Journal of Hydrology, 53 (1981) 277—304
Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

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SOME CHARACTERISTICS AND CONSEQUENCES OF SNOWMELT DURING RAINFALL IN WESTERN OREGON

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(Received April 23, 1980; accepted for publication September 9, 1980)

ABSTRACT

Harr, R.D., 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. J. Hydrol., 53: 277—304.

Hydrometeorological data for two watersheds in western Oregon indicate snowmelt during rainfall has been a dominant hydrologic process which is responsible for erosion within headwater areas and for downstream flooding. The majority of the larger peak flows in both watersheds result from snowmelt during rainfall. In a stream draining a 60-ha watershed in the zone of transient shallow snowpacks, a major peak flow of 10 l/s per ha is five times more likely to result from rain-on-snow than from rain alone. In a 62.4-km^2 watershed, largely within the transient snowpack zone, 85% of all landslides which could be accurately dated were associated with snowmelt during rainfall. By increasing melt caused by condensation and convective heat transfer, clearcut logging, especially on southwestern-facing slopes, may be increasing water input to soil up to 25% during infrequent combinations of shallow snowpacks, heavy rains, relatively warm air and wind. Under more frequent combinations, increases in water input still could be 10%. Limitations in present knowledge are discussed.

INTRODUCTION

Although the major part of precipitation in western Oregon falls as rain, snowmelt concurrent with prolonged rainfall has been a dominant factor in the geomorphology of both headwater and downstream regions. Rainfall combined with nearly complete melting of shallow snowpacks often causes deep saturated zones in forest soils on steep slopes, and the positive pore-water pressures which develop in these saturated zones can reduce the effective strength of soil masses sufficiently to cause landslides (Swanston, 1974). Not only is the headwater landscape altered by landslides (Dyrness, 1967; Rothacher and Glazebrook, 1968), but also large amounts of sediment and organic debris may be deposited in streams (Fredriksen, 1965; Swanson et al., 1976). During periods of high streamflow, streams may alter their channels by undercutting banks, downcutting beds, and redistributing sediment and large organic debris. Much of the alluvial material in the Willamette

Valley and in flood plains of other rivers in western Oregon was deposited during flooding by sediment-laden water of rain-on-snow floods.

The rain-on-snow phenomenon has also affected man's activities in western Oregon. Farmland, homes and cities on flood plains of rivers and streams have been flooded, and transportation systems disrupted numerous times since the region was settled in the middle 1800's. Before the construction of flood-control dams on the Willamette River and its tributaries, the average annual instantaneous peak flow at Salem, Oregon, was estimated to have flooded ~10,800 ha of the Willamette Valley (Brands, 1947). Even with the flood-control system in operation, rain-on-snow runoff of January 1974 caused damage of US $47 million in downstream areas of the Willamette River basin and an additional $19 million in other river basins in western Oregon (U.S.A.C.E., 1975). Similarly, rain-on-snow runoff of December 1964 and January 1965 caused $65 million damage in the Willamette basin and $53 million in the remainder of western Oregon (Waananen et al., 1971).

Some snowmelt during rainfall has occurred nearly every year, but published accounts of rain-on-snow runoff in western Oregon have been restricted to the largest events most damaging to cities, farmland and transportation systems in lowlands (e.g., Brands, 1947; Hoffman and Rantz, 1963; Waananen et al., 1971; U.S.A.C.E., 1975). In many years, erosional damage in headwater regions goes almost unnoticed because such damage often occurs independently of the more publicized downstream flooding.

Throughout the Pacific Northwest, land managers of the U.S.D.A. Forest Service and certain other organizations are attempting to schedule timber harvest operations such that soil and water resources are protected. Success of such harvest scheduling may ultimately depend heavily on our ability to predict the effects of harvest on snowmelt from shallow packs during rainfall.

Concern about the potential effects of clearcut logging on erosion caused by snowmelt during rainfall in headwater areas and the general lack of research information on rain-on-snow runoff led to this paper. The purposes of this paper are to describe the importance of snowmelt during rainfall in certain erosional processes in western Oregon, to discuss potential effects of clearcutting on the rate of this snowmelt, and to stimulate research activity in rain-on-snow hydrology.

SNOWMELT PROCESSES

Snowmelt was studied extensively in Oregon at the Willamette Basin Snow Laboratory (Fig. 1) in the Blue River watershed from 1947 to 1952. Summarized by U.S.A.C.E. (1956), data from this study site, the Central Sierra Snow Laboratory in California, and the Upper Columbia Snow Laboratory in Montana have been supplemented by subsequent studies by the U.S.D.A. Forest Service at the Central Sierra Snow Laboratory (Smith and Halverson,

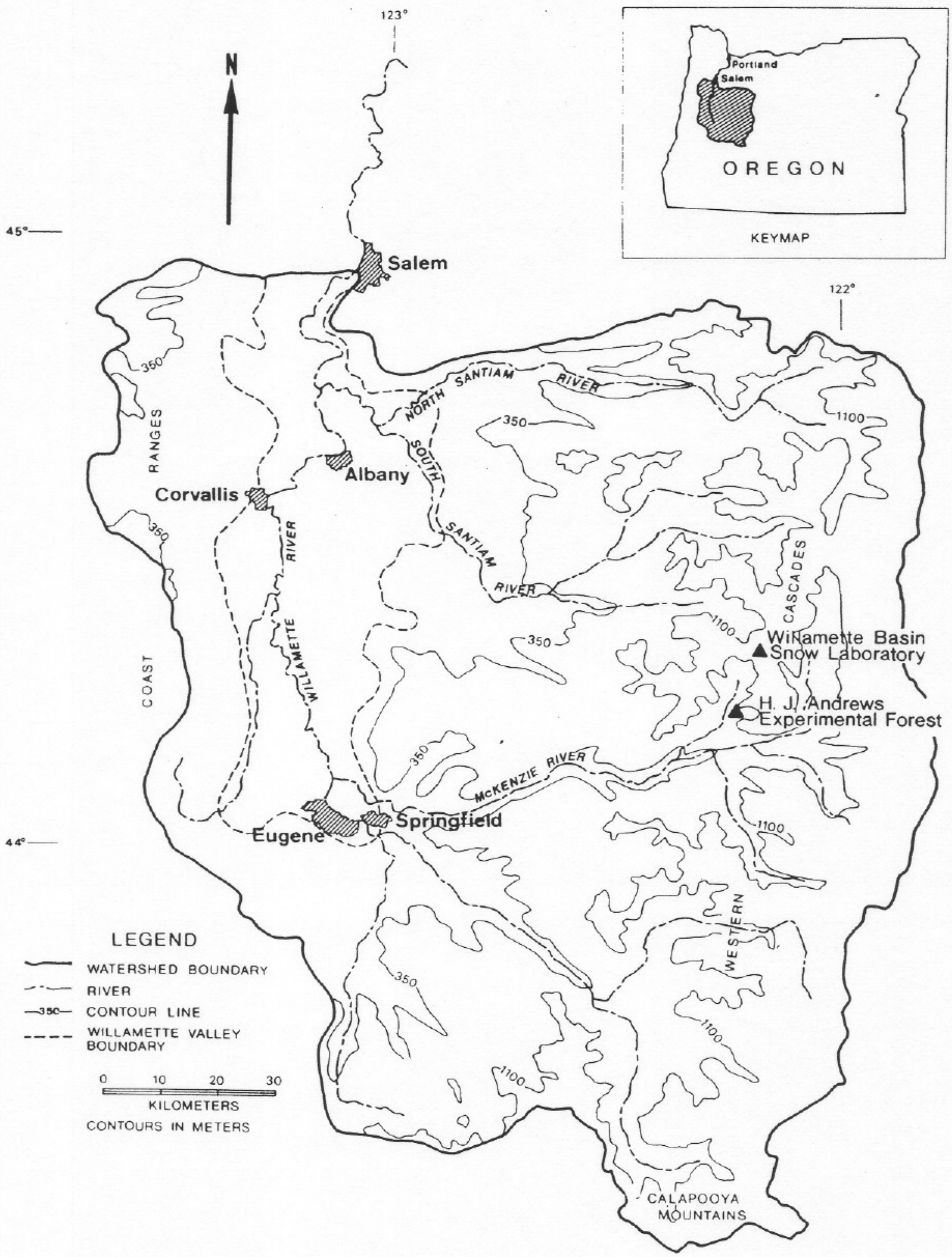

Fig. 1. Map of western Oregon.

1969; Smith, 1974). Little snow hydrology research has been conducted in western Oregon since the early 1950's. Some of the more recent research done at the Ce..tral Sierra Snow Laboratory, in the Sierra Nevada, however, does appear applicable to western Oregon.

Snowpacks in western Oregon, like those in the Sierra Nevada, are "warm" in contrast to the "cold" snowpacks of the central Rocky Mountains and the northeastern U.S.A. (Smith, 1974). A warm snowpack is one whose interior temperatures remain at or near 0°C during the pack's existence. This temperature is hydrologically important because relatively little energy is required to initiate melting. Unlike a cold snowpack which must absorb considerable amounts of water before it ripens (i.e. becomes isothermal at 0°C with its capacity for free water satisfied), a warm pack, because it is always nearly isothermal, can yield water quickly during a period of high air temperature, rainfall, or both if the pack's storage capacity for liquid water has been satisfied. In many instances, the snowpacks at lower elevations in the mountains of western Oregon are shallow enough to be melted completely during rainstorms so that temporary storage of water by the snowpacks and subsequent routing appear to be less important than where packs are deeper.

Several heat-transfer processes melt snow, and the relative importance of each varies with geography and season. Components of melt may be combined to form a general equation for total melt. Total melt M_t is expressed by the relationship:

$$M_t = M_{rs} + M_g + M_{rl} + M_{ce} + M_p \tag{1}$$

where M_{rs} = melt from absorbed short-wave radiation, M_g = melt from ground heat, M_{rl} = melt from absorbed long-wave radiation, M_{ce} = melt from convection and condensation, and M_p = melt caused by the transfer of heat from rain to the snowpack. Details of melt processes are given by U.S.A.C.E. (1956).

Snowmelt during rainfall is a special situation for which certain simplifying assumptions can be made in eq. 1 so that melt may be computed using several indices (U.S.A.C.E., 1960). First, because of cloudiness during rainfall, melt M_{rs} from absorbed short-wave radiation is relatively unimportant; for a forested area it is less than 0.18 cm/day. Also, melt M_g from ground heat is relatively unimportant and less than 0.05 cm/day. Long-wave radiation exchange between forest vegetation or low clouds and the snowpack may be indexed linearly by air temperature such that melt M_{rl} from long-wave radiation is given by:

$$M_{rl} = 0.133 T_a \tag{2}$$

where T_a = daily mean air temperature in °C (average temperature for a 24-hr. period). If air is assumed to be saturated during rainfall, air temperature may be used also to index both convection and condensation melt. For the ranges of vapor pressure or dew point normally experienced in western Oregon, a linear expression of convection and condensation melt may be used which is a function of air temperature and wind. Thus, for an open area, convection—condensation melt M_{ce} can be computed by:

$$M_{ce} = 0.086 V T_a \tag{3}$$

where V is wind speed in meters per second 15 m above the snow surface. In heavily forested areas, wind is so reduced beneath the canopy of undisturbed forests that an average wind speed of 2.4 m/s is assumed, thereby eliminating the wind variable in the melt equation. As a result, convection—condensation snowmelt becomes:

$$M_{ce} = 0.206 T_a \tag{4}$$

Snowmelt M_p caused by transfer of heat from rain may be expressed by:

$$M_p = 0.0126 P_r T_a \tag{5}$$

where P_r = daily precipitation in centimeters. Thus, for a forested area, total snowmelt M_t in centimeters per day can be estimated by:

$$M_t = T_a(0.339 + 0.0126 P_r) + 0.23 \tag{6}$$

Details of snowmelt indices and their derivation are given by U.S.A.C.E. (1956).

The resulting relationships among total snowmelt, rainfall and air temperature are shown graphically in Fig. 2. According to the snowmelt indices on which this figure is based, total snowmelt would be slightly more than 6 cm/day when P_r = 20 cm/day and T_a = 10°C. These climatic conditions, however, occur only rarely in western Oregon. For example, a P_r of 20 cm/day has an estimated return period of ~35 yr. in the H.J. Andrews Experimental Forest 72 km east of Eugene, Oregon, and 50—100 yr in other mountainous areas of western Oregon (Miller et al., 1973). According to air temperature records for the H.J. Andrews Experimental Forest, T_a = 10°C during winter months has coincided with rainfall only four times in 19 yr. of temperature records but never when a snowpack existed. The highest T_a that has occurred with a snowpack present was 7.2°C on December 21—22, 1964. This temperature, which was only partially synchronized with high rainfall, was partly responsible for the extreme runoff that caused severe damage in headwater areas and considerable flooding of lowlands. At lower, more common T_a-values of 4—5°C and P_r-values of less than 12 cm/day, M_t = 2.5 cm/day should be equaled or exceeded on the average about once every 5 yr.

The relative importances of melt caused by various heat-transfer processes as computed by snowmelt indices are shown graphically in Fig. 3. When T_a = 2°C and P_r = 10 cm/day (rainfall with a return period of ~1 yr.), the heat transfer from rain accounts for less snowmelt, M_p, than do heat exchanges from either net long-wave radiation or convection—condensation. Although the phrase "rain-on-snow" implies snow is melted by warm rain, hydrologists have long recognized that this is not entirely the case. Some snow is melted directly by rain, but the heat transferred to the snowpack

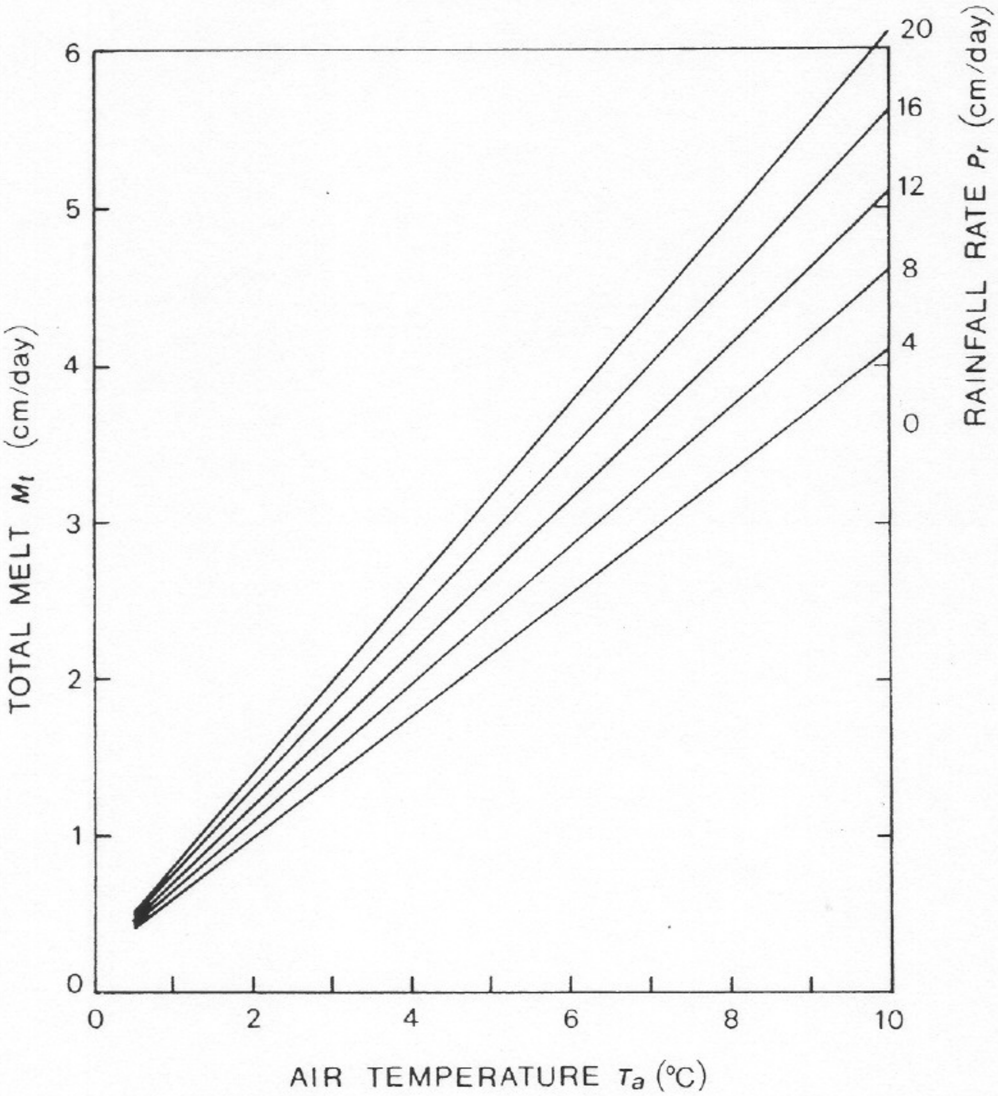

Fig. 2. Relationships among total snowmelt, air temperature, and rainfall rate at a point under forest (adapted from U.S.A.C.E., 1960).

during condensation of water vapor on the snowpack surface appears the greatest single source of heat for snowmelt and comprises ~80% of convection—condensation melt when P_r is less than 13 cm/day (U.S.A.C.E., 1956). Only when P_r is greater than 17 cm/day does the heat supplied by the rain itself surpass combined convection and condensation as a source of heat for snowmelt.

The relative effect of snowmelt on water delivery to soil during rainfall is greatest during periods of low rainfall (Fig. 4). For example, in the case described above in which $M_t = 6$ cm/day (with $P_r = 20$ cm/day and $T_a = 10°$C) snowmelt would increase the daily rate of water delivery to the soil surface by ~30% over that which would occur during rainfall in the absence of a snowpack. But, if $P_r = 2.5$ cm/day and $T_a = 10°$C, the melt rate would increase the amount of water delivered to the soil by ~150%. Peak flows that result from such low values of P_r, however, are small and of little

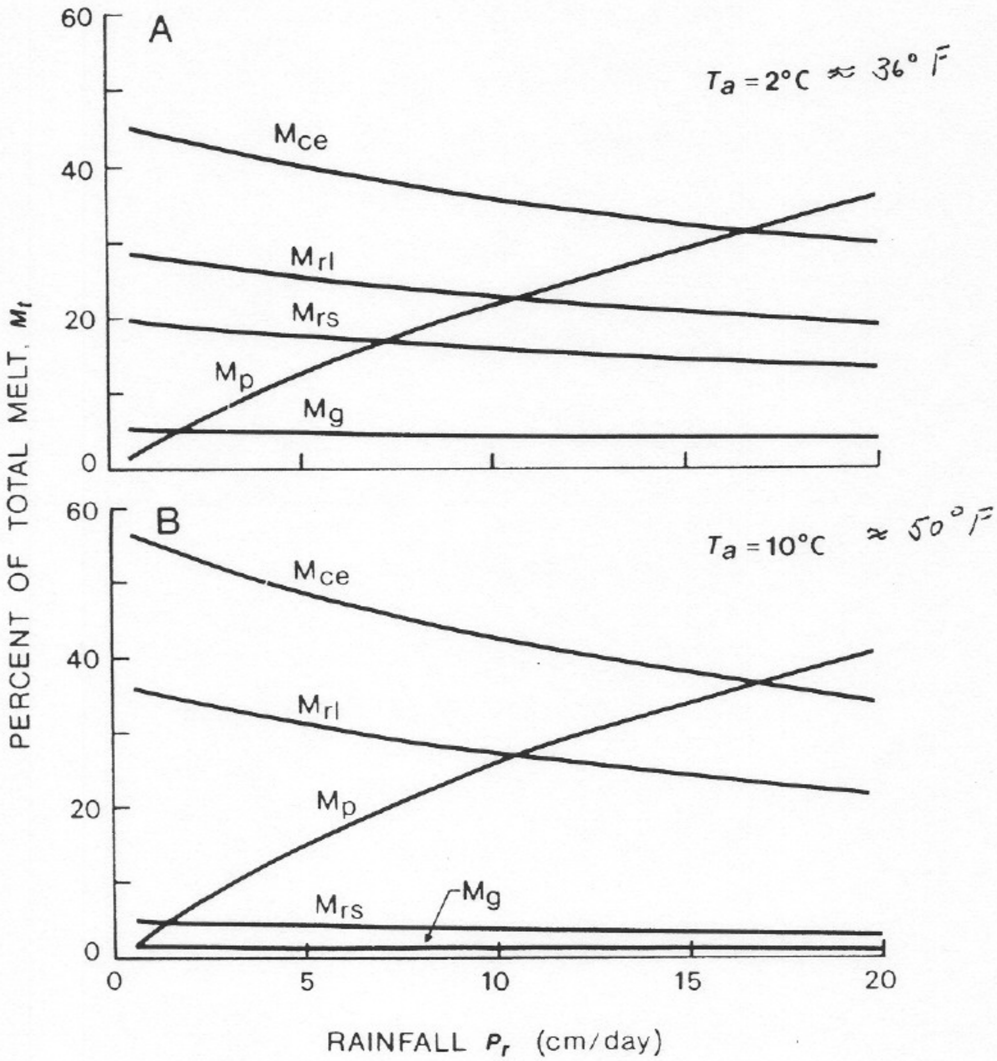

Fig. 3. Proportion of total snowmelt at a point under forest caused by various components of melt during rainfall at air temperatures of 2°C and 10°C. Melt components are defined in the discussion of eqs. 1—6 (adapted from U.S.A.C.E., 1960).

consequence in terms of erosional damage in upland areas or downstream flooding. But if rapid snowmelt occurs during rainfall, the erosion potential of storm runoff may increase. The smallest relative increase in the rate at which water is delivered to the soil would result from high rainfall rates and low temperatures. If $P_r = 20$ cm/day and $T_a = 2°C$, the increase in water delivery to soil would be only ~7%. But because high daily rainfall rates cause high streamflow levels, even a small addition of snowmelt water during high daily rainfall most likely would increase storm runoff volume and the size of instantaneous peak flows, thereby increasing the chance of not only channel erosion and landslides in upland watersheds but also downstream flooding. These simple examples are based on the assumption that the snowpack is shallow enough to be completely melted under the conditions given so that the dynamics of water movement through the pack are of minor

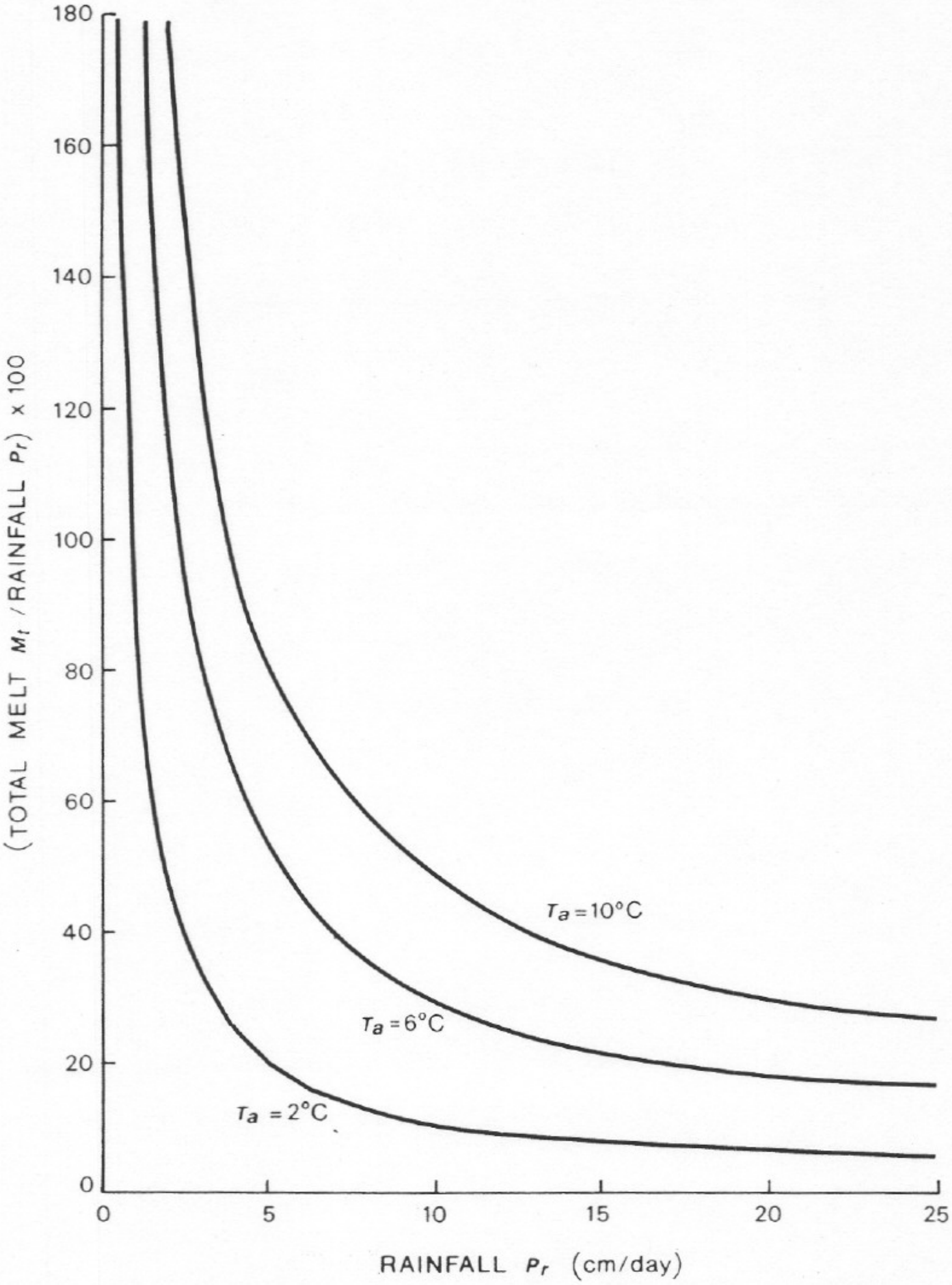

Fig. 4. Total snowmelt M_t as a percentage of daily rainfall P_r (adapted from U.S.A.C.E., 1960).

importance. Nevertheless, these examples do illustrate the importance of snowmelt during rainfall in total water input to soils.

THE REGION

The forest hydrologic system of western Oregon is strongly influenced by the Pacific Ocean and by the mountains of the Coast and Cascade Ranges.

Ordinarily, ~80% of total annual precipitation, which ranges from 120 to 300 cm, falls between October 1 and April 1 when frequent, long-duration (18–72 hr.) frontal storms of sustained relatively low intensities (less than 12 mm/hr.) enter the region from the North Pacific Ocean. Although moderate precipitation may result from frontal cooling of warm air masses, extreme amounts of rainfall have been due to persistent, strong flow of warm, moist air from the vicinity of the Hawaiian Islands up over the two mountain ranges (Hughes and Roe, 1953; Andrews, 1955, 1965; Cole and Scanlon, 1955; Dunn, 1957; Posey, 1965; Wagner, 1972, 1974, 1976).

The proportion of annual precipitation falling as snow varies greatly with elevation. In western Oregon, snow is uncommon below ~350 m but above 1100 m a third to over three-fourths of annual precipitation may fall as snow. Above 1100 m, snow may begin accumulating in November and snowpacks usually exist until late May or early June. Between 350 and 1100 m, snow is common; higher elevations in this zone may receive up to a third of annual precipitation as snow in any one year. In many years, a snowpack may exist for several months at elevations above ~750 m. Snow in the lower portions of the 350–1100-m zone, like snow that accumulates infrequently at elevations below 350 m, generally persists no longer than a week or two because of rapid melting during subsequent rainfall or warm humid periods.

RUNOFF CHARACTERISTICS

Several characteristics of rain-on-snow runoff were determined from flow records of two streams in western Oregon. One stream is the Willamette River at Salem, Oregon, which drains an area of ~18,900 km^2, bounded by the Coast Ranges on the west, the Cascade Range on the east and the Calapooya Mountains on the south (Fig. 1). Major tributaries in this watershed are the Santiam and McKenzie Rivers. The Willamette Valley, flat to gently rolling agricultural land on terraced flood plains, 50–140 m in elevation, occupies ~14% of the watershed. The remainder is largely moderately to steeply sloping forest land ranging up to 1250-m elevation in the Coast Ranges and up to 3050 m in the Cascade Range. About 23% of the watershed lies above 1100-m elevation, and 38% lies between 350 and 1100 m. Most forest land, which occupies ~75% of the basin, is commercial and supports logging and wood processing, the major industry in Oregon.

The second stream drains watershed *2* in the H.J. Andrews Experimental Forest, located ~72 km east of Eugene, Oregon. Elevation of this undisturbed 60-ha watershed, a headwater basin in the McKenzie River drainage, ranges from 525 to 1065 m. Annual precipitation averages 244 cm at a climatic station at 480-m elevation near the watershed-*2* stream gage.

Frequency of occurrence of maximum flows

Streamflow and climatic records for the two watersheds were used to determine frequency of runoff events resulting from rainfall with snowmelt. Peak flows were ranked by size for periods of records, and climatic data were used where possible to separate peak flows caused by rainfall from peak flows caused by rain-on-snow.

Willamette River

Continuous streamflow records exist for the Willamette River at Salem from October 1909 to December 1916 and from 1923 through 1977. In addition, staff gage readings from 1893 to 1908 published in the U.S. Weather Bureau's *Monthly Weather Review* were converted to peak flow to extend records of annual peak flow to 84 yr. (1893—1977). Information contained in diaries of early settlers and in pioneer newspapers has extended the historical record back to the fall of 1813 for a total 164 yr.

Ranking of peak flows greater than 7080 m^3/s and whether or not snowmelt contributed substantially to these peaks are shown in Table I. Information about contributions from snowmelt has come from several sources which have various degrees of subjectivity associated with them. Although some published analyses of storm and runoff conditions are available (Hoffman and Rantz, 1963; Waananen et al., 1971) other information is qualitative. Evidence that snowmelt during rainfall added to many annual peaks during and after the 1940's was obtained from records of precipitation, snowfall-on-ground, and temperature data for selected Willamette River basin stations published in the U.S. National Weather Service's *Climatological Data for Oregon*. Since the early 1960's, climatic records for the H.J. Andrews Experimental Forest near Blue River, Oregon, have supplemented *Climatological Data for Oregon*.

Obviously the least amount of information is available for annual peaks of the 1800's and early 1900's. Accounts of these early floods are sketchy and consist mainly of one or two sentences in early newspapers. For example, regarding the flood of January 1, 1853, the Portland *Oregonian* (January 8, 1853) states:

> "This unusual high water is mainly attributable to the sudden melting of the late snow, and aided to a considerable extent by the rain, which has with but little interruption, continued to fall for about ten days."

Other evidence is less complete. For example, regarding the flood of January 16, 1881, the Portland *Oregonian* (January 19, 1881) states:

> "Then when a warm wind attends a heavy rain and the flood from melting snows in the mountains is joined by the sudden rush of waters from the tributary streams of the Valley, we get a deluge like that of '61 [December 4, 1861] or that which has just been witnessed [January 16, 1881]."

In spite of these limitations, some evidence about snowmelt contributions to peak flow was found for all but 1813, 1843 and 1844, the earliest peaks

TABLE I

Highest annual peak flows of Willamette River at Salem, Oregon, 1814—1977

Rank	Date	Unregulated peak flow*1 (1000 m^3/s)	Snowmelt contri-bution	References for snowmelt contribution
1	Dec. 4, 1861	14.16	yes	Brands (1947); Corning (1973)
2	Dec. 24, 1964	13.37	yes	Waananen et al. (1971)
3	Feb. 5, 1890	12.69	yes	Brands (1947)
4	fall, 1813	—*2	?	
5	Jan. 16, 1881	12.12	yes	*Oregonian**4 (Jan. 19, 1881)
6	Nov. 23—29, 1844	—*2	?	
7	Dec. 27, 1849	—*2	yes	Brands (1947)
8	Feb. 8—15, 1843	—*2	?	
9	Jan. 8, 1923	9.86	yes	Brands (1947)
10	Jan. 15, 1901	9.32	yes	*Oregonian**4 (Jan. 15, 1901)
11	Feb. 6, 1907	9.20	yes	*Oregonian**4 (Feb. 6, 1907)
12	Nov. 25, 1909	8.92	yes	Brands (1947)
13	Jan. 17, 1974	8.67	yes	U.S.A.C.E. (1975)
14	Jan. 1, 1853	—*2	yes	*Oregonian**4 (Jan. 8, 1853); Hussey (1967)
15	Dec. 23, 1955	8.61	yes	Hoffman and Rantz (1963)
16	Feb. 12, 1961	8.61	no	*Climatological Data for Oregon**5; U.S.F.S.*6
17	Jan. 2, 1943	8.52	yes	*Climatological Data for Oregon**5
18	Jan. 22, 1953	8.21	yes	Hughes and Roe (1953); Rantz (1959)
19	Jan. 20, 1971	8.07	yes	*Climatological Data for Oregon**5; U.S.F.S.*6
20	Jan. 27, 1903	8.01*3	yes	*Oregonian**4 (Jan. 25, 1903)
21	Jan. 22, 1972	7.99	yes	*Climatological Data for Oregon**5; U.S.F.S.*6
22	Dec. 30, 1946	7.42	yes	*Climatological Data for Oregon**5
23	Jan. 9, 1948	7.08	no	*Climatological Data for Oregon**5

*1 Regulation of Willamette River began in 1941. Estimates of unregulated peak flows were obtained from the U.S. Army Corps of Engineers, Portland District Office, Portland, Oregon.

*2 Discharge data are unavailable. Runoff event is ranked according to historical information gathered by W.C. Muldrow (Brands, 1947).

*3 Peak of Jan. 29, 1965 also was 8010 m^3/s (283,000 $ft.^3$/s); but because it was the second highest peak of the 1965 water year, it is not included in this table.

*4 *The Oregonian*, Portland, Oregon.

*5 U.S. Department of Commerce, National Weather Service, *Climatological Data for Oregon*.

*6 Climatological records for the H.J. Andrews Experimental Forest, Oregon on file at Forestry Sciences Laboratory, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon.

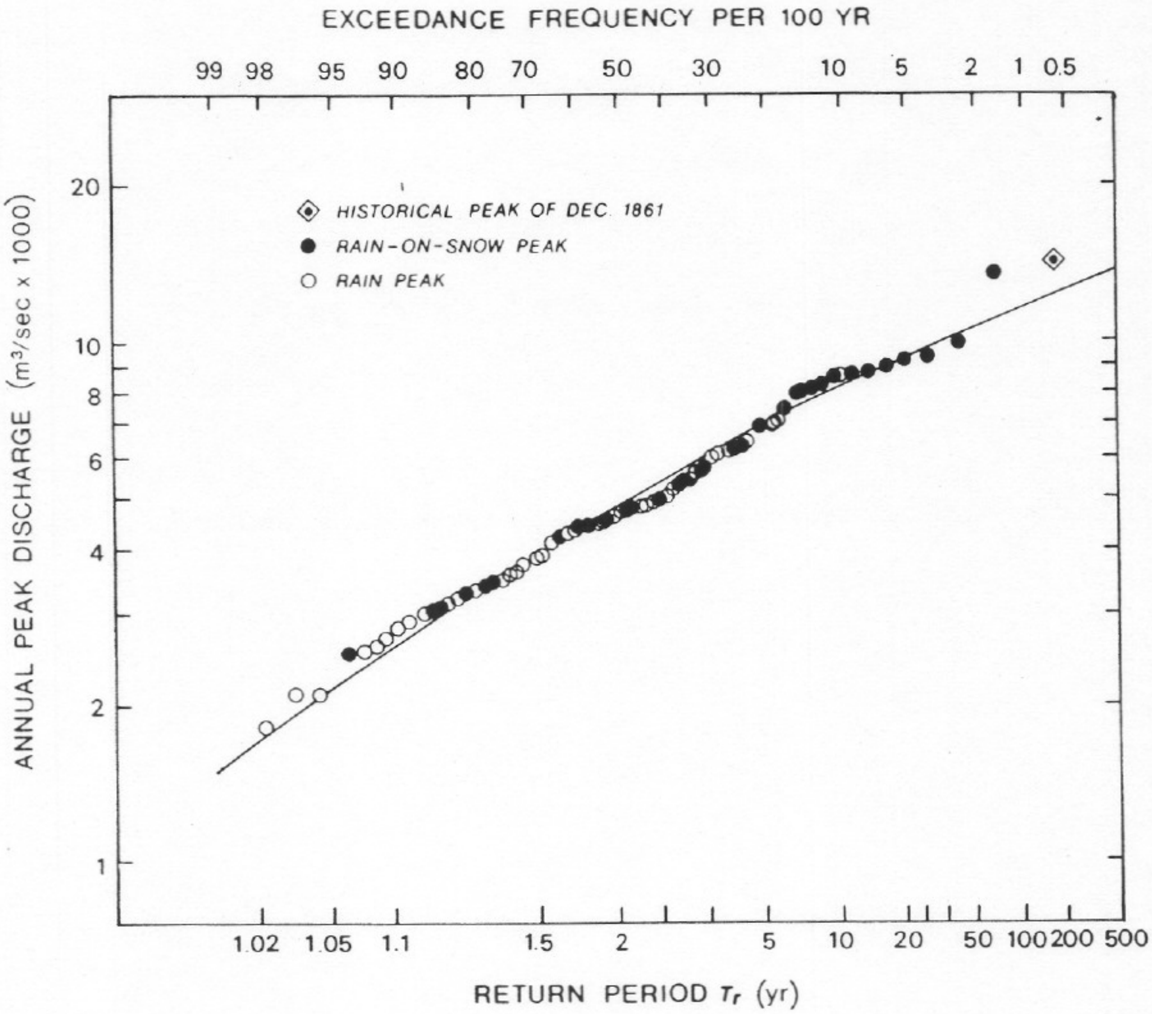

Fig. 5. Historically-weighted, log-Pearson Type-III frequency curve for instantaneous peak flows of the Willamette River at Salem, Oregon, 1814—1977. The historical peak of December 1861 is plotted as the largest in the 164-yr. period. Recorded peaks of 1893—1977 are plotted such that each year represents 1.94 yr. in the 164-yr. period.

for which there are records. Owing to the size of these peaks in relation to the sizes of known snowmelt-related peaks both larger and smaller than these three historical peaks, the latter three most likely also were associated with snowmelt during prolonged rainfall. Probably in only two of the 23 largest peaks shown in Table I was peak flow not associated with snowmelt during prolonged rainfall. Determining the relative magnitude of snowmelt contributions for most of these 23 peaks is impossible without climatological records.

Pre-record peak flow information (Brands, 1947) was used to adjust the systematic record of annual maximum instantaneous peak flows for estimating exceedance probabilities (and return periods) of various sized peak flows (Fig. 5). Observed annual maximum peaks were fitted to a historically weighted log-Pearson Type-III distribution by a procedure outlined by U.S.W.R.C. (1976).

The annual series shown in Fig. 5 can be arbitrarily divided into three parts based on relative preponderance of rain-on-snow peaks. In the part which consists of peaks with return periods greater than 6 yr., 14 of the 16 peaks result from rain-on-snow. Where return periods are 3—6 yr., the number of rain peaks and rain-on-snow peaks are roughly equal; but for return periods less than 3 yr., most peaks result from rain alone. Clearly, rain-on-snow is an important part of major peak flows.

Watershed 2

Continuous measurement of streamflow was begun at watershed *2* in 1952, and precipitation has been measured continuously since November 1951 and air temperature since February 1958. Periodic measurement of snow depth and water equivalent at a few selected locations was begun in December 1957 and has been supplemented by records of snowfall and snow-on-ground at the community of McKenzie Bridge located at 460-m elevation 5 km southeast of watershed *2*. The latter records have been compiled and published by the U.S. National Weather Service in *Climatological Data for Oregon*.

Again, streamflow and climatic records were used to separate instantaneous peak flows caused by rainfall alone from those caused by rainfall with concurrent snowmelt. In most cases, periods of snow accumulation prior to a runoff event could be determined easily from air temperature and precipitation records or snow measurements. In some cases, however, missing records or the occurrence of heavy snowfall at air temperatures of 2° to 3°C made snow accumulations difficult to detect with this technique. In such instances, the quick response of streamflow to changes in precipitation rates was used to designate periods of snow accumulation. If rate of streamflow decreased or remained fairly constant during moderate precipitation, the precipitation obviously was snow, and the next runoff event was deemed snowmelt-related.

More than half of the larger winter runoff events in watershed *2* resulted from rain with various amounts of snowmelt. In the 1958—1977 period, for which the most complete climatological records exist, there were 92 instantaneous peak flows greater than 2.2 l/s per ha of which 56 (61%) resulted from rain-on-snow. Of the 44 peak flows greater than 4.4 l/s per ha in the longer 1953—1977 period, 26 (59%) were judged rain-on-snow.

Results of a log-Pearson Type-III frequency analysis of watershed-*2* instantaneous peak flows are shown in Fig. 6. Of the 12 peak flows greater than the mean annual peak of 7.5 l/s per ha, all but 3 resulted from rain with snowmelt.

As one might expect after examining Table II and Figs. 5 and 6, rain peaks and rain-on-snow peaks have different frequencies of occurrence. Largest rain-on-snow and rain peak flows at watershed *2* are ranked in Table II, and results of a partial duration frequency analysis of these data are plotted in Fig. 7. The curves have been fitted by eye rather than by the log-Pearson

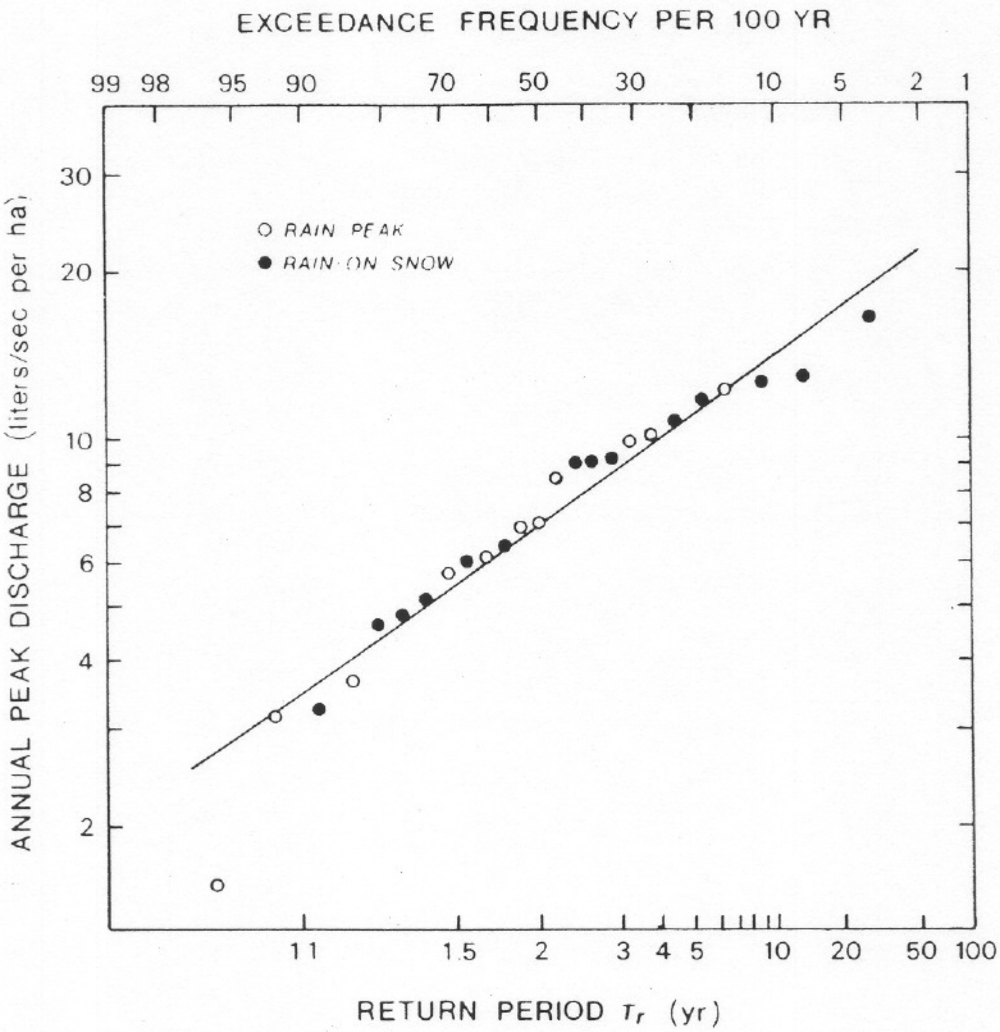

Fig. 6. log-Pearson Type-III frequency curve for peak flows at watershed *2*, H.J. Andrews Experimental Forest, 1953—1977.

Type-III analysis outlined above because the short-term record does not allow computation of the necessary skew coefficient for each type of peak flow, nor do generalized skew coefficients exist for the two types of peak flow. Nevertheless, differences between frequencies of occurrence of the two types of runoff events are apparent. For example, consider a peak flow of 10 l/s per ha, an event of sufficient magnitude to cause extensive erosion in headwater areas and to be associated with downstream flooding. A peak of this size caused by rain alone has a return period of ~15 yr. at watershed *2*, but the same size peak flow caused by rain-on-snow has a return period of only ~3 yr. The rates and duration of water input necessary to generate a peak flow of 10 l/s per ha are nearly five times more likely to result from rain-on-snow than from rainfall alone.

Rain-on-snow peak flows and rain peak flows are also distributed differently throughout the wet season. In the 1953—1977 period, 83% of annual rain-on-snow peak flows at watershed *2* occurred in December and January

TABLE II

Ranking of highest rain-on-snow and rain peak flows, watershed *2*, H.J. Andrews Experimental Forest, 1953—1977

Rank	Rain-on-snow		Rain	
	date	magnitude (l/s per ha)	date	magnitude (l/s per ha)
1	Dec. 22, 1964	16.44	Jan. 18, 1953	12.13
2	Jan. 27, 1965	13.41	Feb. 10, 1961	10.24
3	Dec. 20, 1957	12.95	Nov. 22, 1953	8.46
4	Jan. 21, 1972	12.63	Feb. 15, 1958	7.61
5	Jan. 8, 1976	11.87	Nov. 24, 1960	7.38
6	Dec. 11, 1956	10.72	Jan .18, 1970	7.01
7	Dec. 19, 1961	9.81	Nov. 9, 1968	7.00
8	Jan. 18, 1971	9.11	Dec. 20, 1973	6.95
9	Dec. 4, 1968	9.03	Nov. 26, 1971	6.50
10	Jan. 15, 1956	9.02	Nov. 19, 1955	6.45
11	Mar. 2, 1972	8.96	Dec. 19, 1953	6.39
12	Dec. 21, 1955	8.66	Jan. 27, 1959	6.16
13	Jan. 17, 1971	8.50	Nov. 22, 1961	6.12
14	Dec. 5, 1971	7.90	Dec. 12, 1955	5.95
15	Dec. 1, 1975	7.50	Feb. 23, 1968	5.67
16	Jan. 15, 1974	6.67	Dec. 26, 1964	5.44
17	Dec. 30, 1954	6.36	Jan. 26, 1970	5.12
18	Jan. 12, 1972	6.36	Dec. 9, 1971	5.08
19	Dec. 1, 1964	6.05	Feb. 26, 1957	5.06
20	Jan. 28, 1967	5.97	Mar. 26, 1962	4.18
21	Feb. 6, 1953	5.11	Dec. 7, 1973	4.11
22	Jan. 6, 1966	5.09	Jan. 28, 1954	3.74
23	Nov. 19, 1958	4.94	Nov. 8, 1963	3.67
24	Feb. 1, 1963	4.80	Jan. 10, 1971	3.46
25	Dec. 9, 1953	4.55	Nov. 24, 1970	3.33

(Table III). Annual rain peak flows, on the other hand, are fairly evenly distributed throughout the November—February period.

Hydrograph characteristics

Rain-on-snow conditions produce streamflow hydrographs that generally differ from hydrographs caused by rain alone. The differences can be illustrated by comparing characteristics such as rates of instantaneous peak flows, rates of hydrograph rise and peak flows as functions of 12-hr. rainfalls preceding the peak flows for both types of runoff events. On the average, rain-on-snow peak flows at watershed *2* have been higher than rain peak flows. This can be seen in the frequency analyses described above and also by comparing the 25 largest runoff events of each kind (Table II). In addition, maximum rates of streamflow caused by rain-on-snow commonly have been more than 60% of average rate of rainfall for the 12-hr. period

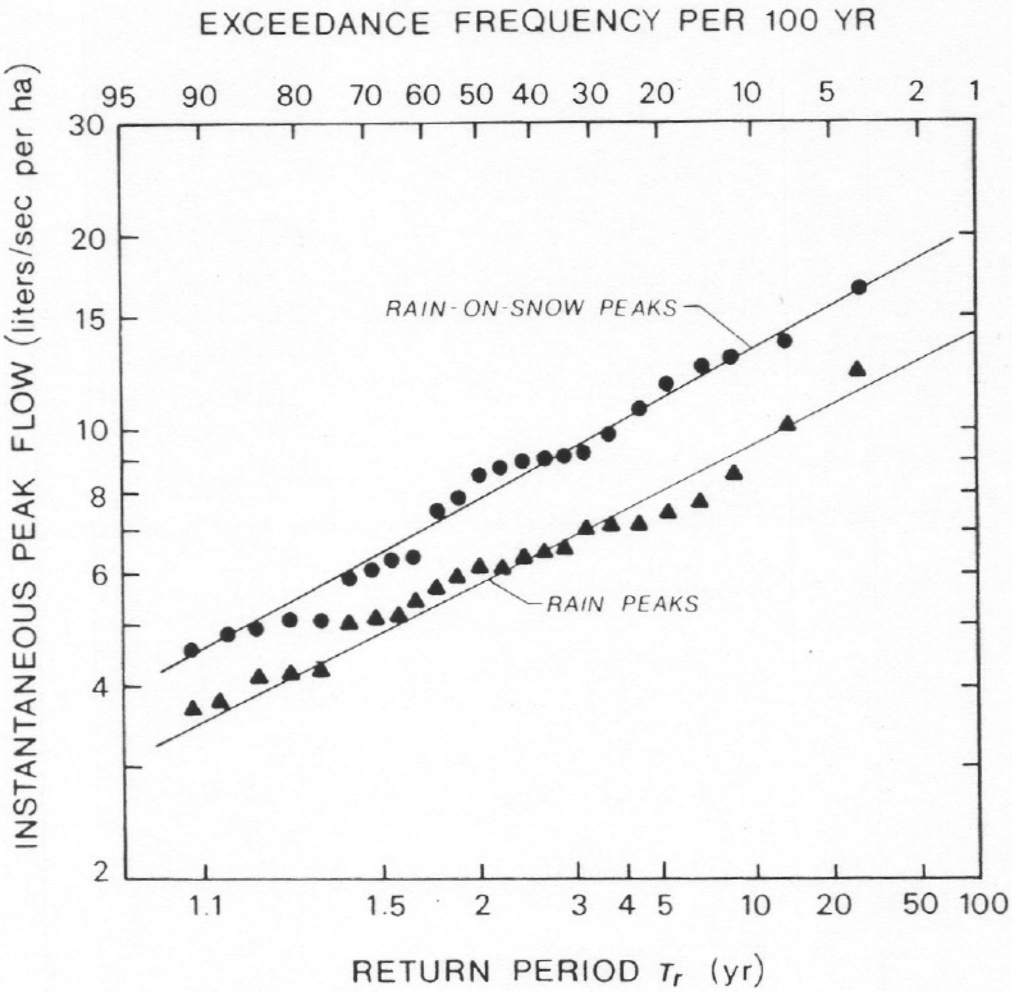

Fig. 7. Frequency curves for peak flows resulting from rain-on-snow and from rainfall at watershed 2, H.J. Andrews Experimental Forest, 1953—1977.

TABLE III

Distribution of largest annual, rain-on-snow, and rain peaks at watershed 2, H.J. Andrews Experimental Forest, 1953—1977

Type of peak flow	Number of peaks				
	Nov.	Dec.	Jan.	Feb.	Mar.
Annual*1	2	7	11	3	2
Rain-on-snow*2	1	11	9	2	1
Rain	7	6	6	4	2

*1 Highest instantaneous peak flow of a water year.

*2 Highest instantaneous peak flow caused by rain with snowmelt. Total number of this type of peak flow is only 24 because no rain-on-snow peak occurred during the 1977 water year.

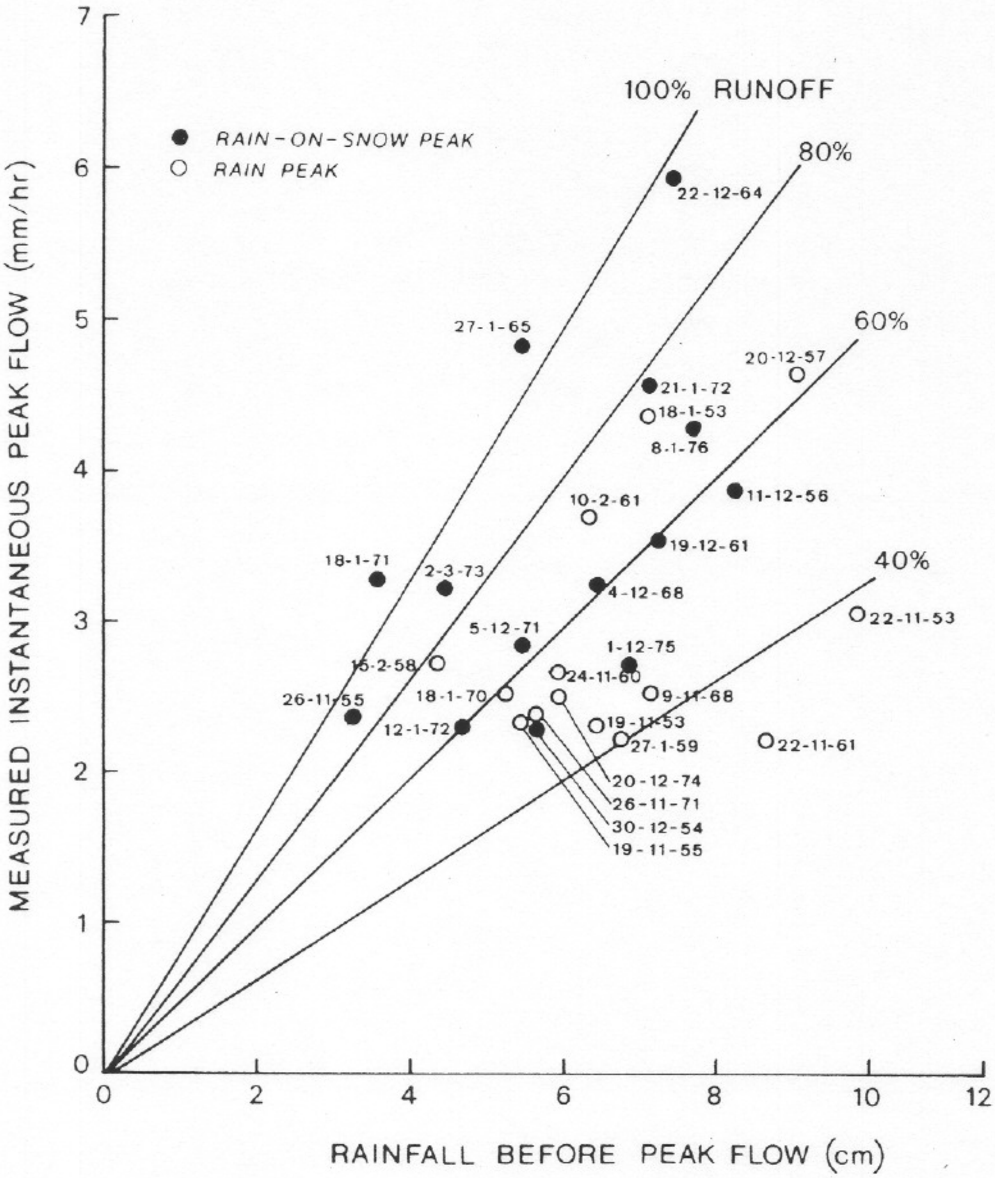

Fig. 8. Peak flow vs. 12-hr. rainfall before peak flow for runoff events at watershed 2, H.J. Andrews Experimental Forest, 1953—1977.

preceding the peak flow (Fig. 8); and in two cases they have exceeded 100%. In contrast, most peak flows caused by rain alone have been less than 60% of average 12-hr. rainfall preceding the peak flow. Rising limbs of rain-on-snow hydrographs are generally steeper than those of rain hydrographs; maximum 6- and 12-hr. rates of hydrograph rise for rain-on-snow events average 42% more than rates of rise for rain events (Table IV). For the highest peak flows, those greater than 10 l/s per ha, mean maximum 6- and 12-hr. rises of rain-on-snow hydrographs are respectively 76 and 84% greater than mean maximum rates for rain events.

Differences in size of peak flows and rates of hydrograph rise might be expected to be due to differences in rate of water input, but this could not

TABLE IV

Maximum 6- and 12-hr. hydrograph rises for rain-on-snow and rain runoff events at watershed *2*, H.J. Andrews Experimental Forest

Type of runoff event	Number	Maximum 6-hr. hydrograph rise (l/s per ha)	Maximum 12-hr. hydrograph rise (l/s per ha)
Rain-on-snow	17	3.93	5.76
Rain	10	2.78	4.04

be demonstrated simply. For example, maximum rates of hydrograph rise were poorly correlated with rates of water input (rainfall plus estimated snowmelt) for the same 6- and 12-hr. periods.

There are at least two factors which preclude further meaningful analysis of the cause of differences in rate of hydrograph rise. First, the periods of critical water input responsible for observed maximum rates of rise cannot be determined. Although watershed-*2* streamflow responds quickly to changes in rate of water input, there is a variable time lag between water input and the increase in streamflow corresponding to that input. The length of the lag depends on the relative levels of soil moisture in the watershed and the size of the area producing runoff. Secondly, both the water-holding capacity of the snowpack and the ability of the pack to route water can alter the watershed's response to water input. Snow functions much like soil; until the waterholding capacity of the snowpack is filled, the pack will not yield water to underlying soil. Moreover, the presence of ice lenses can restrict the movement of water through the snowpack. Because there is no information available about differences in either snowpack or soil moisture conditions for the runoff events examined, no other analyses were made. Even if a hydrology model developed for this watershed (Overton and White, 1978) had an adequate snowmelt submodel, its 1-day time resolution could not help in analyzing the differences in 6- and 12-hr. rates of rise.

SNOWMELT's CONTRIBUTION TO WATER INPUT

Estimated relative increases in water input caused by snowmelt have been variable at the site near watershed *2* where precipitation and air temperature have been measured. Increases have averaged 17% for the 24-hr. water input, ranging from 4 to 37% (Table V). According to snowmelt estimates based on indices described earlier, the largest absolute and second largest relative increase (32%) occurred during the runoff event of December 22, 1964. This 32% increase agrees favorably with the 29% increase computed by Anderson (1970) and the 24% increase calculated from data presented by Beaumont (1965) for December 21—23, 1964, at two other locations in western Oregon. The smallest estimated relative increase in water input to

TABLE V

Increases in water input caused by snowmelt 12 and 24 hr. before peak flows at watershed 2, H.J. Andrews Experimental Forest, 1953—1977

Date of peak flow	12 hr. before peak flow			24 hr. before peak flow		
	mean air temperature (°C)	rainfall (cm)	water input increase (%)	mean air temperature (°C)	rainfall (cm)	water input increase (%)
Dec. 22, 1964	8.4	7.4	26	7.2	11.6	32
Jan. 27, 1965	3.3	5.4	15	2.8	10.4	15
Dec. 20, 1957	2.8	9.0	8	2.8	15.2	11
Jan. 21, 1972	4.7	7.1	16	3.9	12.1	18
Jan. 8, 1976	0.6	7.7	3	0.6	14.0	4
Dec. 11, 1956	5.0	8.2	15	4.3	9.7	23
Dec. 19, 1961	2.8	7.2	10	1.7	9.5	11
Jan. 18, 1971	3.1	3.5	20	3.1	6.9	22
Dec. 4, 1968	5.6	6.4	20	5.0	10.6	24
Mar. 2, 1972	2.8	4.4	15	2.2	10.8	12
Dec. 5, 1971	3.9	5.4	17	2.8	9.7	16
Dec. 1, 1975	1.1	6.8	5	1.1	9.1	8
Nov. 26, 1955	4.5	3.2	30	4.0	4.9	37
Nov. 19, 1955	3.3	5.4	15	3.3	8.5	20
Dec. 30, 1954	3.1	5.6	13	1.7	9.4	11
Jan. 12, 1972	2.2	4.6	12	1.7	9.3	11

soil occurred during the runoff event of January 8, 1976. Although rainfall during the 24 hr. prior to the January 8, 1976 peak was greater than during the 24 hr. prior to the December 22, 1964 peak, very little melt occurred in the former case, because air temperature was only slightly above 0°C. The largest estimated relative increase in water input occurred during the runoff event of November 26, 1955. But, because rainfall and snowmelt amounted to only 4.9 and 1.8 cm, respectively, instantaneous peak flow was much less than for most other rain-on-snow runoff events. Lack of measurements of snow depth and density, air temperature and precipitation elsewhere on watershed 2 precludes a more rigorous analysis of snowmelt's contribution to water input.

Snowmelt's contribution should be considered whenever frequency of occurrence of water input events is needed for design or research purposes. Precipitation frequency atlases, common sources of rainfall information, deal only with precipitation and not snowmelt. For example, suppose the quantity of water that would be delivered to the soil during a 25-yr.—24-hr. event (a 24-hr. storm with a return period of 25 yr.) is desired for a selected location in the western Cascade Range of Oregon. The precipitation frequency atlas for Oregon (Miller et al., 1973), which gives isopluvials of precipitation based on data from U.S. National Weather Service stations, on topography and on storm track information, shows 25-yr.—24-hr. precipitation to be

17 cm. If a snowpack exists, more water could be delivered to the soil than indicated by the atlas. According to eq. 6 and Fig. 2, a 20-cm thick fresh snowpack with a density of 15% could be completely melted in 24 hr. if $P_r = 17$ cm and $T_a = 5°C$. Total water input of 20 cm (17 + 3 cm) would equal to the atlas' estimate of the 100-yr.—24-hr. water input if rainfall were the only source of water.

LANDSLIDES

Most landslides in the H.J. Andrews Experimental Forest that could be accurately dated (F.J. Swanson, pers. commun., 1977) have been associated with rain-on-snow conditions. Of 58 road-related slope failures, 48 (83%) occurred during periods of snowmelt during rainfall. Similarly, 10 of 11 slope failures in clearcut areas and 10 of 11 debris torrents in channels occurred during rain-on-snow runoff. Collectively, 85% of all slope failures were associated with snowmelt during rainfall. Many occurred during the rapid snowmelt and heavy rainfall of December 1964.

Although most landslides occur during periods of relatively high rates of water input to soil, there are a number of other factors that interrelate to cause landslides. One such factor is the management history of an area, including time since road construction, quality of road design, location and strength of deteriorating roots (Burroughs and Thomas, 1977; Ziemer and Swanston, 1977). Another major factor is the recent weather history including time since the last landslide-producing storm and the number and magnitude of water input events that did not cause landslides. If a major landslide-producing water input event occurred during the previous 5—10 yr., perhaps all slopes sufficiently unstable failed at that time, so that a succeeding water input event of equal magnitude produced few if any landslides. Conversely, a major input event may not cause any landslides but may merely weaken the soil mass so that a succeeding water input of equal or less magnitude would cause the mass to fail.

EFFECTS OF CLEARCUTTING

Up to this point the author has attempted to describe differences between rain-on-snow runoff and rain runoff and to illustrate the importance of snowmelt during rainfall in erosion processes in headwater areas. What remains is a discussion of the potential effects of clearcut logging on this type of snowmelt. Although forest cutting can also influence snow accumulation, only snowmelt will be discussed here.

The potential influences of forests on snowmelt have been known for some time, but actual effects have not been clearly established for periods of rainfall in mountainous, forested areas such as those of western Oregon.

This is particularly true where snowpacks are shallow and transient during the winter. Based on observations made between 1934 and 1941, Kittredge (1953) concluded that forest cover in the Sierra Nevada of California, by reducing the rate of melting snow, may reduce flood crests which result primarily from heavy rains. Working with 14 watersheds in western Oregon, Anderson and Hobba (1959) concluded that clearcutting 2.6 km^2 of forest in the area below the snowmelt line increased peak flow 2.9 m^3/s during rain-on-snow conditions. Later, however, Anderson (1970) seemed less positive about the influence of clearcutting as he speculated about the role of forests in modifying snowmelt during rainfall. Rothacher (1971, 1973), using the paired watershed technique, found no increase in size of two major rain-on-snow peak flows in watershed *1*, a northwest-facing clearcut watershed adjacent to watershed *2* in the H.J. Andrews Experimental Forest. More recently, Harr and McCorison (1979) found average peak flow in a small watershed in western Oregon was delayed and smaller after timber in the watershed was clearcut. Changes in runoff were attributed to changes in short-term snow accumulation and melt caused by removal of forest vegetation.

According to the snowmelt indices described previously, clearcut logging could increase rate of snowmelt during rainfall because turbulent transfer of energy and water vapor to the snow surface would be increased after removal of forest vegetation. For example, consider snowmelt when $P_r = 13.5$ cm and $T_a = 6°C$. If eq. 4 is used for convection—condensation melt at a point under forest, total melt $M_t = 3.3$ cm. If the effect of forest cutting on snowmelt can be described adequately by eq. 3, the equation for convection—condensation melt at a point in the open, and wind speed $V = 5$ m/s, total melt M_t would be 4.6 cm, an increase in total melt of ~40% over that under forest (Fig. 9). At higher values of V, total melt could be more than doubled after timber harvest.

Although clearcut logging should increase snowmelt substantially during rainfall, the resultant increase in total water input to soil would be increased appreciably only when infrequent combinations of meteorological variables occurred. In the first example given above, total water input would be increased from 16.8 cm (3.3 + 13.5 cm) to 18.1 cm (4.6 + 13.5 cm), an increase of only 8% (Fig. 10). Likewise, if $T_a = 10°C$ and V and P_r remain the same as above, total water input to soil in the open would be ~12% greater than that in the forest. But if $T_a = 10°C$, $P_r = 20$ cm and $V = 10$ m/s, a rare combination of melt variables, water input to soil after timber cutting could be 25% greater than if trees had not been cut.

But even the relatively small 8% increase in water input to soil described above could affect erosion in upland watersheds. According to Fig. 11, a water input event of 16.8 cm has a return period of ~12 yr. But the 18.1-cm water input that could result from increased melt following timber cutting would have a return period of ~25 yr. In other words, cutting trees could cause water input to soil of a magnitude that would occur, on the average, only every 25 yr. under forest whereas the same weather conditions after

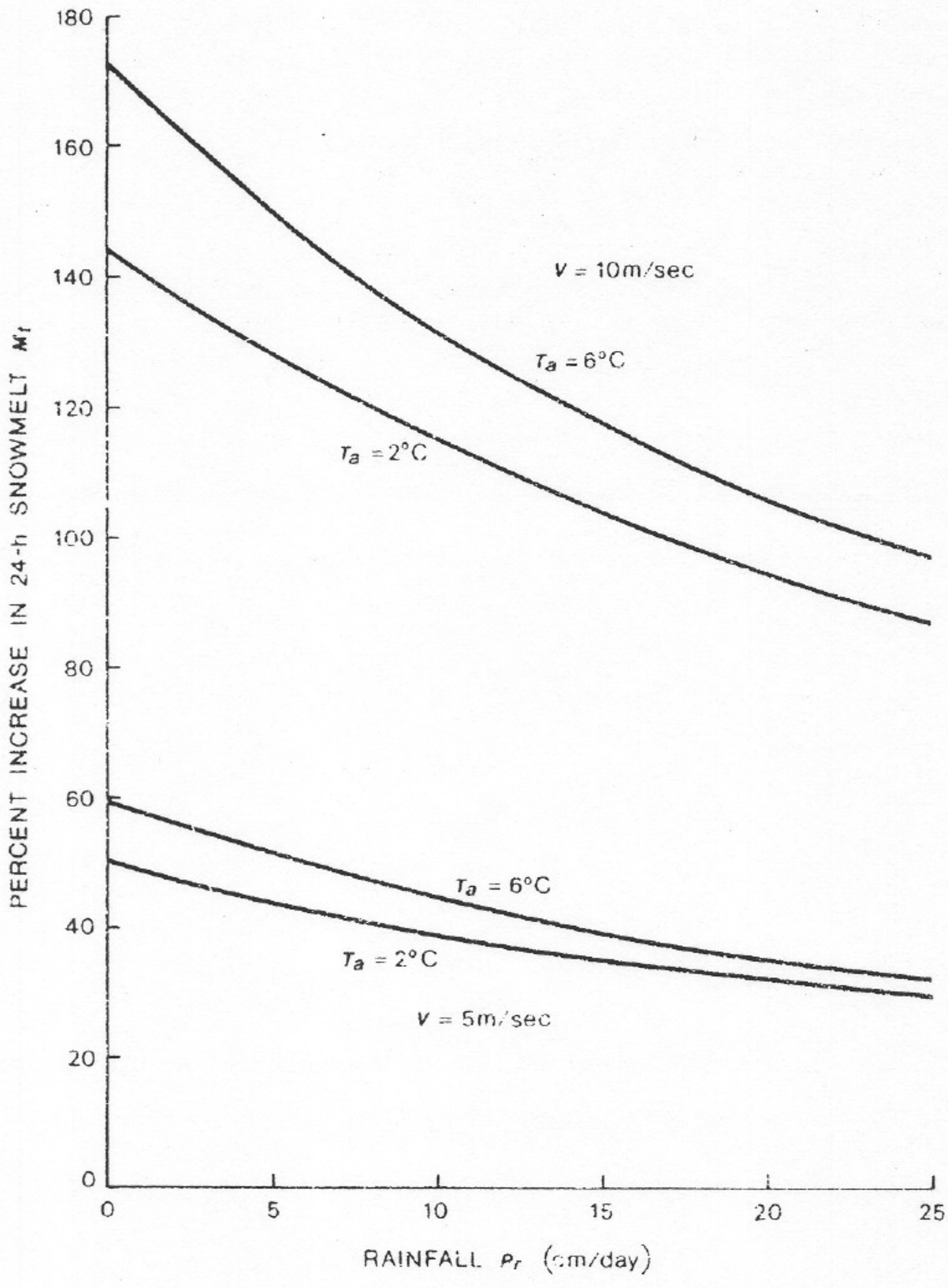

Fig. 9. Percent increase in snowmelt M_t as a function of daily rainfall P_r, mean daily air temperature T_a, and wind velocity V (adapted from U.S.A.C.E., 1960).

cutting would result in water input to soil that would occur on the average every 12 yr. under forest. In general, amount of erosion caused by a storm runoff event is inversely related to the frequency of occurrence of that size event. Most likely more landslides and higher streamflows accompanied by greater channel erosion would be associated with a 25-yr. water input event than with a 12-yr. event.

The P_r-, T_a- and V-values used in the above analysis are not extreme. Individually, these values have occurred numerous times during the last 25 yr.

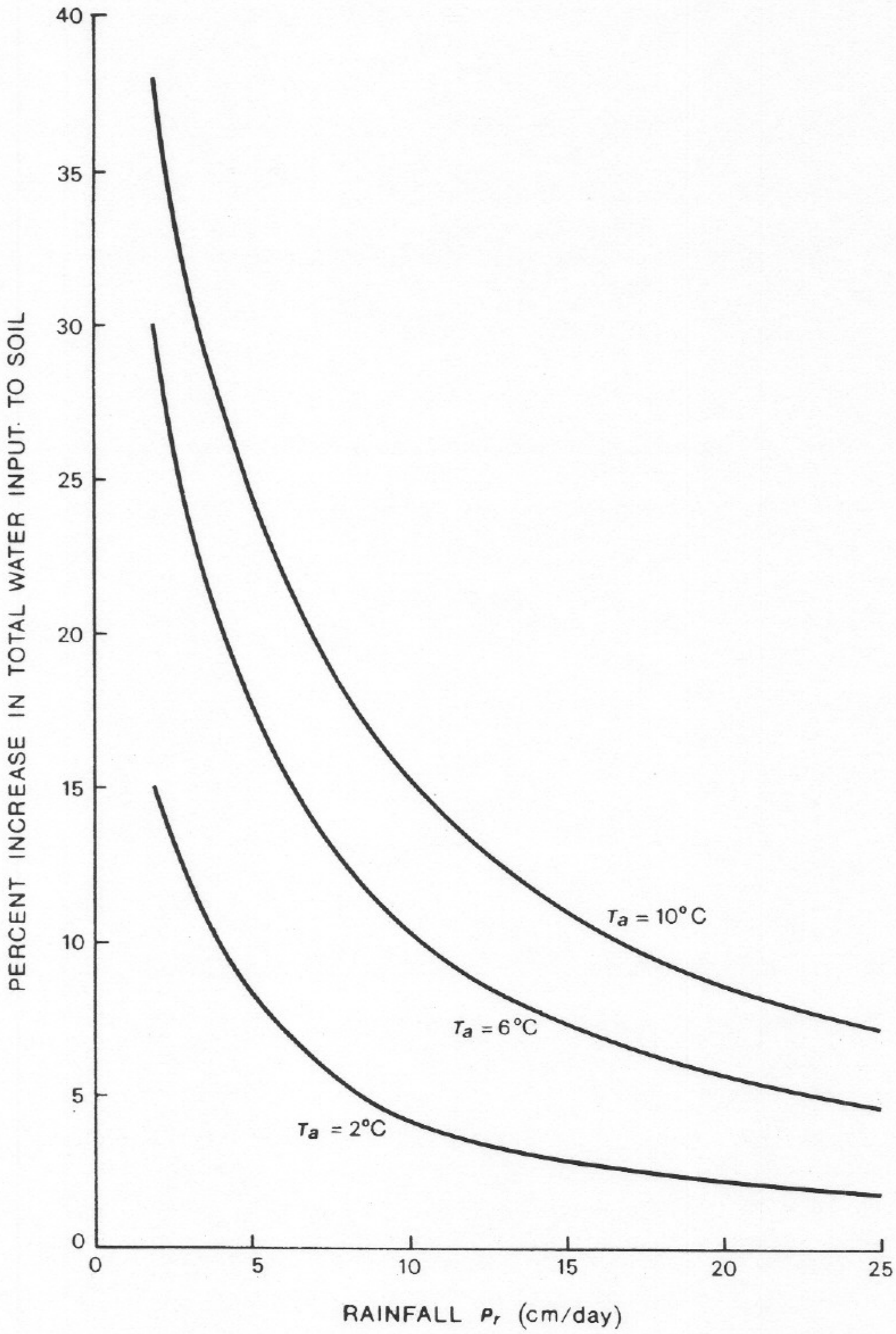

Fig. 10. Percent increase in total water input to soil as a function of daily rainfall P_r, mean daily air temperature T_a at wind velocity $V = 5$ m/s (adapted from U.S.A.C.E., 1960).

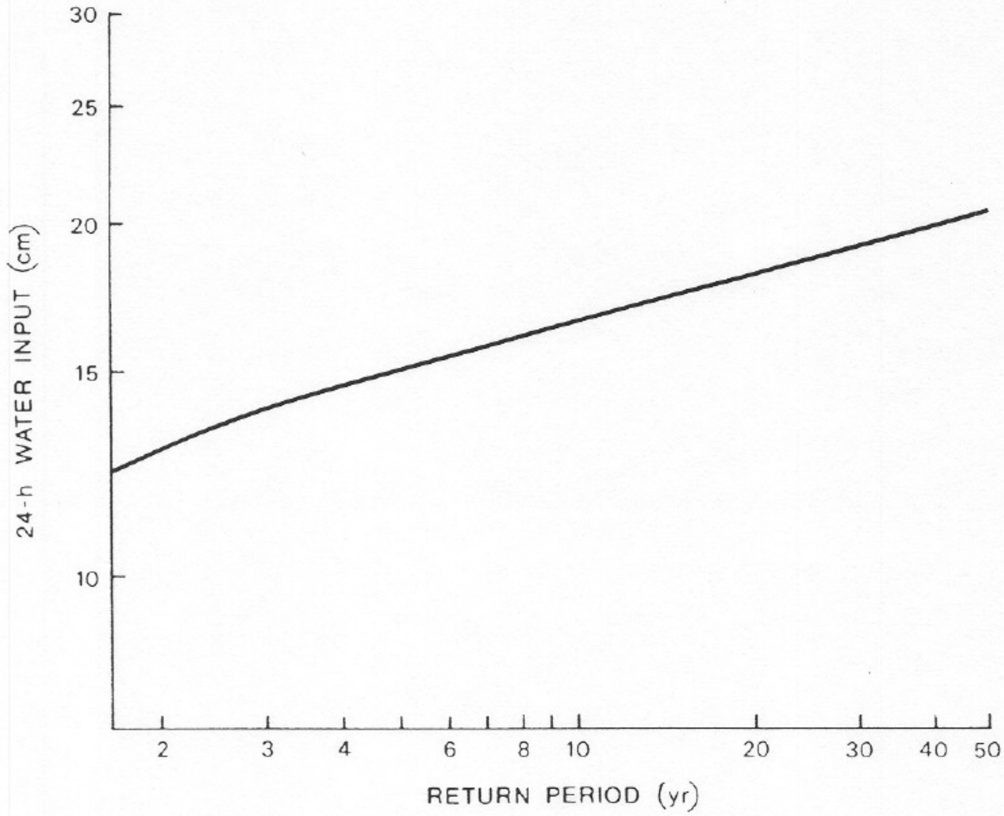

Fig. 11. Frequency curve for total water input (rainfall + estimated snowmelt) to soil at watershed *2* climatic station, H.J. Andrews Experimental Forest, 1958—1977.

According to records for the climatic station near watershed *2*, $P_r = 13.5$ cm has a return period of ~4 yr. About 26% of all days between November 1 and March 31 during the 1958—1977 period had a mean daily temperature T_a equal to or greater than 6°C (Fig. 12). (In this case, mean daily temperature is the average of the maximum and minimum temperatures of each day.) The frequency of occurrence of average daily wind velocity $V = 5$ m/s is unknown because no wind data exist. This V-value probably occurs on the order of 3—4 times between November 1 and March 31 of each year. In many instances, heavy rainfall in winter is accompanied by both high air temperature and high wind velocities as warm moist air is forced over the western Cascade Range.

Rate of snowmelt during rainfall should depend to a certain extent on aspect of slopes and entire watersheds. Because winds during winter frontal storms are from the west-southwest, land surfaces (and entire watersheds) oriented toward this direction are more exposed to higher wind speeds than are slopes oriented toward other directions. Higher rates of convection—condensation melt should be expected on west-southwest facing slopes because of greater wind velocity (see eq. 3) and correspondingly greater turbulent exchange of energy and water vapor to the snow surface.

In the H.J. Andrews Experimental Forest, differences in aspect of watersheds may have accounted for differences in unit-area peak flows observed during rain-on-snow runoff. On December 22, 1964, for example, stream-

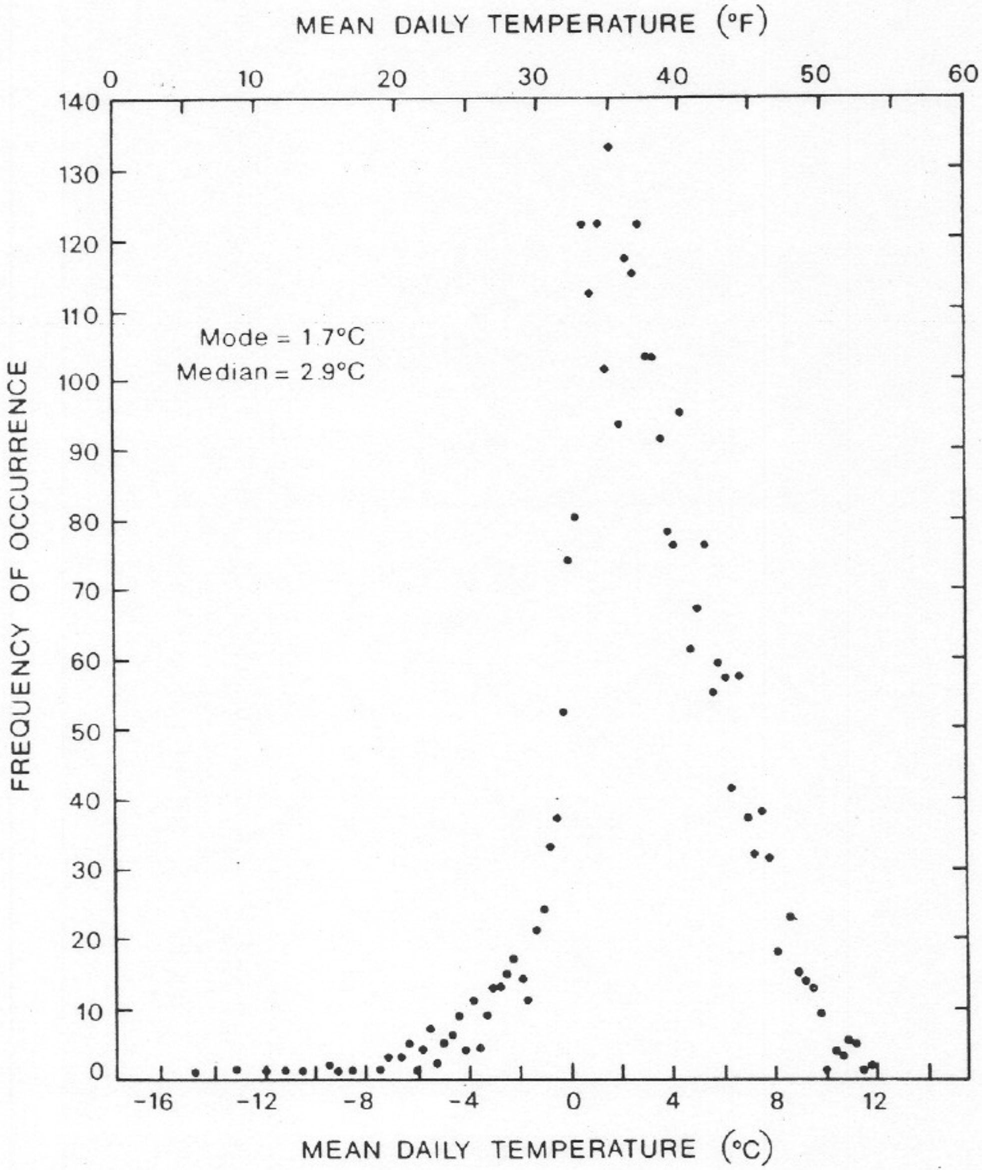

Fig. 12. Frequency distribution of mean daily air temperature T_a at watershed *2* climatic station, H.J. Andrews Experimental Forest, 1958—1977.

flow peaked at 16.4 l/s per ha in watershed *2*, which faces northwest and 30.2 l/s per ha in the 62.4 km^2 Lookout Creek watershed, the west-southwest-facing parent watershed of watershed *2*. If the unit area rate of discharge at watershed *2* is representative of north-facing subwatersheds — and size of flows at two adjacent experimental watersheds indicates that it may be — then peak flows in south-facing watersheds must have greatly exceeded 30.2 l/s per ha in order for Lookout Creek itself to peak at such a high rate.

The author's arguments have been somewhat speculative, and his examples have been simplified to illustrate two key-points: (1) snowmelt during rainfall is a dominant hydrologic process involved in erosion in headwater areas in western Oregon; and (2) clearcut logging may be increasing rate of snowmelt during rainfall. Implicit in this discussion has been the assumption that the indices for snowmelt during rainfall which were developed by U.S.A.C.E. (1956) describe melt processes reasonably well. These indices were used to compare melt in a forest with that in a logged area although the indices were not specifically intended for such a use; there simply was not any other information available. Although this use and the accuracy of the snowmelt indices themselves may be questioned, it remains that, without additional information about the rain-on-snow phenomenon and how it is affected by timber harvest, we cannot say with certainty that clearcutting does or does not affect rate of shallow snowpack melt during rainfall.

Being able to predict the effects of timber cutting on snowmelt during rainfall is only a partial answer to the overall harvest—snowmelt—erosion question. Not all increases in melt rate would necessarily cause increased erosion. For example, consider a second-order channel below the confluence of two first-order streams that drain similar watersheds. Flows that were synchronized and additive below the confluence before logging could be desynchronized if logging in one watershed increased rate of melt relative to melt in the unlogged watershed. Lower maximum flows would mean reduced erosion in the second-order channel. Conversely, previously nonsynchronized flows could be synchronized after logging. At this point we have little chance of predicting whether or not increased melt would increase channel erosion without knowing more about snowmelt during rainfall, how it might be affected by timber harvest, and how physiographic characteristics interact.

Data from experimental watershed studies in western Oregon are of little value to the clearcutting—snowmelt question — such studies were desigined primarily for examining rain—runoff relations and water yield. Measurement of snow conditions and meteorological variables involved in snowmelt have not been made to the degree necessary for us to understand the rain-on-snow phenomenon and how it is affected by clearcutting. If the clearcutting—snowmelt—erosion question is to be answered, then studies must be designed to relate melt to the meteorological and physiographic variables that influence melt rather than to gross climatic data that are part of rain hydrology studies, as done in this paper. Snowmelt during rainfall may significantly affect erosion processes and the life-span of man-made hydraulic structures in headwater areas. In addition, the possible consequences of increasing the rate of this melt by timber harvest present a strong argument for more study of the rain-on-snow phenomenon in the Pacific Northwest.

ACKNOWLEDGEMENT

Helpful discussions with Richard L. Fredriksen and Jere Christner and manuscript review by Robert L. Beschta and James L. Smith are gratefully acknowledged. The estimates of Willamette River unregulated peak flows supplied by the U.S. Army Corps of Engineers are greatly appreciated.

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