

THE EFFECT OF ELEVATION ON SNOWFALL AND RAINFALL - FIRST
RESULTS FROM THE MT. MANSFIELD NETWORK

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ABSTRACT

Snow and precipitation data from the Sleepers River Research Watershed near Danville, Vermont furnished the basis for a model for predicting snowfall accumulation over mountain watersheds using only temperature and precipitation measurements available from the National Weather Service network. Estimation of snowfall at the higher elevations in New England remains one of the more uncertain and unverified functions of the model.

To better understand and predict the elevation effect over a greater range of elevation, we established a special network of recording precipitation gages and snowcourses over the 1000- to 4000 ft (305-1230 m) elevation range on Mt. Mansfield. The first year of observations (October 1976 - October 1977) showed a complex, nonlinear pattern of precipitation increase with increasing elevation.

Snowfall increase with elevation results from greater storm duration rather than greater storm intensity. In contrast, for summer storms, precipitation increase with elevation results from both greater storm intensity and duration. Elevation effects are shown to vary with synoptic storm types.

INTRODUCTION

One objective of the Sleepers River Research Watershed near Danville, Vt. is to gain an improved understanding of how elevation affects precipitation, particularly snowfall. Another is to develop methods for estimating mountain or watershed precipitation, snow accumulation, snowmelt and water input from the weather station information readily available at valley stations. A model for estimating these quantities at higher elevations, using only temperature and precipitation data from National Weather Service network stations as inputs, was developed (Hendrick and DeAngelis, 1976). This model shows considerable skill in estimating snowpack buildup and melt up to 2590 ft (790 m), which is the highest point in the Danville watershed. However, when tested up to 4000 ft (1220 m) on Mt. Mansfield, Vt., snow accumulation was considerably overpredicted. Clearly, we must better understand the precipitation-elevation relationships if the model is to accurately predict precipitation over the higher elevations of the Northeast.

With the cooperation of the Mt. Mansfield Company, seven weighing-type recording shielded precipitation gages were installed up the east side of Mt. Mansfield from 1080 ft (330 m) to 3850 ft (1174 m) at approximately 500-ft (152-m) elevation intervals.

Data from these gages were recorded and reduced to hourly values of precipitation beginning in October 1976. Snow depths were measured weekly at each site and density and water equivalent were measured weekly at the lowest site, M1, and three times during the 1976-77 winter at all other sites from M2 to M7. Daily values of precipitation are available from the nonrecording shielded gage at 3950 ft (1300 m) just south of the nose summit operated for the National Weather Service network (MM). During the 1977-78 winter, hygrothermographs were added at sites M1, M4, and M7 to provide temperature and humidity profiles and to better determine the type of precipitation. Figure 1 shows a profile of this network.

Here we report the first year's results of this 2-year experiment, with some preliminary indications as to how elevation affects precipitation and snow accumulation over Vermont's highest mountain range.

EFFECT OF ELEVATION ON TOTAL PRECIPITATION

Figure 2 shows the total precipitation for the winter-spring season, October 27, 1976 through May 15, 1977 and for the summer season May 16, 1977 through October 15, 1977. Precipitation for these periods at the following sites was included to extend the seasonal precipitation data to both lower and higher elevations: the Burlington airport, 18 miles (30 km) west of the mountain at an elevation of 332 ft (101 m); Morrisville, Vt., 8 miles (13 km) northeast of the mountain at an elevation of 680 ft (207 m); and the Channel 3 TV building (MM) at an elevation of 3950 ft (304 m) near the top of the mountain about one quarter mile (0.4 km) south of our M7 site.

The most interesting features of Figure 2 are the dip in both winter and summer precipitation around the 3000-ft (1000 m) level and the general similarity between the winter and summer curves. The most obvious explanation, particularly since three gages, M4, M5,

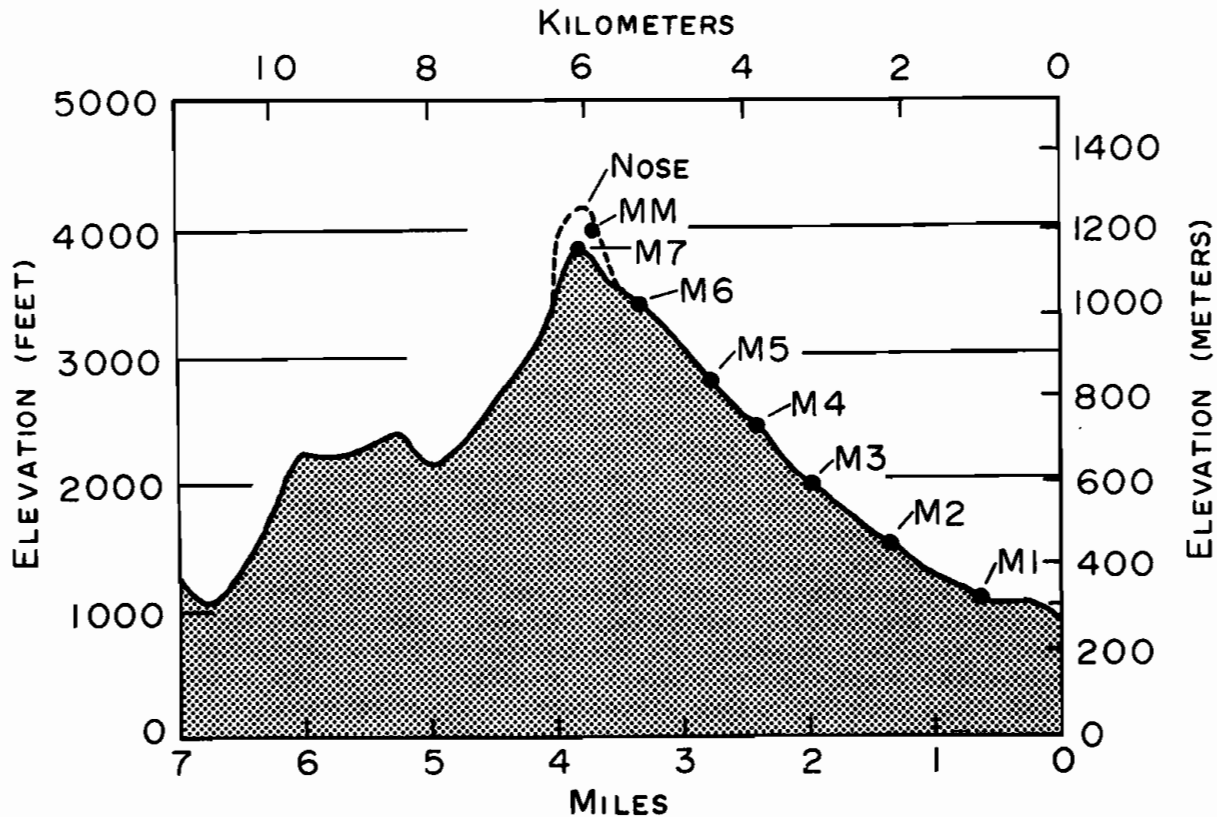


Figure 1. Profile of Mt. Mansfield network, azimuth $300^{\circ} \leftrightarrow 120^{\circ}$.

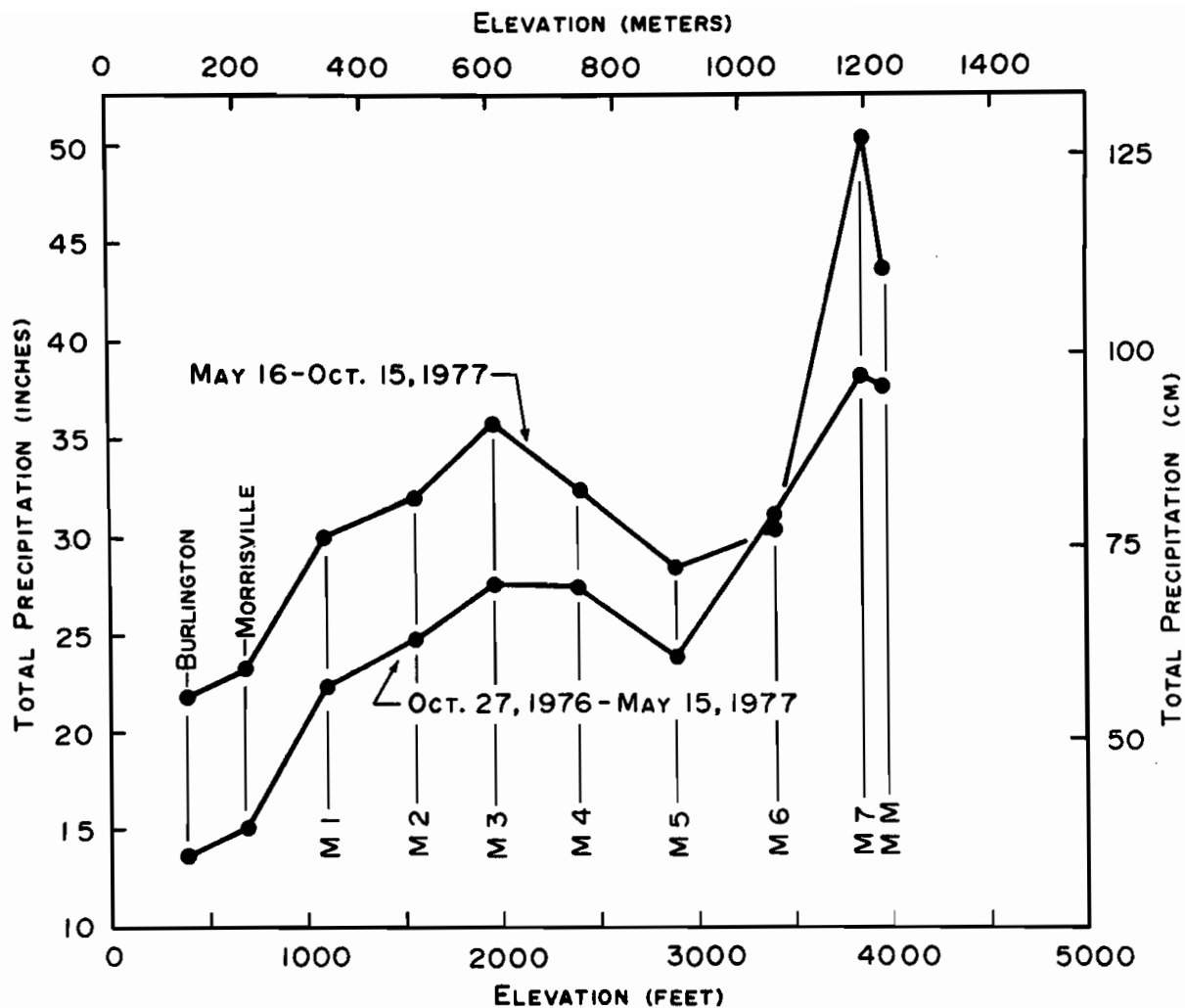


Figure 2. Seasonal precipitation 1976-1977.

and M6, all reflect this dip, which is centered at M5, is some type of shadowing effect to the lee of, and about 1000 ft (300 m) below, the crest of the ridge. Also, the M5 site (located on a narrow ridge extending eastward from the general southeast facing slope) may be somewhat affected by tall conifer trees and may not catch a representative amount of precipitation for its elevation. All seven sites are in small clearings with some interference from tree crowns. The M1 through M3 sites are affected by tall hardwood tree tops; M4 and M5, by fairly tall but scattered conifer tops; M6, by short conifer tops; and M7, by one or two conifer tops slightly higher than the gage. However, if tree interference is assumed to be the cause of the apparent precipitation dip below the summit ridge, it is difficult to explain the similarity between the winter and summer precipitation profiles. Deciduous foliage and the straighter fall of raindrops compared to snowflakes should reduce the dip around M5, but this was not observed.

To assist in interpreting these 1976-77 total precipitation data, we installed another precipitation gage in October 1977 about 300 ft (100 m) from the M5 gage in a more open location at approximately the same elevation. During the first half of the 1977-78 winter, more precipitation was recorded at the new gage (M5b) than at M5, but it is too early to conclude whether the apparent dip in precipitation below the mountain crest is due to immediate gage environments or is characteristic of the precipitation-elevation relationship on Mt. Mansfield.

EFFECT OF ELEVATION ON PRECIPITATION DURATION AND INTENSITY

Figure 3 shows the total precipitation, duration and average intensity for November 1, 1976 through March 31, 1977. The precipitation was mostly snowfall. Hourly results from the Burlington recording gage were added.

Clearly, the increase of snowfall with elevation is almost totally accounted for by increased duration. From this single year of observation we might conclude that it snows more on the mountains because it snows longer, rather than harder. The negligible role of intensity in explaining the increase of precipitation with elevation is also demonstrated in Figure 4, which shows that the cumulative distributions of hourly intensities at the lowest (M1) and highest (M7) gages are nearly coincident.

Analysis of the rainfall duration and intensity of spring and summer is not complete, but preliminary indications are that intensity may increase somewhat with elevation in the warmer seasons.

EFFECT OF STORM TYPE AND CHARACTERISTICS ON PRECIPITATION CHANGES WITH ELEVATION

It would be of interest to know if different synoptic types of storms or storm events with certain characteristics as recorded at a valley gage affect precipitation changes with elevation. From October 1976 through May 15, 1977, a total of 92 separate events (each event separated by at least eight hours without precipitation) occurred at the base station M1. These were classified as to four synoptic types:

Type 1 - storm centers passing to the south of the mountain (coastal storms)

Type 2 - storm centers passing to the north of the mountain (St. Lawrence valley storms), or warm air overrunning from the south or west

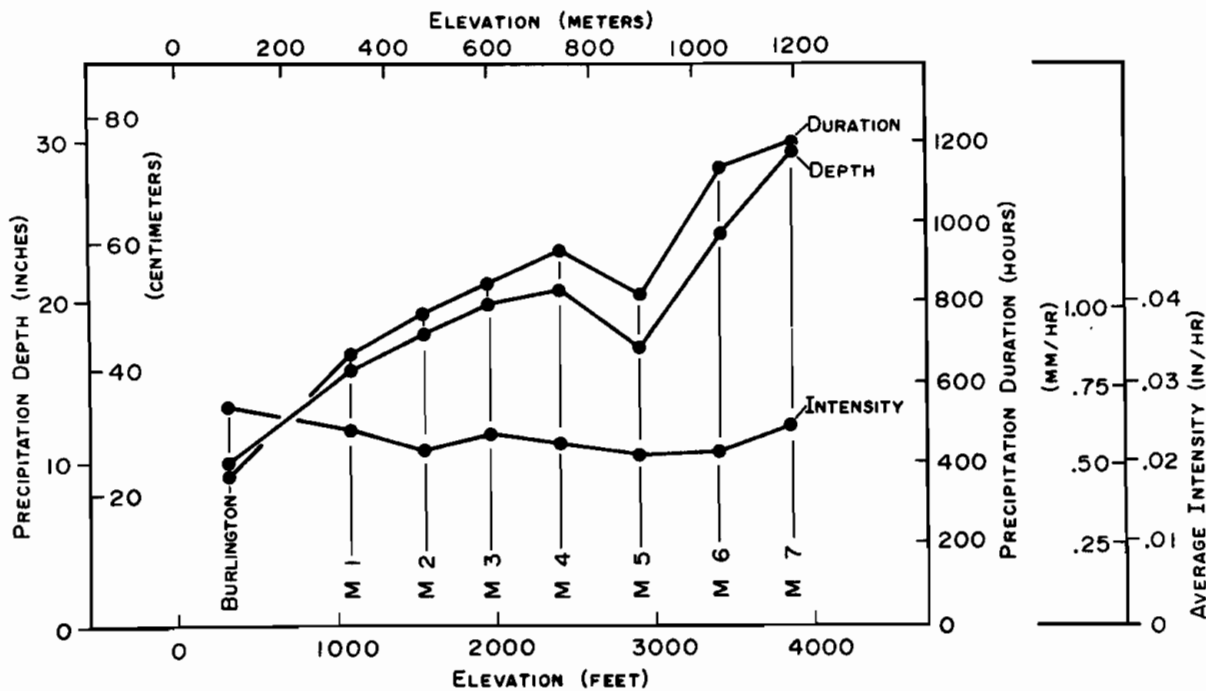


Figure 3. Effect of elevation on total precipitation, duration, and average intensity, November 1, 1976 - March 31, 1977.

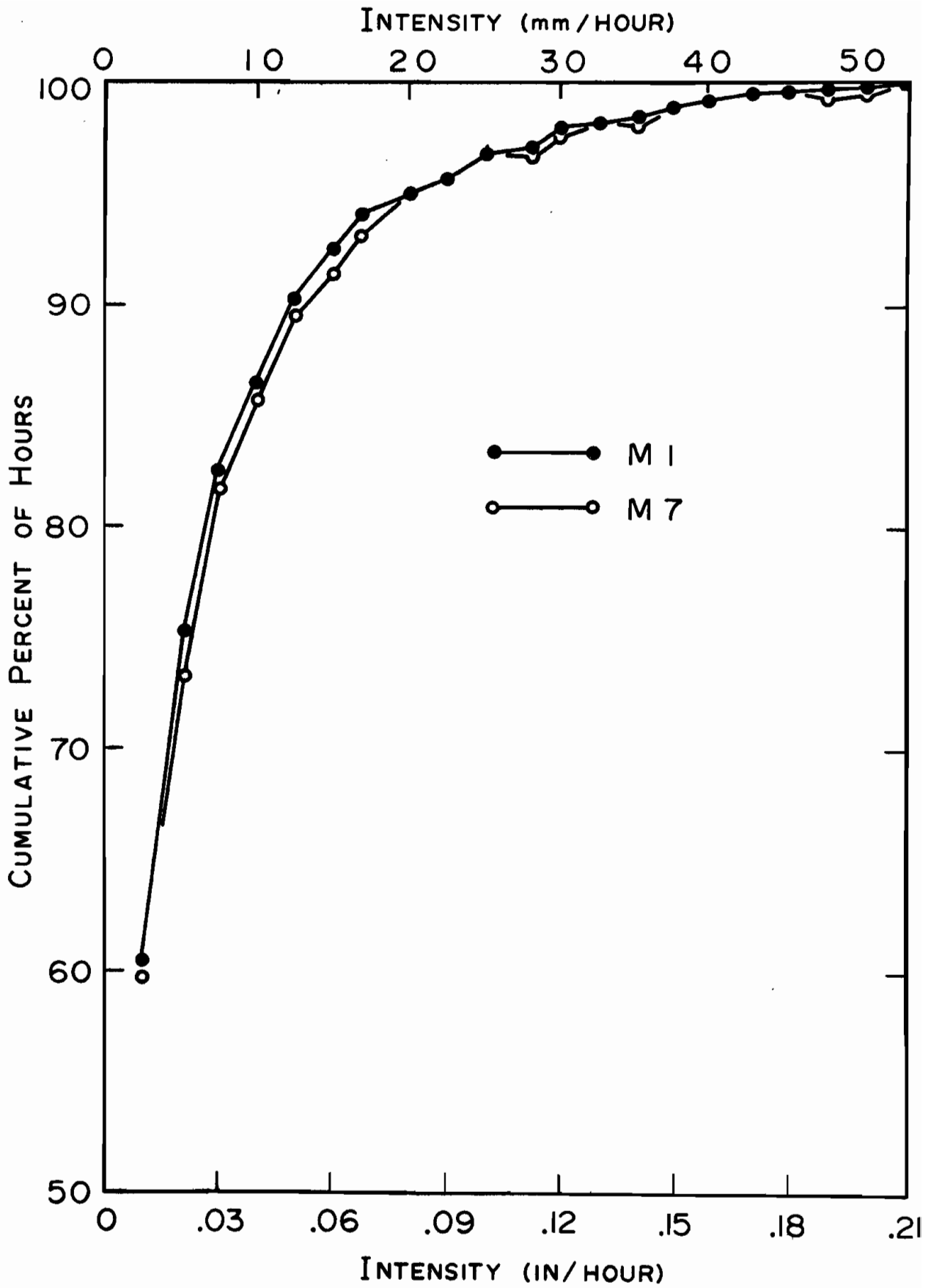


Figure 4. Cumulative percentage distribution of precipitation hours by intensity at sites M1 and M7, November 1, 1976 - March 31, 1977.

Type 3 - simple cold or occluded frontal passages without strong storm centers

Type 4 - cold cyclonic flow from the northwest, sometimes persisting a day or two following the passage of a strong storm center (mostly snow flurries)

Figure 5 shows the effect of elevation on the total precipitation produced by storm types. Type 1 storms were not as numerous as Types 2 and 4, but they produced more precipitation at greater intensities at all elevations. The K values in Figure 5, a measure of the increase in precipitation per thousand feet between M1 and M7, are defined as

$$K = (P_7/P_1 - 1)/(e_7 - e_1)$$

where P_7 and P_1 are precipitation at M7 and M1, respectively, and e_7 and e_1 are elevations of M7 and M1, in thousands of feet, respectively. The K values show that increases in precipitation from the lowest to the highest elevations are similar for all storm types except Type 4 which has about 3 times the percentage increase as the other types. Type 4 is the synoptic situation that ordinarily requires some external effects, such as surface heating, Great Lakes passage, or mountain lifting to produce precipitation. In this study, Type 4 precipitation events, which are caused primarily by mountain lifting, show a much greater rate of increase in precipitation with elevation than do storms that carry their own internal dynamics for precipitation production.

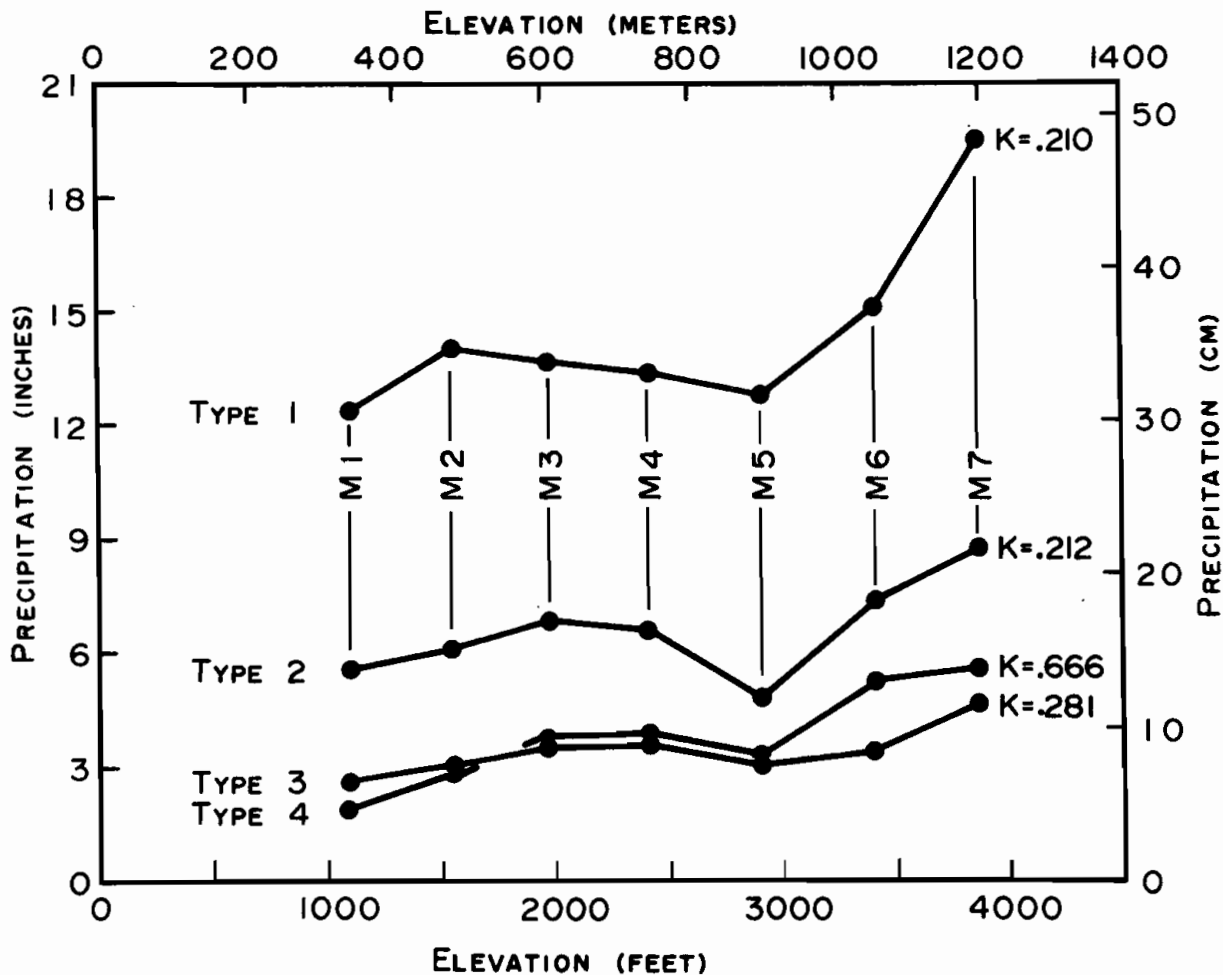


Figure 5. Effect of elevation on total precipitation by storm type, November 1, 1976 - May 15, 1977.

Figures 6 and 7 show the effects of storm type on intensity and duration at different elevations. As was true for all storms (Figure 3), precipitation for each storm type increased with elevation because of duration rather than intensity. An exception is Type 1, which showed an increase in intensity at the highest elevation only.

The 92 individual storm events were next classified by categories of average intensity at M1 and examined for percentage increase in precipitation from M1 to M7. Figure 8 shows that the least intense class of storms, those averaging 0.01 inch/hr (0.25 mm/hr) or less, increase most rapidly with elevation in terms of the ratio of precipitation at any higher elevation station (Pe) to precipitation at the base station (Po), in this case M1. The three classes from more than .01 inch/hr (.25 mm/hr) to .03 inch/hr (.75 mm/hr) are clustered at a much slower rate of increase. The most intense classes, from more than .03 inch/hr (.75 mm/hr) to more than .05 inch/hr (1.27 mm/hr), show the slowest rate of increase in storm precipitation with elevation. Analysis of storms by classes of total storm precipitation showed a similar result, with those storms having the least precipitation showing the greatest rate of precipitation increase with elevation. By plotting the average K value for storms grouped in classes of total storm precipitation, we get the curve shown in Figure 9. By rearranging and restating the previously described equation, $P_e = P_o + P_o K (e_e - e_o)$ can furnish an estimate of increased precipitation on a per storm

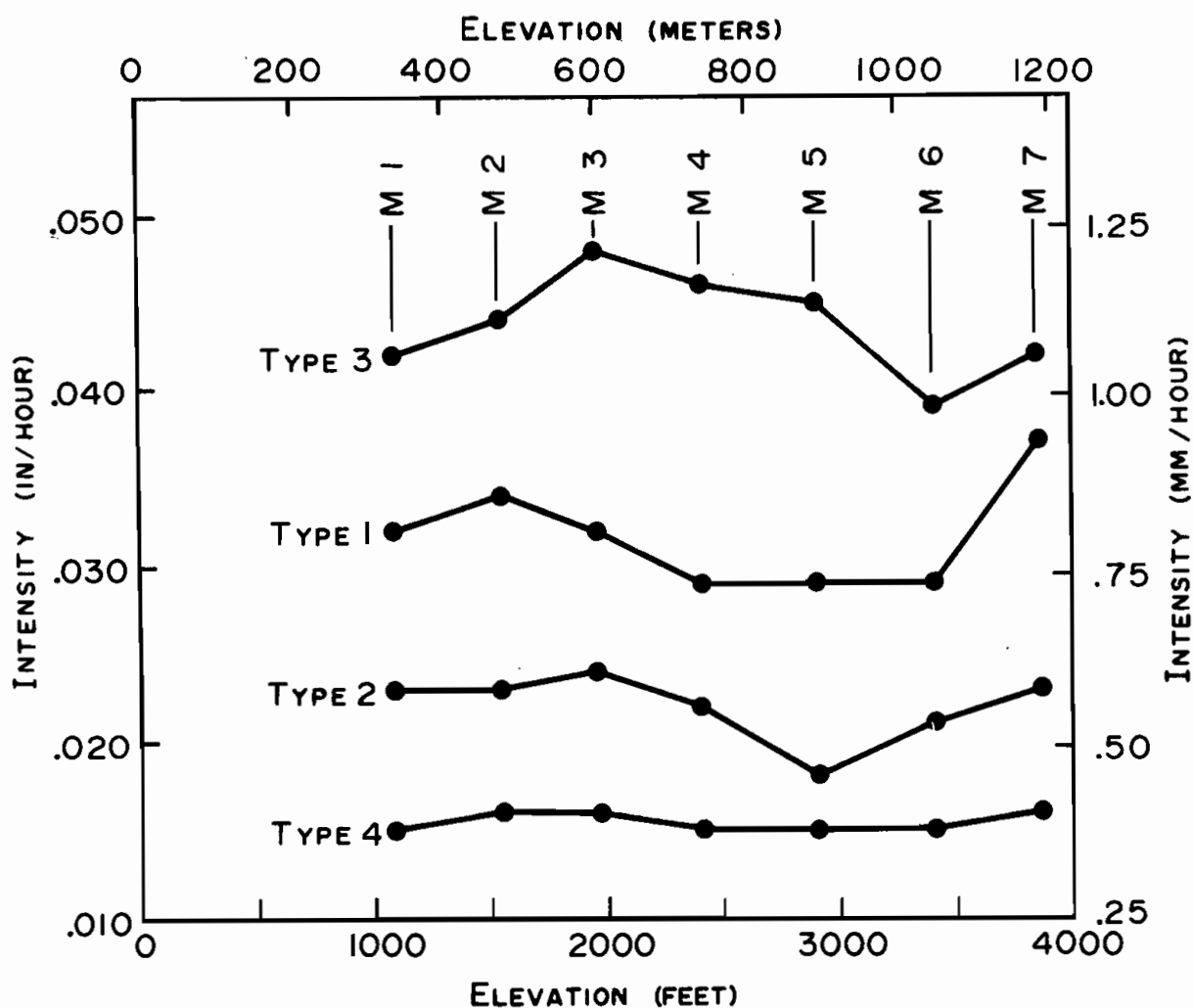


Figure 6. Effect of elevation on average intensity by storm type, November 1, 1976 - May 15, 1977.

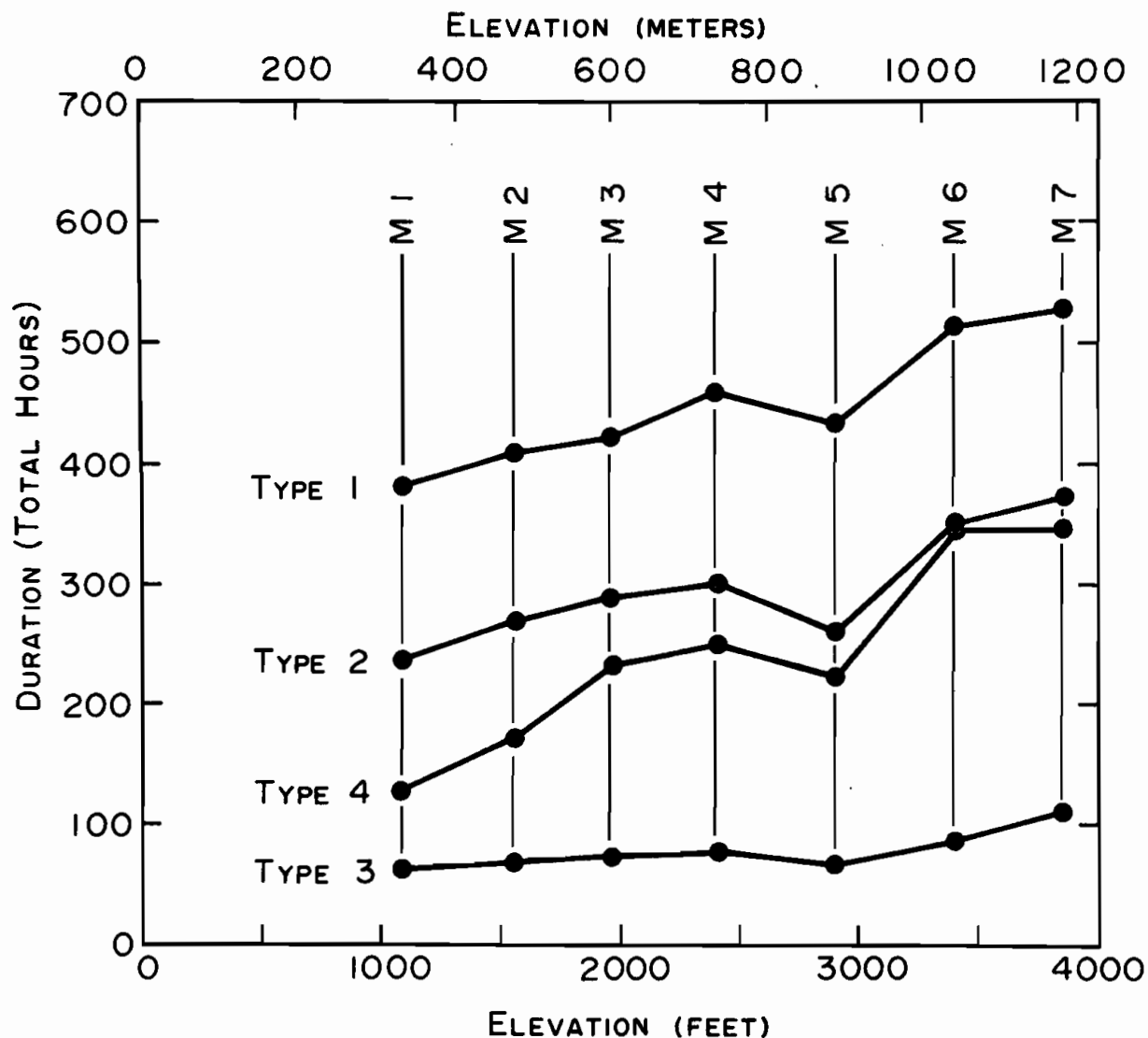


Figure 7. Effect of elevation on total seasonal hours of duration by storm type, November 1, 1976 - May 15, 1977.

basis at higher elevations (P_e, e_e) using a valley station precipitation gage (P_o, e_o). This requires further analysis of correlation and interstorm variation to obtain the best possible estimate.

EFFECT OF ELEVATION ON SNOW ACCUMULATION

The effect of elevation is, of course, more pronounced on snow accumulation than on precipitation because decreasing temperature with elevation causes a greater percentage of the precipitation to fall as snow, and also delays the snowmelt. A comparison of snow-pack accumulations and melt at the lowest station, M1, and the station with the greatest snow accumulation, M6, is shown in Figure 10. It is assumed that water equivalents are proportional to depths for any given date, an assumption supported by water equivalent determined at snow courses in January and March.

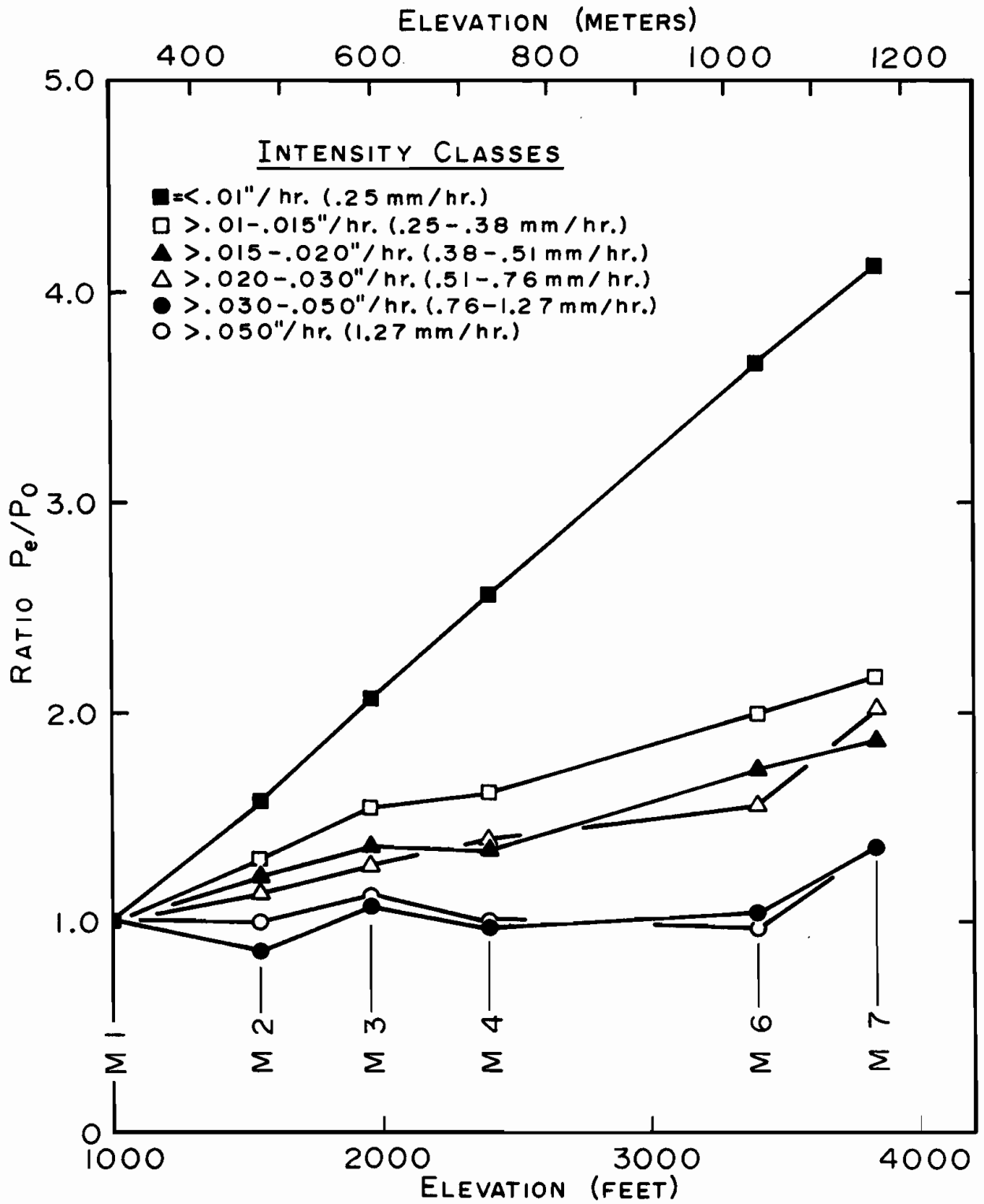


Figure 8. Ratio of P_e/P_1 for intensity classes of storms, November 1, 1976 - May 15, 1977.

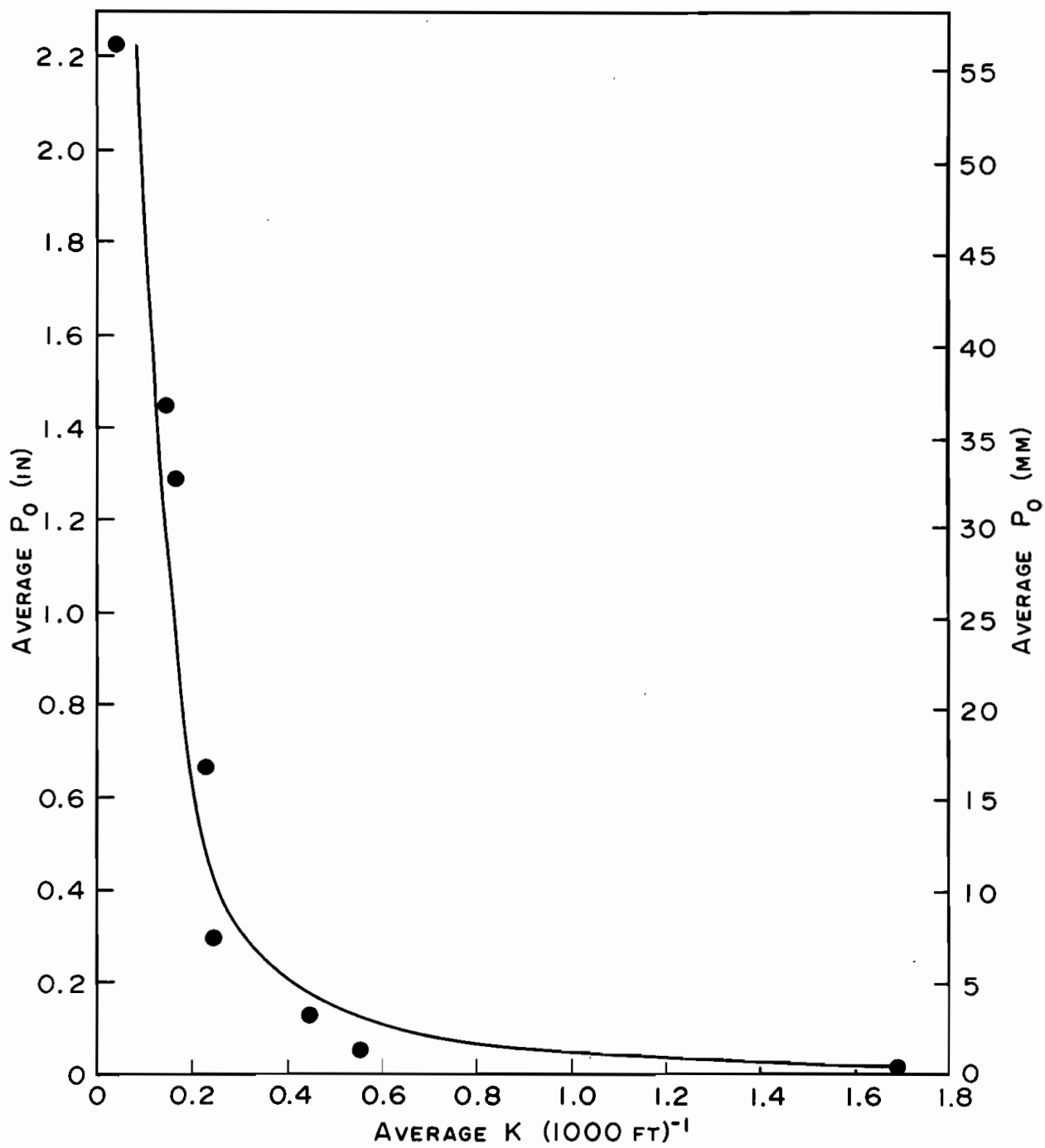


Figure 9. Average rate of precipitation increase (K) from the lowest to highest station for storm events classified by precipitation amount, November 1, 1976 - May 15, 1977.

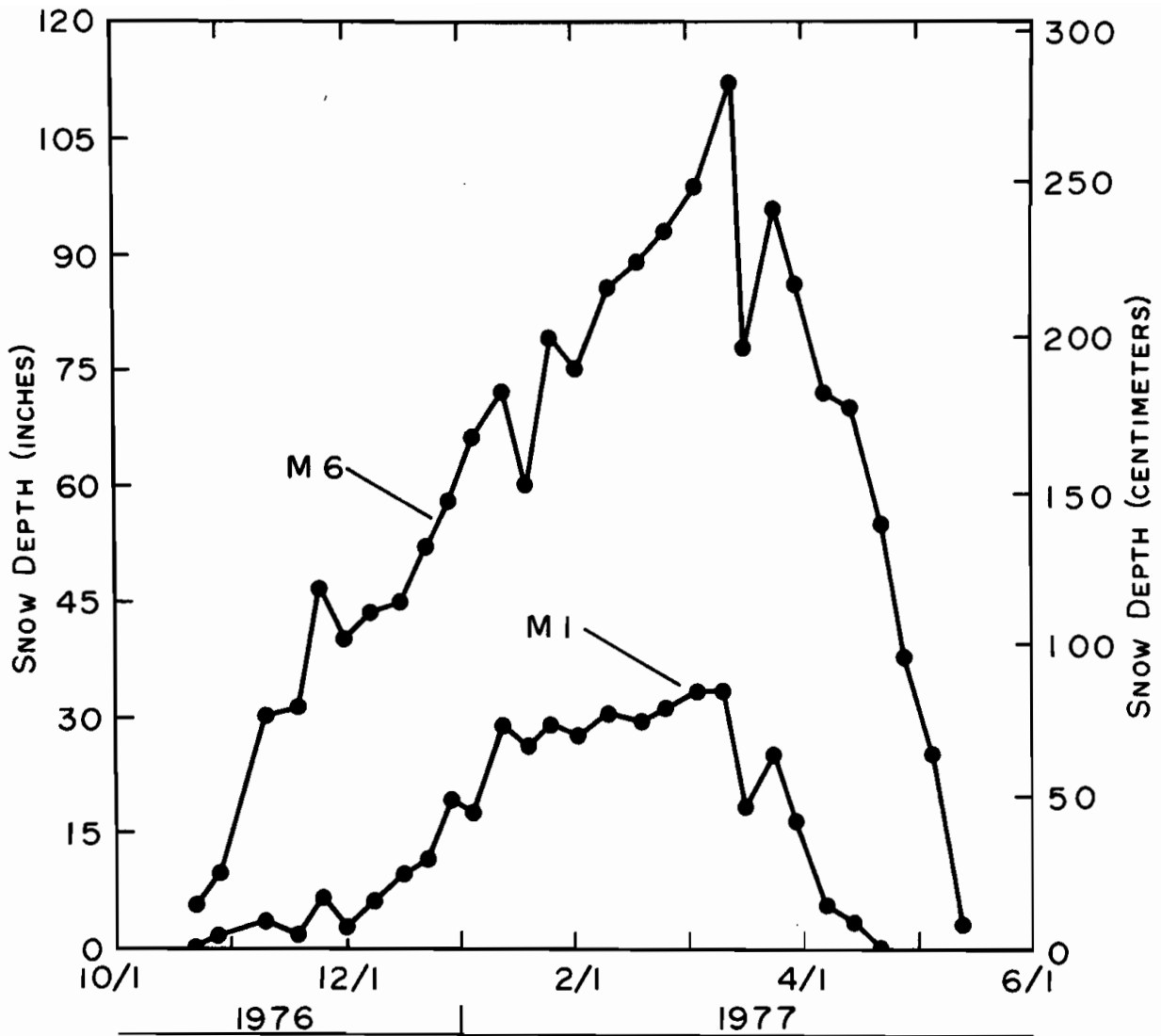


Figure 10. Snow depth of M1 and M6, 1976-77 season.

Figure 11 shows a comparison between accumulated precipitation at M7 and the estimates of the snowpack water equivalent based on snow depths and periodic density measurements. During the winter of 1976-77, almost no rain fell and no snow thawed at the higher elevation; thus, all precipitation remained stored in the snowpack until the mid-March thaw. Estimates of mountain snowpack accumulation based on valley meteorological data must involve estimates of temperature change with elevation along with the effect of elevation on precipitation. The use of an average lapse rate of $-3.5^{\circ}\text{F}/1000'$ is probably sufficient for this purpose.

DISCUSSION

As indicated earlier, this is a report of an effort to improve our understanding of the effects of elevation on precipitation, snowfall and snow accumulation. We are midway along in this effort and our observational program on Mt. Mansfield is providing some of the most detailed elevation-precipitation data ever gathered on northeastern mountains. Early indications are that the total storm precipitation and average storm intensity information from a valley station may be the most reliable indicators of the rate of

change of precipitation with elevation. The data derived from these 2 years of observations will be carefully analyzed to derive a precipitation-elevation-snow accumulation model based on readily available National Weather Service network data.

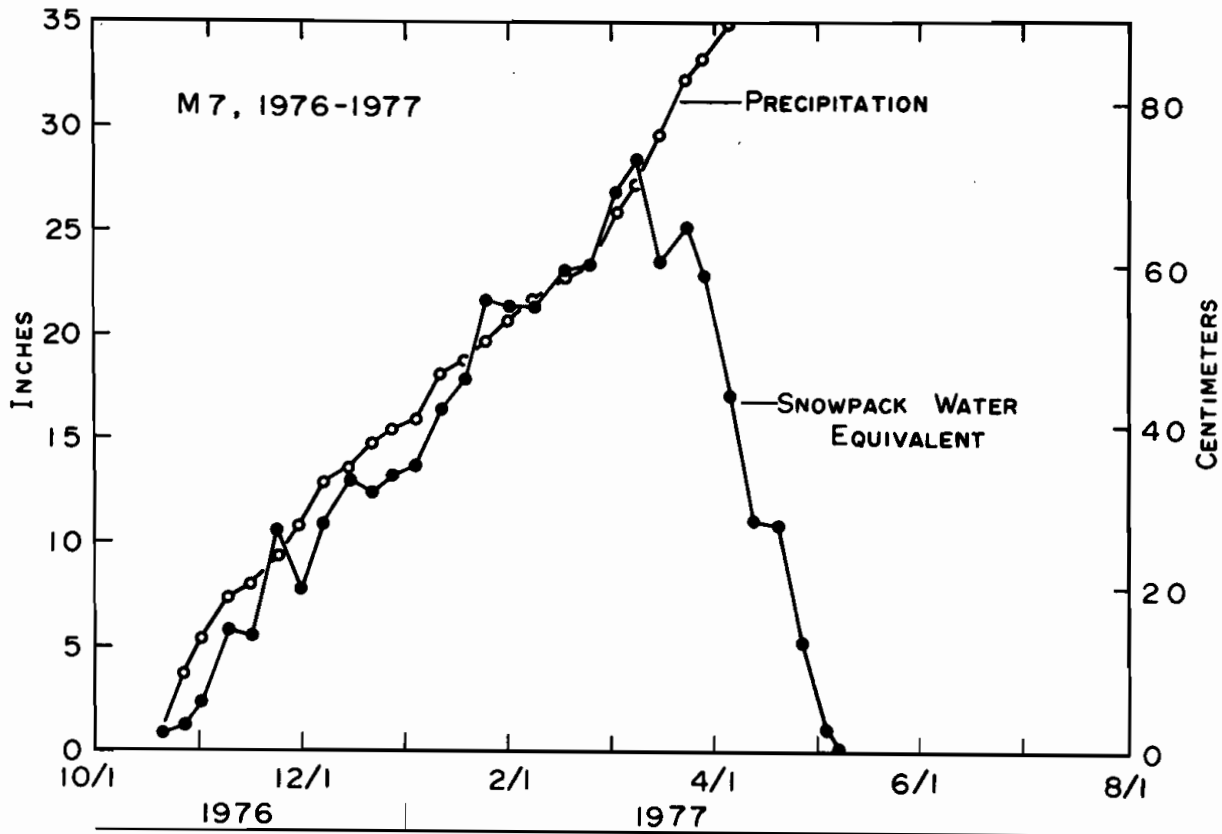


Figure 11. Comparison of precipitation and snowpack water equivalent for M7, 1976-77 season.

ACKNOWLEDGMENTS

The authors are greatly indebted to the Mt. Mansfield Company for their interest in this project and their most willing cooperation in permitting our use of their ski lifts in winter and their toll road in summer for our gage observations and maintenance.

We are also delighted to report that not one of our gages, which are easily seen and accessible from the toll road, hiking and ski trails has ever been tampered with or damaged in any way by the thousands of recreationists using the area.

REFERENCES

Hendrick, Robert L. and Roger J. DeAngelis. July 1976. Seasonal Snow Accumulation, Melt and Water Input - A New England Model. J. Appl. Meteor. 15(7):717-727.