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PROBABILITY DISTRIBUTIONS OF RAIN ON SNOW FOR NORTHCENTRAL OREGON

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INTRODUCTION

Rain-on-snow events can be a major factor in flood damage and can significantly increase water yield in some watersheds of the Pacific Northwest. Winter runoff that occurs on steeply sloping croplands and rangelands can result in serious soil erosion and sediment production. Although the literature documents this type of winter storm event (Johnson and McArthur, 1973; Zuzel et al., 1982; Zuzel et al., 1983), quantitative data on the frequency and magnitude of these events is entirely lacking. Johnson and McArthur (1973) state that the usual flood producing conditions are periods of extreme cold resulting in frozen soils with a shallow snow cover, followed by the intrusion of rain-producing warm, moist air masses and strong southwest winds.

These conditions were modeled by Zuzel et al. (1983) using data collected at an erosion-monitoring site in northcentral Oregon. The results confirmed that rain on a shallow snowpack with frozen soil is one of the key factors in the production of accelerated upland runoff. They also showed that condensation melt associated with the intrusion of warm, moist Pacific air masses accelerates the snowmelt rate beyond that expected from radiation, sensible heat and heat content of the rain.

Quantification of the frequency and magnitude of these rain-on-snow events is essential to more accurate predictions of both runoff and soil loss. The study reported here developed these probabilities for Moro, Oregon (Figure 1) located in the southwest part of the Columbia Plateau major land resource area, MLRA B8 (USDA, 1981). Average annual precipitation for Moro is 288 mm of which 70% occurs during the November through April period. The winter climate is also characterized by a shallow transient snowpack subject to several accumulation and melt cycles each winter. Frozen soils are common and occur nearly every year.

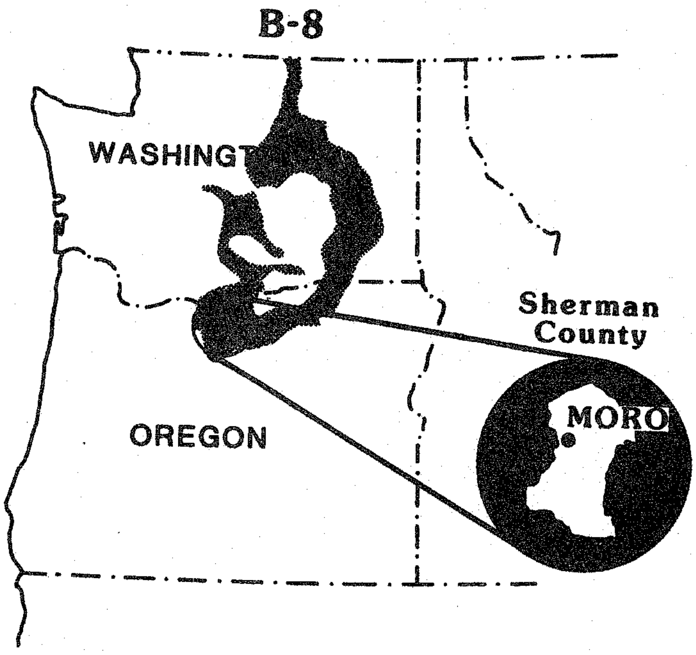

Figure 1. Location of the study sites in northcentral Oregon.

DATA SOURCES

We obtained daily weather data, including maximum and minimum air temperatures, precipitation, snowfall and snow on the ground from National Weather Service records for Moro, Oregon for 1948 through 1978. Missing data were estimated from the nearest weather station record which contained the necessary variable. We also obtained crest gage data for 1959 through 1978 for Gordon Hollow at DeMoss Springs, Oregon, from the U.S. Geological Survey, Water Resources Division records. The crest gage records contain only the water year peak discharge so lesser peaks which occurred during the period of record were not available. The crest gage site was located 2 km north of Moro, Oregon, and has a drainage area of approximately 23 km^2. Elevation of the basin varies from 475 to 664 m while the elevation of the Moro weather station is 560 m.

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METHODS

The algorithm we used to extract rain-on-snow events from the 1948-1978 Moro weather record is shown in Figure 2. The conditions which must be met for a rain-on-snow event to have occurred are: 1) precipitation had occurred, but snowfall had not occurred; 2) the maximum air temperature was greater than 0°C, and 3) snow was present on the ground the previous day. The condition of no snowfall excludes events where snowfall occurs at air temperatures greater than 0°C; snow on the ground the previous day excludes rain on bare soil events; and maximum air temperature greater than 0°C excludes events with freezing rain or sleet. We correlated the resulting rain-on-snow events with the crest gage record from Gordon Hollow at DeMoss Springs, Oregon, and developed a probability distribution of daily rain-on-snow amounts. We also determined the number of years of occurrence and number of occurrences per year of rain on snow. It should be noted that dates of peak discharge occurrence listed in crest gage records are not always exact, so that detailed examination of weather records was necessary to determine or confirm the date of peak in all cases.

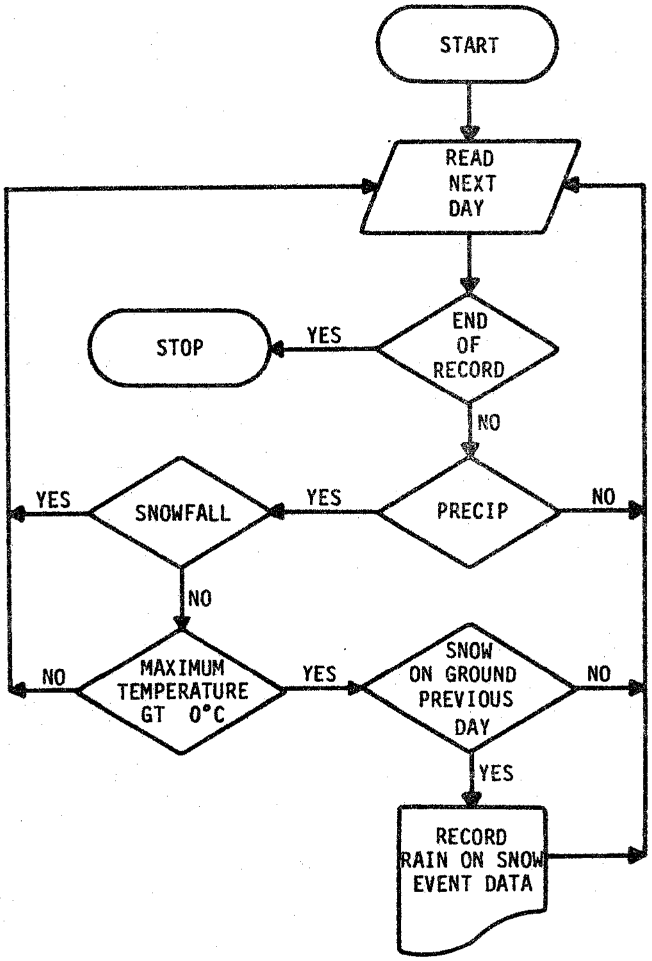

Figure 2. Flowchart of the algorithm used to extract rain-on-snow events from weather records.

RESULTS AND DISCUSSION

Analysis of the Moro weather record using the algorithm shown in Figure 2 produced 133 rain-on-snow events. Rain on snow occurred in 28 of the 30 years of record at this location; an occurrence probability of 0.933. The average number of events per year was four. However, the amount of precipitation was less than 2.5 mm for 50% of these events. Antecedent snow on the ground ranged from 3 to 46 cm with a mean of 9 cm. Summary statistics for the events are presented in Table 1.

Table 1. Summary statistics for 133 rain-on-snow events at Moro, Oregon, 1948-1978.

Variable	Mean	Median	Std. Dev.	Max.	Min.
Precipitation (mm)	4.20	2.54	5.41	32.0	0.3
Maximum Air Temperature (°C)	5.72	6.00	3.02	14.0	1.0
Minimum Air Temperature (°C)	-2.29	-2.00	3.53	5.0	-14.0
Snow on Ground (cm)	4.68	3.00	6.20	38.1	0.0
Antecedent Snow on Ground (cm)	9.18	8.00	8.05	45.7	2.5
Snow Loss (cm)	4.50	3.00	4.41	25.4	0.0

The empirical and theoretical distributions of daily precipitation for the rain-on-snow events are shown in Figure 3. We approximated the observed distribution

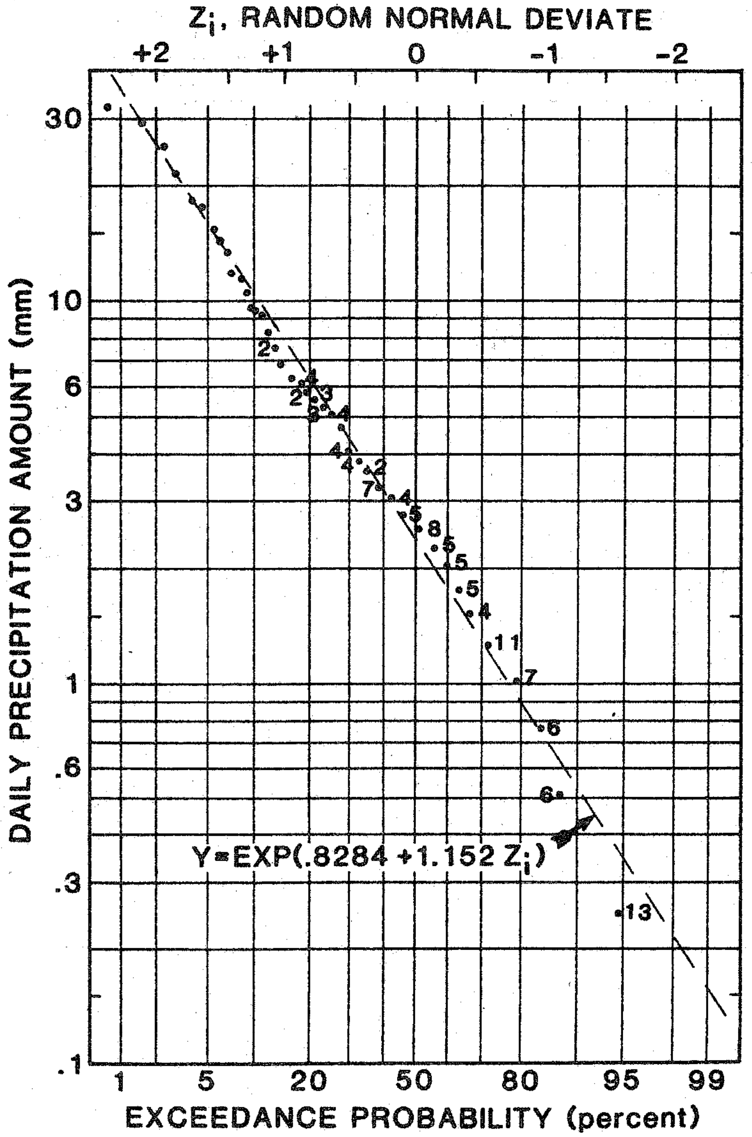

Figure 3. **Probability distribution of daily precipitation amount for rain-on-snow events.**

with a lognormal distribution with parameters $\mu_y = 0.8284$ and $\sigma_y = 1.152$ where μ_y is the mean of the logarithims of daily precipitation amount and σ_y is the standard deviation of the logarithims. We generated a sample of 500 points using these parameters in the equation:

$$Y = \text{EXP}\ (\mu_y + \sigma_y Z_i), i = 1{,}500 \qquad (1)$$

where Y is a daily rainfall amount in millimeters; Z_i is a random normal deviate, N(0,1); and μ_y and σ_y are as previously defined. A comparison of the observed and generated data is shown in Table 2.

Table 2. Comparison of the statistics of the observed and generated daily rainfall amounts for rain-on-snow events at Moro, Oregon, 1948-1978.

Statistic	Observed	Generated
Mean (mm)	4.20	4.36
Standard Deviation (mm)	5.41	5.63
Skew	2.91	3.74
Maximum (mm)	32.00	52.74
Minimum (mm)	0.25	0.06

We applied both the chi-square and Kolmogorov-Smirnoff goodness-of-fit tests and could not reject the hypothesis that the data conform to the lognormal distribution (P=0.95). We concluded that the theoretical distribution with the stated parameters adequately approximates the observed frequency distribution. Since the probability of rain on snow in any year is 0.933, the distribution of daily rainfall amount for rain on snow becomes:

$$Y = 0.933 \, [\mathrm{EXP} \, (\mu_y + \sigma_y Z_i)] \qquad (2)$$

where all terms are as previously defined. This shifts the theoretical distribution slightly to the left and has the effect of decreasing the exceedance probability of any given rainfall amount. The solution of equation (2) with the derived parameters and/or the data shown in Figure 3 provides a useful means of describing daily rainfall amounts for rain on snow in probabilistic terms. However, from this analysis alone, we were unable to infer the minimum daily amount necessary to produce runoff. While it is reasonable to assume that a minimum daily rainfall amount is necessary to generate runoff, both runoff volume and peak are also dependent on antecedent moisture, snow depth, snow water equivalent, and the presence or absence of frozen soil.

The number of rain-on-snow events per year ranged from zero in the two years when the event did not occur to 11 events per year in 3 of the 30 years. The distribution of the number of events per year is plotted in Figure 4. In this case, we modeled the

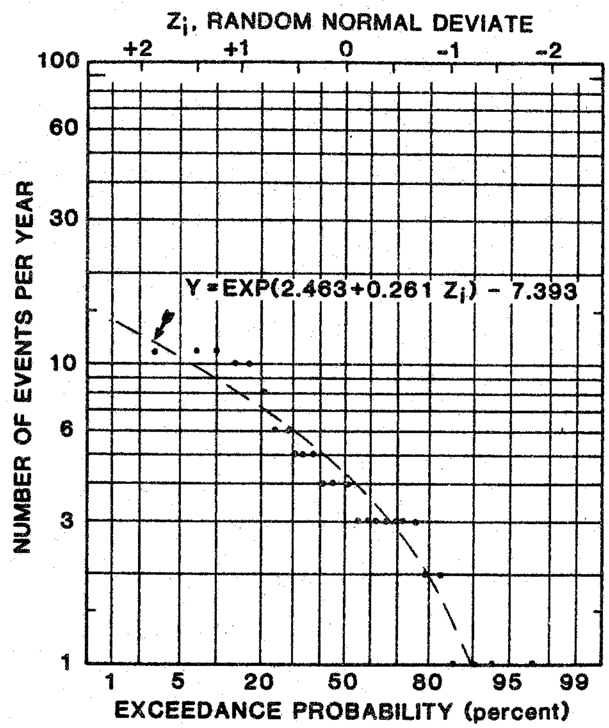

Figure 4. Probability distribution of the number of rain-on-snow events per year.

observed distribution with a 3 parameter lognormal distribution having the parameters shown in Figure 4. We also generated a sample of 500 points using the equation given in Figure 4. A comparison of the observed and generated data is shown in Table 3.

Table 3. Comparison of the statistics of observed and generated number of rain-on-snow events per year for at Moro, Oregon, 1948-1978.

Statistic	Observed	Generated
Mean	4.8	4.9
Standard Deviation	3.2	3.1
Skew	0.82	0.51
Maximum	11	17.0
Minimum	1	- 2.0

The crest gage data analysis for Gordon Hollow provided us with an estimate of the precipitation amount necessary to produce runoff as well as suggesting the relationships between runoff peak, snow on the ground, and daily rainfall amount. The gage had been in operation since 1959 and of the 20 yearly peak discharges recorded through 1978, five years had no flow, one peak discharge occurred in June and 14 occurred during the November through March period. Our analysis showed that 8 of these 14 events (57%) were the result of rain on snow while the remaining 6 events were the result of rain with no snow cover. Peak discharges ranged from 1.2 to 27.9 m^3/sec with a mean of 9.1 m^3/sec, while precipitation ranged from 5 to 32 mm with a mean of 15.0. Statistics of the rain-on-snow runoff events are shown in Table 4 as well as the correlation coefficients of each variable with peak discharge.

Table 4. Summary statistics for 8 rain-on-snow runoff events causing maximum annual peak discharge at Gordon Hollow at DeMoss Springs, Oregon.

Variable	Mean	Median	Std. Dev.	Max.	Min.	r
Precipitation (mm)	14.98	13.97	8.74	32.0	5.3	0.890
Average Air Temperature (°C)	4.87	4.50	1.96	8.0	3.0	-0.318
Maximum Air Temperature (°C)	8.62	8.00	2.88	12.0	4.0	-0.147
Antecedent snow on ground (cm)	6.87	3.00	7.72	25.4	2.5	0.637
Peak Discharge (m^3/sec)	9.1	4.3	10.4	27.9	1.2	1.00

A regression analysis using antecedent snow on the ground and precipitation amount as independent variables and peak discharge as the dependent variable produced the results shown in Table 5. Average air temperature and maximum air temperature were also included to show the relative importance of these variables in rain-on-snow events. This analysis was intended to show the relationships between the variables and not to develop predictive equations. It should be noted that while both antecedent snow on the ground and precipitation each explain a significant percentage of the observed variation in peak

Table 5. Coefficients of determination for the effect of 2 independent variables on peak discharge at Gordon Hollow at DeMoss Springs, Oregon.

Variable	r^2	r*
Antecedent snow on ground (cm)	40.6	30.7
Precipitation (mm)	79.3	75.8
Both	80.4	72.6
Average Air Temperature (°C)	10.1	0.0
Maximum Air Temperature (°C)	2.2	0.0

r* = coefficient of determination adjusted for degrees of freedom.

flow, the combination of both does not increase explained variance to a significant degree. Moreover, when one adjusts the coefficient of determination for degrees of freedom, no advantage is realized by using both variables in this regression. We believe that this is because the values of snow on the ground are concentrated at 3 to 5 cm. If a wider range of snow data were available, snow on the ground would probably assume more significance. Figure 5 illustrates the range of values of snow on the ground, precipitation, and peak discharge.

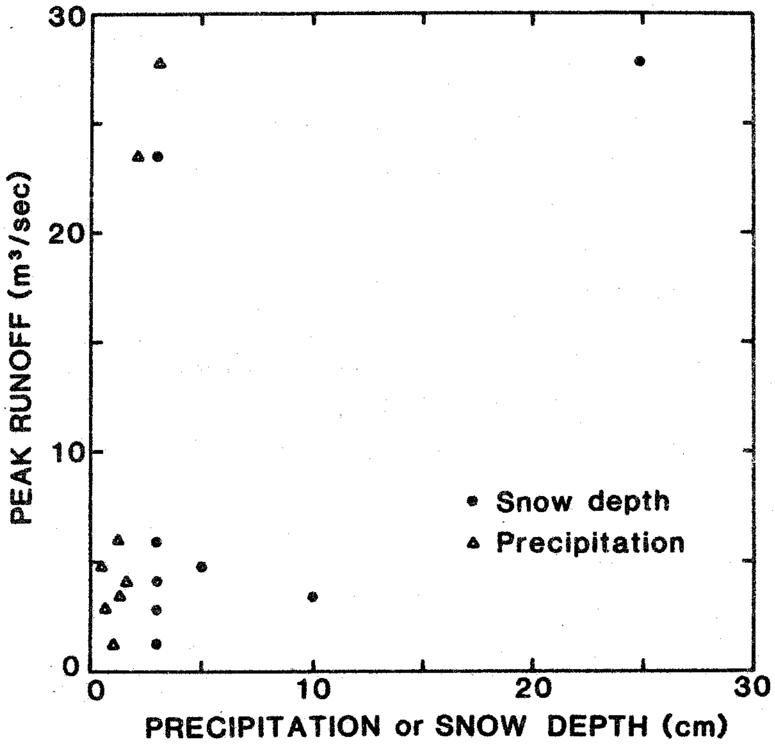

Figure 5. Observed values of precipitation, snow depth and peak runoff.

SUMMARY AND CONCLUSIONS

The analysis used here demonstrates that the temporal distribution of rain-on-snow events can be adequately defined given a sufficiently long weather record containing the variables shown in Figure 2. Rain on snow occurred in all but 2 years of the 30 year record we analyzed. When rain on snow did occur, the number of events per year varied from 1 to 11.

The crest gage data analyses suggested that in a rain-on-snow occurrence, about 5 mm per day of precipitation was necessary to generate runoff from the test watershed. The conditional distribution (Equation 2) shows that the probability of a rain-on-snow event greater than or equal to 5 mm is 0.24. During the November through March period, rain-on-snow events associated with 57% of the yearly peak discharges recorded at the Gordon Hollow crest gage. Daily precipitation amount and antecedent snow depth jointly accounted for 73% of the variance of these runoff peaks.

Probability distributions, such as described in this study, define the frequency of runoff, flood, and sediment producing events and can be used as inputs to deterministic watershed and field scale models. The distributions should also be useful in hydrologic design and planning. The fact that 57% of the yearly peak discharges recorded at the crest gage over a 20 year period were the result of rain on snow emphasizes the importance of these events in runoff generation.

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