scale

Natural storm plots and rainfall simulator plots are generally 1 m to a few m wide and 1 to a few 10's of meters long in the direction of flow. This scale is called the "plot scale" herein. Furthermore, these plots are usually situated on uniform, relatively steep slopes so that most of the soil eroded leaves the downstream end of the plot as sediment yield (often called soil loss in the agricultural literature and especially in publications related to the Universal Soil Loss Equation (USLE), Wischmeier and Smith, 1978 and its subsequent modifications, i.e. the Revised Universal Soil Loss Equation (RUSLE), Renard, et al., 1997). The plots are usually located on relatively steep slopes to minimize on-plot sediment deposition and maximize soil detachment by raindrop impact and overland flow. The plots are designed this way to focus on evaluating soil erodibility.

Experimental plot research leading to development of the USLE was conducted over long periods of time and at many locations around the world. However, the main emphasis was on cultivated agricultural areas. Wischmeier (1962) analyzed plot data from natural storms (as opposed to rainfall simulator data) and noted that about 75% of soil loss resulted from an average of the 4 largest storms measured each year.

Hjelmfelt, et al. (1986) examined sediment yield (soil loss) from replicated 3.2 by 27.4 m plots, cropped to continuous corn, and with conventional tillage. The plots examined were at Kingdom City, MO and consisted of a 37 year period of record. Sediment yield from these plots are summarized in Table 1.

The data in Table 1 can be interpreted as follows. The 513 runoff producing storms measured over a 37 year period produced a total sediment yield of 285 t/ha. The 33 storms with sediment yields larger than 2 t/ha represent 6.4% of the total number of storms and the sediment yield from these 33 events represents 66% of the total sediment yield. Similarly, the 20 storms with sediment yields greater than 4 t/ha represent 3.9% of the events and 52% of the total sediment yield and the 6 storms with sediment yields greater than 8 t/ha represent only 1.2% of the events but account for 24% of the total sediment yield over the 37 year period of monitoring. For these data, the single largest storm per year (not the 4 largest as Wischmeier suggested) accounts for about 75% of average annual sediment yield. The relationship between the number of storms and sediment yield for the Kingdom City Plots is shown in Fig. 1.

Table 1. Summary of sediment yield (SY) from 3.2 x 27.4 m plots at Kingdom City, MO. Analyses are based on information presented by Hjelmfelt, et al., (1986).

Data Set	No. of Events	Total Sediment Yield (t/ha)[1]	Percent of Storm Events	Percent of Total Sediment Yield
All Storms	513	285.	100.	100.
SY > 2 t/ha[2]	33	187.	6.4	66.
SY > 4 t/ha	20	147.	3.9	52.
SY > 8 t/ha	6	68.	1.2	24.
Largest Storm[3]	1	14.85	0.2	5.2

1. Total sediment yield from the 37 years of data was 285 t/ha so that the mean annual sediment yield was 7.70 t/ha/y.
2. The notation "SY > 2 t/ha" means all the storm events with sediment yields > 2 t/ha and similarly for 4 and 8 t/ha.
3. The largest storm event in 37 years of record occurred in June 1970.

For the erosion plots at Kingdom City, MO, the large events are critical in defining the long-term mean annual sediment yield. The largest 1% of the sediment yield events accounts for about a quarter of the mean annual sediment yield and the largest 4% of the events accounts for about half of the mean annual sediment yield. Monitoring for periods of record that missed the few largest storms in the 37 years would produce data that would seriously underestimate the long-term mean annual sediment yield. Conversely, monitoring for short periods which do include several large storms would seriously overestimate the long-term mean annual sediment yield. For example, the largest event in the 37 year period occurred in June 1970 and produced 14.85 t/ha of sediment yield. This single event represents 0.2% of the number of events and 5.2% of the long-term mean annual sediment yield.

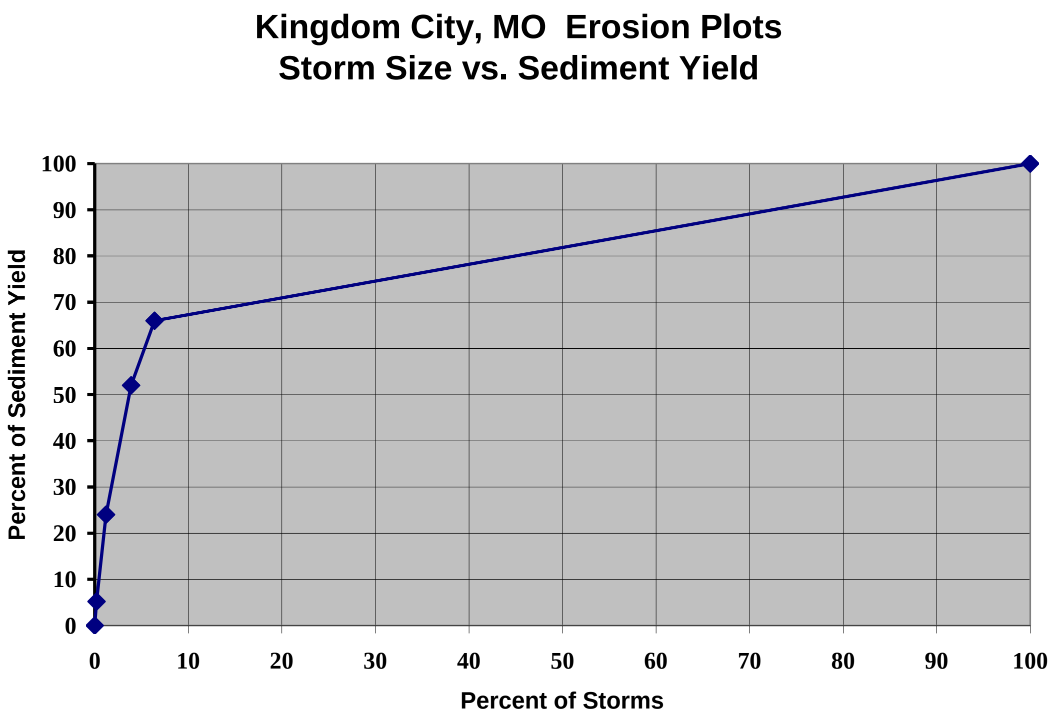

Figure 1. Illustration of the relationship between storm size and sediment yield on the erosion plots at Kingdom City, MO.

To compare with these results from a cultivated cropland area, the next section describes analysis of sediment yield data from a semiarid "hillslope" watershed in SE Arizona.

The 149 km^2 Walnut Gulch Experimental Watershed (Walnut Gulch hereafter) is operated by the USDA-Agricultural Research Service (USDA-ARS) and is located in southeastern Arizona, USA at approximately 31^o45' N latitude and 110^o W longitude, and at elevations ranging from 1250 to about 1900 m above MSL. The climate of Walnut Gulch is classified as semiarid or steppe, with about 70 percent of the annual precipitation occurring during the summer months from convective thunderstorms of limited aerial extent. Soils on Walnut Gulch are generally well-drained, calcareous, gravelly to cobbly loams. Shrub vegetation, such as creosote bush, acacia, tarbush, and small mesquite trees, dominates (30 to 40 percent canopy cover) the Lucky Hills area of Walnut Gulch. The smallest watershed at Lucky Hills is called Lucky Hills 5 Watershed and drains only a portion of a hillslope (Lane, et al., 2001)

Sediment yield data were monitored on the 0.182 ha Lucky Hills 5 watershed on Walnut Gulch from 1973 until 1992. However, because of equipment failure, not all events were monitored so that the following analyses are for individual events rather than mean annual sediment yield. As will be shown, the influence of large storms on sediment yield is also profound at this semiarid rangeland location.

Table 2. Summary of sediment yield (SY) from Watershed Lucky Hills 5 at Walnut Gulch, near Tombstone, AZ. Forty monitored events, 1973-1992, from the 0.182 ha "hillslope" watershed were analyzed.

Data Set	No. of Events	Total Sediment Yield (t/ha)	Percent of Storm Events	Percent of Total Sediment Yield
All Storms	40	22.7	100.	100.
SY > 0.5 t/ha[1]	11	18.2	27.5	80.
SY > 1 t/ha	6	14.6	15.	64.
Largest Storm[2]	1	8.24	2.5	36.

1. The notation "SY > 0.5 t/ha" means all the storm events with sediment yields > 0.5 t/ha and similarly for 1 t/ha.
2 The largest storm event in 20 years of record occurred in July 1975.

Notice that large storms also dominant sediment yield from this semiarid watershed. In fact, the single largest storm in the 20 year period accounted for 36% of the total sediment yield from the 40 monitored events. The 6 largest storms accounted for over 60% of the total sediment yield and the 11 largest storms accounted for 80% of the total sediment yield

The relationship between storm size and sediment yield for Watershed Lucky Hills 5 is summarized in Fig. 2. Notice that except for the single largest storm, the slope of the curve in Fig. 2 is "flatter" that the curve in Fig. 1. The reason for this is unknown at present, but may be because of differences between event mean and annual mean sediment yield and the difference between small and larger sample size (40 at Lucky Hills 5 and 513 at Kingdom City).

<u>Data and Information from the Small Watershed Scale</u>

Hjelmfelt, et al. (1986) also examined data from a small watershed (33.5 ha) operated by the USDA-ARS and cropped to corn with conventional tillage on field contours. The watershed contains significant gullies and is located near Treynor, IA. The data consisted of an 18 year period of record. There were 357 storm events during the 18 years of record and the 34 largest storms (storm sediment yield > 4 t/ha) were analyzed. The overall mean annual sediment yield was 22.6 t/ha.

The single largest storm in the 18 years of record accounted for some 16% of the total sediment yield, the largest 2 storms accounted for 24%, and the largest 34 storms accounted for about 88% of the total sediment yield during the 18 year period of record.

The relationship between the number of large storms and the percent of the total sediment yield they represent is shown in Fig. 3.

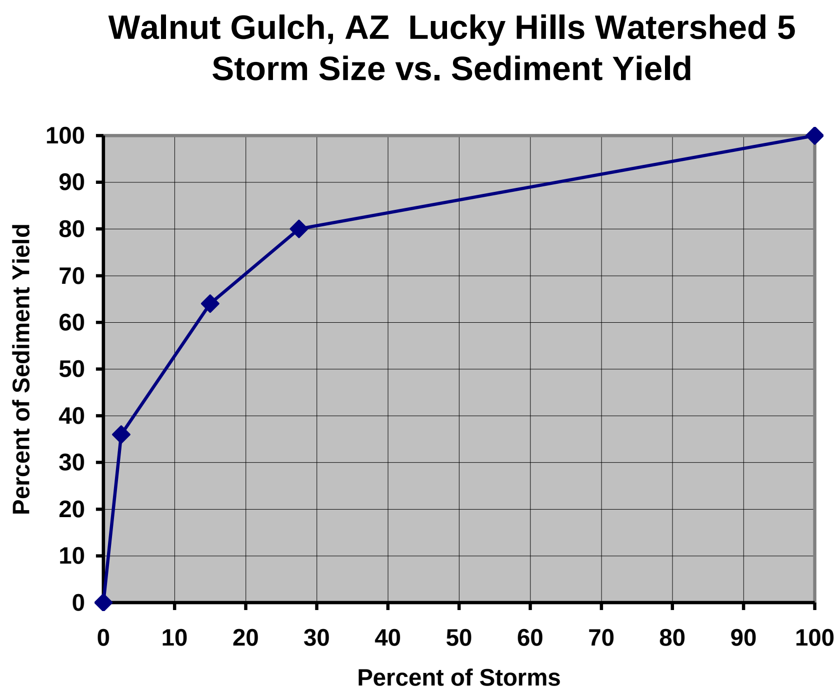

Figure 2. Illustration of the relationship between storm size and sediment yield on Lucky Hills Watershed 5.

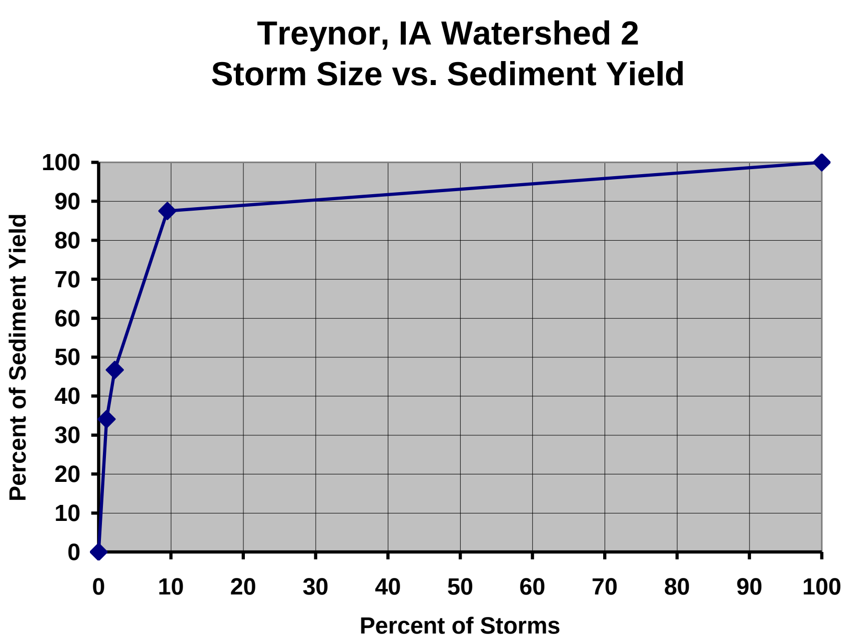

Figure 3. Illustration of the relationship between storm size and sediment yield on a gullied watershed near Treynor, IA.

Lawrence (1996) presented annual sediment yield from 4 small watersheds on the Santa Rita Experimental Range near Tucson, AZ. The USDA Agricultural Research Service operates 8 small experimental watersheds, established in 1974, within the Santa Rita Experimental Range, to study the influence of land use and management practices upon gully erosion and sediment yield. Four of these small watersheds (1.06 to 4.02 ha) with gullies are the subjects of this study. In 1974, 2 of the watersheds (6 and 7) were treated to control the invasion of mesquite (*Prosopis velutina* Woot.), and were subsequently retreated as needed. Watersheds 5 and 8 remained untreated. Grazing practices include yearlong cattle grazing on 2 watersheds (7 and 8) and a rotation system on the other 2 (watersheds 5 and 6). Treatment and management have remained constant since the study's inception. The watersheds are instrumented to measure precipitation, surface runoff, and sediment yield (Lawrence, 1996).

Annual sediment yields for each of the 16 years from 1976 – 1991 were computed and from them a mean annual sediment yield for all 16 years was computed for each of the small watersheds. In a slight variation of the previous analyses, contributions of sediment yield from the individual years (not events) were used to analyze the relationship between sediment yield in "large sediment yield years" and the 16–year total sediment yield. The results of these analyses are shown in Fig. 4.

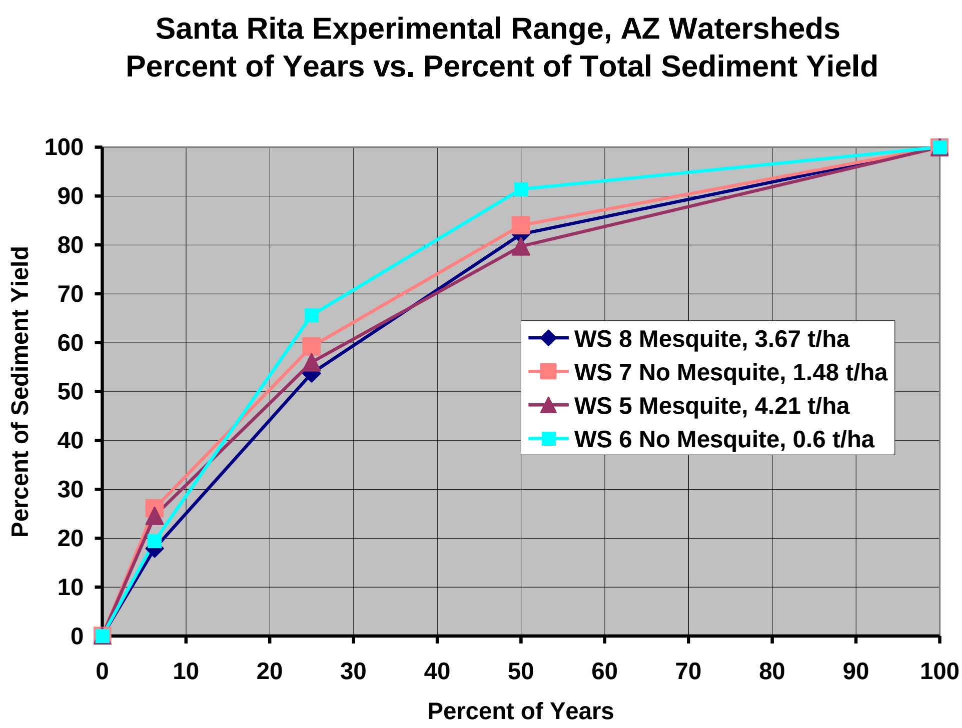

Figure 4. Relation between sediment yields in the years with the largest annual sediment yields to the 16-year total sediment yield on four watersheds at the Santa Rita Experimental Range in southern Arizona.

The data in Figure 4 can be interpreted as follows. During 16 years of data, the year with the largest sediment yield (fraction of years = 1/16 = 0.0625) accounted for about 18 to 26% of the mean annual sediment yield. The 4 years with the largest sediment yield (25% of the period of record of 16 years) accounted for about 54 – 66 % of the mean and the 8 years with the largest sediment yields accounted for about 80 - 90% of the mean annual sediment yields on the 4 watersheds.

Summary of Findings and Discussion

Findings - Role of Large Events in Determining Mean Annual Sediment Yield

Data from cropland and rangeland plots and small watersheds, where sediment yield is dominated by rainfall-surface runoff events, were analyzed to examine the role of large storms in determining mean annual sediment yield. From analyses of erosion and sediment yield data from experimental erosion plots (Kingdom City, MO) and a small watershed at the hillslope scale (Lucky Hills on Walnut Gulch, AZ), a small gullied watershed in Iowa (Treynor, IA), and four small gullied watersheds in Arizona (Santa Rita Experimental Range, AZ), it is apparent that the larger, rarer, sediment yield events largely determine long-term mean annual sediment yield.

Discussion

The conclusion and a hypothesis generated from the above analyses are that: 1) the large storm events determine mean annual sediment yield and 2) they are also responsible for the most rapid periods of landscape evolution.

The role of the large events is to erode significant amount of soil from the hillslopes and deliver large amounts of sediment to the stream channel systems in watersheds. These channel systems can be both sinks for sediment (net deposition) and sources of sediment (net erosion of channel bed and banks). Net deposition and net erosion in the channel networks determine landscape evolution within the watershed by controlling base level at the toes of hillslopes, within the individual channels, and at the junctions of channels all the way to the watershed outlet. The role of the smaller events then seems to be to rework and shape these sediments remaining after a large event to try to bring them back in quasi-equilibrium with the most commonly observed discharges in the watershed. These “most commonly” observed discharges range from the most frequent small events up to something near the mean annual flood – the approximate boundary between small and large events as defined herein.

Some Implications for Monitoring, Modeling, and Reclamation

Implications

The implications for monitoring are that the monitoring program must be operated long enough so that the time series of monitoring data have a “reasonable chance” of including large events (for example regulatory events of 25 year frequency) determining mean annual sediment yield and the resulting rates of landscape evolution. Following standard probability theory (e.g. Rao and Hamed, 2000) for frequency analyses of annual data it is possible to relate the length of the monitoring period, N in years, to the probability of including a flood/sediment yield event of a given return period, T in years. Example calculations are included in Table 3.

Table 3. Calculation of the probability of a monitoring period N years long including the flood/sediment yield event of a given return period, T in years.

Return Period T (yrs)	Length of Monitoring Period in Years					
	N = 1	N = 2	N = 10	N = 20	N = 50	N = 100
2	0.5	0.75	0.999	~1	~1	~1
5	0.2	0.36	0.893	0.988	~1	~1
10	0.1	0.19	0.651	0.878	0.995	~1
25	0.04	0.078	0.335	0.558	0.870	0.983
50	0.02	0.080	0.183	0.332	0.636	0.867
100	0.01	0.020	0.096	0.182	0.395	0.634

The data in Table 3 can be interpreted as follows. For a monitoring period of N=2 years (column number 3 in Table 3) there is a 75% chance of including the 2 year flood/sediment yield event (flood event hereafter) but only a 7.8% chance of including the 25 year flood event. Now, if we define a "reasonable chance" as a 50% probability, then for the 10 year flood, one would have to monitor 7 years or longer to include the 10 year flood, 17 years or longer for the 25 year flood, 34 years or longer for the 50 year flood, and 69 years or longer for the 100 year flood.

Thus, it is obvious that to include the larger, rarer events in the monitoring data, with a "reasonable chance" being defined as 50% probability, then the monitoring period, should be about 70% as long as the return period. If one were to define "reasonable chance" as a 90% probability of including the T year flood, then the required monitoring period would increase. Using the 25 year flood as an example, if we wanted a 90% probability that the monitoring period included a 25 year flood, then the monitoring period would need to be 57 years long. This means that the monitoring period should be about 2.3 times as long as the return period if the return period is to include the T year flood with 90% probability.

A main scientific limitation for monitoring data is that they define the system being monitored and lack the ability to predict what would happen if the system were changed (for example by an alternative reclamation design). That is, empirical data (and empirical models based on them) only describe the circumstances under which the data were collected. If one changes the climatic input, the topographic design, soil properties, re-vegetation methods, etc. then one would need to collect new empirical data to represent whatever was changed.

This is where process-based modeling is of value (see Clark et al., 2006 and Lane and Wigmosta, 2006 for examples) in predicting the future response of alternative designs and reclamation methods. However, the state-of-the-science is such that process-based models need some calibration data to determine their appropriate parameter values. Thus, the limitations of the length of monitoring periods carry over into simulation modeling, evaluation of alternative reclamation systems based on monitoring data and simulation modeling, and ultimately, to the quality of the site reclamation.

Acknowledgments

Funding for this research was provided by the Los Alamos National Laboratory, for which we are very grateful, and by L. J. Lane Consulting, Inc. Collection, processing, and publishing quality, long-term monitoring data require significant resources, insight, and a commitment to the future. We gratefully acknowledge the excellent, long-term plot and watershed monitoring programs of the USDA-Agricultural Research Service which provided the hydrologic data that made this research possible. Finally, I thank the anonymous reviewers for their helpful comments and suggestions to improve the paper.

Literature Cited

Clark, D. L., Janecky, D. R., and Lane, L. J. 2006. Science-based cleanup of Rocky Flats. Physics Today, Sept. 2006, pp:34-40, (Feature Article). http://dx.doi.org/10.1063/1.2364243.

Hjelmfelt, A. T., Jr., Kramer, L. A., and Spomer, R. G. 1986. Role of large events in average soil loss. *In*: Proceedings of the Fourth Federal Interagency Sedimentation Conference, Las Vegas, NV, March 24-27, 1986. Vol. I, pp. 3-1 – 3-9.

Lane, L. J., Nichols, M. H., Levick, L. R., and Kidwell, M. R. 2001. A simulation Model for erosion and sediment yield at the hillslope scale. Chapter 8 In: Landscape Erosion and Evolution Modeling (Harmon, R. S. and Doe, W. W., III), Kluwer Academic/Plenum Publishers, New York, pp. 201-237. http://dx.doi.org/10.1007/978-1-4615-0575-4_8

Lane, L. J. and Wigmosta, M.S. 2006, The role of processes-based models and scaling in geomorphic designs, Proceedings America Society of Mining and Reclamation, 2006 pp 409-42. http://dx.doi.org/10.21000/JASMR06010409

Lawrence, P. A. 1996. The role of data sources and simulation model complexity in using a prototype decision support system. Unpublished PhD Dissertation, School of Renewable Natural Resources, University of Arizona, Tucson, AZ, 332 pp.

Rao, A. R. and Hamed, K. H. 2000. Flood frequency analysis. CRC Press, Boca Raton, Florida, USA. 350 pp.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C. (coords.) 1997, Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE): USDA Agricultural Handbook No. 703.

Wischmeier, W. H. 1962. Storms and Soil Conservation. J. Soil and Water Conservation, 17(2): 55-59.

Wischmeier, W. H. and Smith, D. D. 1978. Predicting rainfall erosion losses, Agriculture Handbook No. 537, USDA Sci. and Educ. Admin.: Washington. DC.