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EFFECT OF ANTECEDENT CONDITIONS ON FROZEN GROUND FLOODS

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ABSTRACT

Predicting frozen ground occurrences can be helpful in preventing flood damage in areas that are subject to winter floods. Discriminant analysis was used to study frozen and unfrozen ground runoff events for four watersheds in the Pacific Northwest. Part of the discriminant procedure was used to choose a set of meteorological factors for each area that can distinguish between frozen and unfrozen ground runoff events. These variables were then used to define a system to classify other past or future runoff events.

The occurrence of a frozen ground runoff event is dependent on the combination of several meteorological factors interacting together rather than on the influence of one single variable such as the average minimum air temperature. This methodology proved successful for two of the watersheds studied. It was found that a unique set of variables could be used for classification, depending on which watershed is being analyzed.

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ACKNOWLEDGEMENTS

This project was undertaken to obtain a deeper understanding of the causative factors of floods occurring on frozen soil. Since this same situation also causes much erosion, this project was also of interest of the Palouse Conservation Field Station, Agricultural Research Service, Pullman, Washington. Personnel from that Station, particularly Dr. D.K. McCool, were very helpful in selecting watersheds, gathering data and helping to distinguish frozen ground runoff events from ordinary runoff events. Drs. Leonard Lane, Tucson, Arizona and Willard M. Snyder, Athens, Georgia, both of the ARS, reviewed the discriminant analysis procedure used.

Mr. Robin McArthur, Soil Conservation Service, Boise, Idaho, helped extensively with pointing out flood prone problem areas and in explaining the hydrologic significance of frozen soil in Idaho.

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INTRODUCTION

Frozen ground is one of the most important factors causing winter flooding in the Pacific Northwest. A heavy rainfall on snow and frozen soil combined with snowmelt during the winter and early spring may often lead to a severe flood. On February 26, 1948, a flood on the South Fork of the Palouse River caused extensive damage in the city of Pullman, Washington. This flood resulted from a general rainstorm of about 1.6 inches in a 6-hour period which occurred on frozen and snow-covered ground. Johnson and McArthur (1973), in a study of winter flooding in Idaho and surrounding areas for 1955-1972, found that the amount and intensity of the rainfall, the amount of snowmelt, and the imperviousness of the frozen soil combine to affect the flood severity.

Climatological factors have been found to be important in studying the occurrence of frozen ground. McCool and Molnau (1974) used the historical climatological record to study both the frequency and the severity of frozen soil conditions. They concluded that climatological data can be very useful in assessing the overall frozen ground hazard for a given location. The meteorological factors affecting the freezing of soil include air temperature, solar radiation, wind, and precipitation (Moulton, 1968). Sourwine (1929) suggested a method to quantitatively relate air temperature data to the relative danger of the ground freezing in any given locality. His results strongly suggest that the combined effect of low temperature and the duration of the cold period are essential factors in estimating the occurrence of frozen ground. McArthur (1971) studied flood runoff from rainfall and snowmelt over a frozen soil mantle in Idaho and concluded that winter flooding is caused by a specific set of meteorological conditions.

It is evident that if a specific relationship between meteorological factors and the occurrence of frozen ground floods could be derived much flood damage could be avoided by determining when a frozen ground flood could occur at a given location.

OBJECTIVES

The prediction of frozen ground occurrences under certain conditions will help local planners to regulate development in areas subject to winter floods. If a frozen ground flood forecasting procedure could be developed, it would allow precautions to be taken in order to limit damage in the threatened areas. The specific objectives of this study are as follows:

1. Apply a multivariate statistical procedure for identifying the hydrologic parameters that are important in distinguishing frozen and unfrozen ground floods.
2. Develop a system for determining the probability of occurrence of frozen ground floods in the past or future for a sequence of meteorological events.

PROCEDURES

For the purpose of this study, frozen ground floods are defined as rainfall and/or snowmelt runoff events which occur when there is an impermeable crust of frozen soil covering the watershed such that the infiltration rate is decreased and the runoff is more than would occur under conditions of unfrozen soil or permeable frozen soil.

Discriminant Analysis

Discriminant analysis is a multivariate method that begins with the desire to statistically distinguish between two or more groups of events. To distinguish between these groups one selects a collection of discriminating variables that measure characteristics on which the groups are expected to differ. The cases are divided into groups and the analysis is used to find classification functions (linear combinations of the variables) that best separate the groups. These functions are useful for classifying new cases.

The application of this type of analysis on hydrologic problems is a fairly new field and is still in its development and trial stage. Rice (1967) stated that multivariate methods free the hydrologist from the need to describe a phenomenon as a single number. Using multivariate methods, the hydrologist can cope with the highly correlated "independent" variables common in hydrology. Also, these methods provide a flexible approach that is more in harmony with the nature of many hydrologic problems. De Coursey (1973) used discriminant analysis to analyze factors related to the adequacy of standard slope protection on small dams. His analysis showed that a linear combination of a set of variables could be used to distinguish between two groups; those sites with no damage and those sites with some observed damage. Thus a discriminant equation can be used to assign structures to either of the two groups.

The application of discriminant analysis for the determination of frozen or unfrozen runoff events is new. Although some of the assumptions of discriminant analysis do not fit the real world perfectly, this method may still be useful for classifying frozen and unfrozen floods.

The Statistical Computer Programs

In this study, three statistical computer packages were used; SAS-Statistical Analysis Systems (Barr and Goodnight, 1972), BMD-Biomedical Computer Programs (Dixon, 1975), and SPSS-Statistical Package for the Social Sciences (Nie and others, 1975). The BMD-Stepwise Discriminant Analysis can be used to select a subset of variables that maximizes group differences. Variables are entered into the classification function one at a time, until the group separation ceases to improve as measured by a preset criteria. At each step, BMD uses a one-way analysis of variance F-statistic to determine which variable should next be added. The program also computes canonical correlations and coefficients of the discriminant functions which are useful in plotting a two-dimensional picture of the dispersion. This is helpful in obtaining an idea of the group dispersion. Various other statistical values are printed to present a more detailed picture of how well each case has been classified. The discriminant analysis procedure is successful if few cases are classified into the wrong groups. If a large percentage of the cases are classified correctly one knows that groups differences do exist and that the selected set of variables does explain those differences. The BMD output presents this classification information in a table of counts indicating how many cases from each original group are assigned to each of the possible groups.

Once the best set of discriminating variables is chosen, any unknown cases may be classified into one of the groups. The SAS-Discriminant Analysis can be used for this purpose. The classification of data is concerned with quantitative methods for the assignment of an individual observation to one of several groups on the basis of multiple measurements on that observation. It is assumed that each observation belongs to one of the groups. Several relevant characteristics of the individual observation are measured and on the basis of this information a classification decision is made. The method used to assign observations to a group must have a minimum probability of error.

The SPSS-Discriminant Analysis has the capability for both a stepwise selection of discriminating variables and a classification of unknown cases. The program performs discriminant analysis either by entering all of the discriminating variables directly into the analysis or through a variety of stepwise methods selecting the best set of discriminating variables. Once a set of variables is found which provides satisfactory discrimination for cases with known group membership, a set of classification functions can be derived which will permit the classification of new cases with unknown membership. In order to check the adequacy of the discriminating functions, the program will classify the original set of cases to see how many are correctly classified. In the classification procedure the probability of membership in each group is computed and the case is assigned to the group with the highest probability. This program also produces plots of the classification results. These are particularly useful in studying the separation of the group controls and the degree to which the groups overlap. The SPSS computer package at the University of Idaho is a new release and some parts of the Discriminant Analysis routine are not working correctly to date including the plots for a two group case. Therefore, some caution should be used when interpreting its results and the BMD and SAS programs were used as checks for the SPSS.

Description of Study Watersheds

Four drainage basins were chosen for testing these procedures: Missouri Flat Creek near Pullman, Washington; McCay Creek near Pilot Rock, Oregon; Blackfoot River near Blackfoot, Idaho; and Rock Creek near Rock Creek, Idaho. Figure 1 shows the general location of these watersheds.

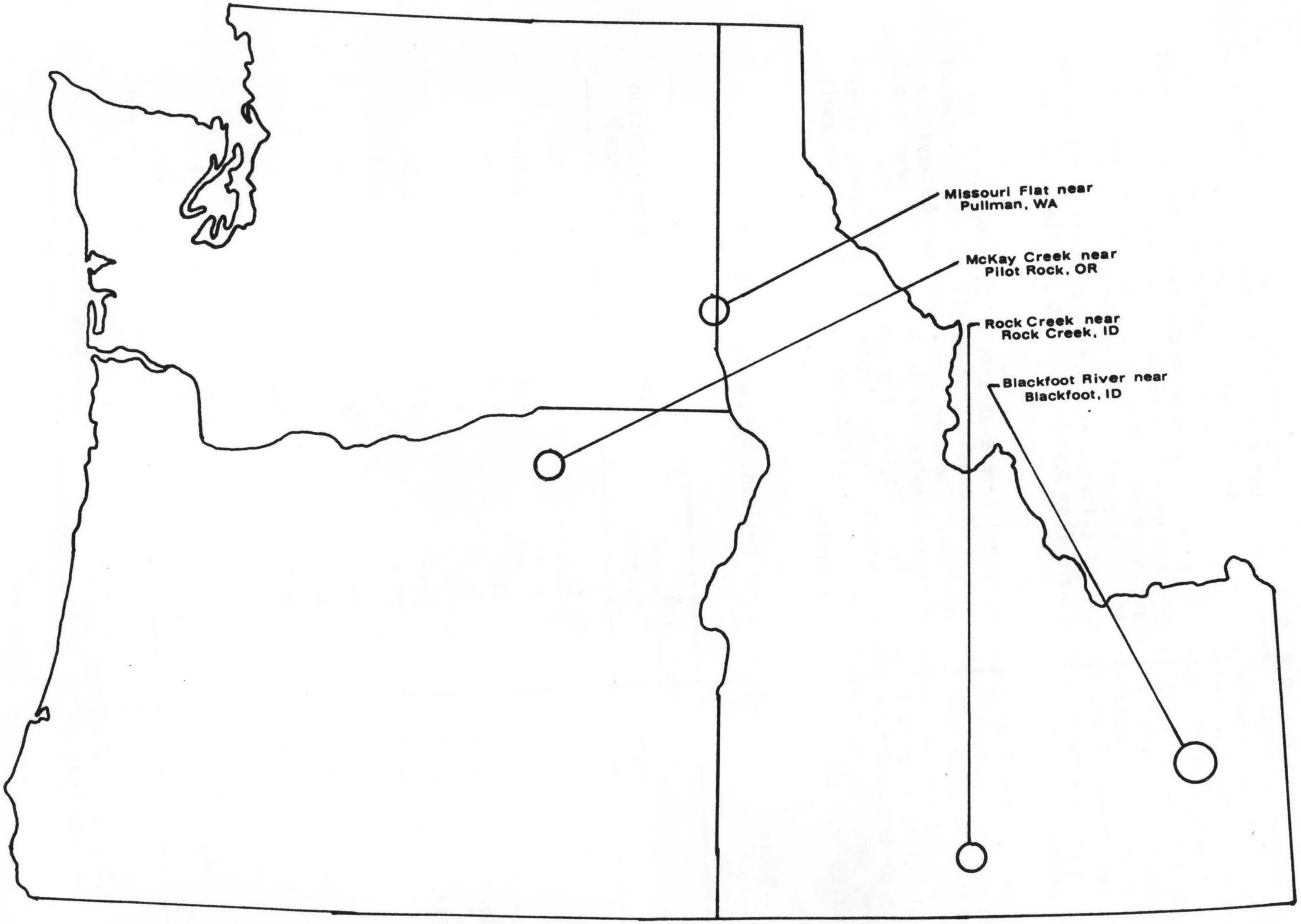

Figure 1. Map showing location of study areas.

These watersheds were selected by using several criteria. First, a known history of frozen ground floods must exist. This was established by visits to the Walla Walla District, Corps of Engineers, and to the Soil Conservation Service, Boise, Idaho. Next the chosen watersheds were checked for available climatic data. This caused some problems since the best runoff records did not necessarily coincide with good climatic records. This was particularly true with the Blackfoot River since it was desired to include at least one large watershed in the analysis. This basin has a long history of frozen ground floods but no good climatic station exists within the basin. The nearest acceptable records were from Aberdeen, about 55 miles from the basin center.

The Missouri Flat Creek watershed covers an area of 27.1 square miles and is approximately 12 miles long. It consists of mostly rolling cultivated land averaging 2800 feet in elevation. The mean annual maximum temperature is 57.4°F and the mean annual minimum temperature is 36.4°F. The mean annual snowfall of this basin is 22.4 inches. Most of the precipitation for the area is distributed from October through March. Table 1 lists monthly temperature, snowfall, and precipitation data at Pullman, which is approximately four miles from the center of the basin.

Table 1. Climatic data for Pullman, Washington (1940-1971)

	Temperature			
Month	Maximum	Minimum	Snowfall (inches)	Precipitation (inches)
October	59.7	38.0	0.2	1.94
November	43.9	30.4	2.0	2.94
December	36.3	25.5	5.9	3.05
January	34.4	21.7	7.1	3.13
February	40.6	27.0	3.6	2.16
March	46.0	29.6	3.1	2.01
April	55.8	35.2	0.5	1.54
May	64.6	41.0	0.0	1.55
June	71.0	46.3	0.0	1.70
July	82.2	49.2	0.0	0.46
August	81.4	49.2	0.0	0.46
September	72.3	44.6	0.0	0.75

The McKay Creek watershed covers an area of 180 square miles with an elevation of 1322 feet at the outlet. The mean annual maximum and minimum temperatures are 62.6°F and 41.5°F respectively. The precipitation generally occurs from October through January. Table 2 lists the climatic data for the weather station at Pendleton which is approximately 20 miles from the center of the basin.

Table 2. Climatic data for Pendleton, Oregon (1940-1971)

Month	Temperature		Snowfall (inches)	Precipitation (inches)
	Maximum	Minimum		
October	63.4	41.6	0.1	1.13
November	49.0	33.5	1.4	1.49
December	42.0	29.6	3.5	1.57
January	38.4	25.1	5.8	1.55
February	46.6	31.1	2.4	1.04
March	53.2	34.1	1.2	1.05
April	61.9	39.7	0.1	0.98
May	70.6	46.5	0.0	1.27
June	78.2	52.6	0.0	1.01
July	88.5	58.7	0.0	0.25
August	85.9	57.5	0.0	0.34
September	76.9	50.7	0.0	0.59

The Blackfoot River near Blackfoot, Idaho has a large drainage area comprising 1295 square miles with an average elevation of about 5800 feet. The mean annual maximum and minimum remperatures at the Aberdeen experiment station are 60.1°F and 30.6°F respectively and it receives a mean annual precipitation of 8.73 inches. Table 3 shows the monthly climatic data at Aberdeen. Although Aberdeen is about 55 miles from the basin center and is further than Idaho Falls, soil temperature data over a long period was available at Aberdeen.

The Rock Creek watershed near Rock Creek, Idaho covers an area of 80 square miles with an average elevation of 6330 feet. The nearest weather at Twin Falls reports a mean annual maximum temperature of 63.1°F and a mean annual minimum temperature of 34.9°F. The mean annual precipitation for the area is 9.53 inches. Table 4 lists some pertinent data for Twin Falls, about 25 miles from the center of the basin.

Table 3. Climatic data for Aberdeen, Idaho (1914-1974)

Month	Temperature Maximum	Temperature Minimum	Snowfall (inches)	Precipitation (inches)
October	63.2	30.3	0.4	0.84
November	46.2	22.2	1.7	0.71
December	34.6	14.8	5.5	0.80
January	30.9	10.7	7.9	0.73
February	37.1	16.5	4.5	0.59
March	46.7	22.9	2.4	0.70
April	59.4	29.9	1.8	0.88
May	69.6	37.5	0.0	1.08
June	78.1	44.0	0.0	0.89
July	88.7	50.1	0.0	0.42
August	86.5	47.7	0.0	0.47
September	76.0	38.7	0.0	0.62

Table 4. Climatic data for Twin Falls, Idaho (1905-1974)

Month	Temperature Maximum	Temperature Minimum	Snowfall (inches)	Precipitation (inches)
October	65.6	34.1	0.3	0.78
November	50.0	26.4	1.5	1.05
December	39.2	20.6	4.4	0.97
January	36.5	18.1	6.5	1.11
February	42.6	23.1	3.6	0.80
March	51.9	27.6	2.0	0.85
April	62.3	33.6	0.9	0.96
May	71.7	41.0	0.3	1.01
June	79.9	47.4	0.0	0.88
July	90.3	53.5	0.0	0.29
August	88.1	50.8	0.0	0.26
September	77.8	42.1	0.0	0.57

RESULTS AND DISCUSSION

Discriminating Variables

As a result of studying the literature on climatic factors which influence the occurrence of frozen ground, a group of variables were chosen which might be helpful in discriminating between frozen and unfrozen ground runoff events. These variables are listed in Table 5.

Table 5. Discriminating variables used in frozen ground analysis

	Variable	Unit
1.	Number of days in freeze period	days
2.	Accumulative freeze index	degree (F) days
3.	Precipitation 2 days before the start of freeze period	inches
4.	Precipitation during freeze period	inches
5.	Precipitation 4 days after freeze period	inches
6.	Snowfall during freeze period	inches
7.	Depth of snow on ground at start of freeze period	inches
8.	Streamflow for 4 days after freeze period	cfs-days
9.	Accumulative thaw index	degree (F) days
10.	Precipitation from 1 Oct. to start of freeze period	inches
11.	Number of days from 1 Oct to start of freeze period	days
12.	Average minimum temperature during freeze period	degrees (F)

The number of days for which the mean daily temperature was less than freezing is used as the duration of freezing weather.

The freeze index is the summation of degree-days for which the mean daily air temperature is below 32^{o}F beginning on the day during which the mean daily temperature falls below 32^{o}F. It gives and indication of the duration and severity of the freeze period. The thaw index is the number of degree-days for which the mean daily air temperature is above 32^{o}F. The precipitation two days before the freeze period and from October 1 to the start of the given freeze period give an indication of the soil moisture prior to the freezing temperatures. This affects the type of frost which is formed and the resultant permeability of the ground.

The streamflow for four days after a freeze event ends is an indication of the severity of the flood or runoff that resulted from the precipitation and the snow on the ground. The ratio of runoff to precipitation during and after the event could have been used. However, it was felt that the use of each one of these variables separately would be preferable to having a variable that is calculated from other variables. It is also recognized that the principle use of this variable is in identifying past events since it would not be available for real time forecasting.

The variables involving snowfall and snow cover are important in relation to how the soil is insulated from ambient conditions. The number of days below freezing and the average minimum temperature give an indication of the severity and intensity of the freeze. With a combination of some or all of the above variables it is desired to derive a function for distinguishing between frozen and unfrozen runoff events. The necessary climatological and streamflow records were obtained from the publications of the National Weather Service and the U.S. Geological Survey.

For each watershed, the variables in Table 5 were determined. Then each freeze event was scrutinized to determine if frozen ground could have occurred during that freeze period. This was done in one of two ways: either the soil temperature records were used and the minimum daily temperature at the four inch depth was used with a 30 or 32^{O}F threshhold. Alternatively, a precipitation-runoff relationship was derived for periods when significant runoff occurred. If an event showed greater than normal runoff, it could be classified as frozen ground. This method did not make it possible to determine the status of periods when no significant runoff occurred.

Missouri Flat Creek

The analysis of the Missouri Flat Creek watershed data was initially begun using 143 runoff events, 54 of which were known to be either frozen or unfrozen observations. The first eight variables of Table 5 were chosen as the first set of variables to be used to obtain classification functions and the 54 known cases were classified into one or the other of the groups. The discriminant analysis classified two of the known frozen ground events into the unfrozen group and one of the unfrozen cases was classified into the frozen ground group. Using the 89 unknown observations in the SAS-Discriminant Analysis, it was found that 10 were classified as frozen ground events and the remaining 79 were classified as unfrozen.

With this method all eight discriminating variables are considered as a system and it is the total effect of all eight variables which decides into which group an observation will be classified. With these eight variables, 94 percent of the known cases were correctly classified into their respective group. Figure 2 shows a plot of the first two canonical discriminant functions derived from eight variables for the 54 known observations. It shows that the two groups are generally well separated although there is some overlapping between them.

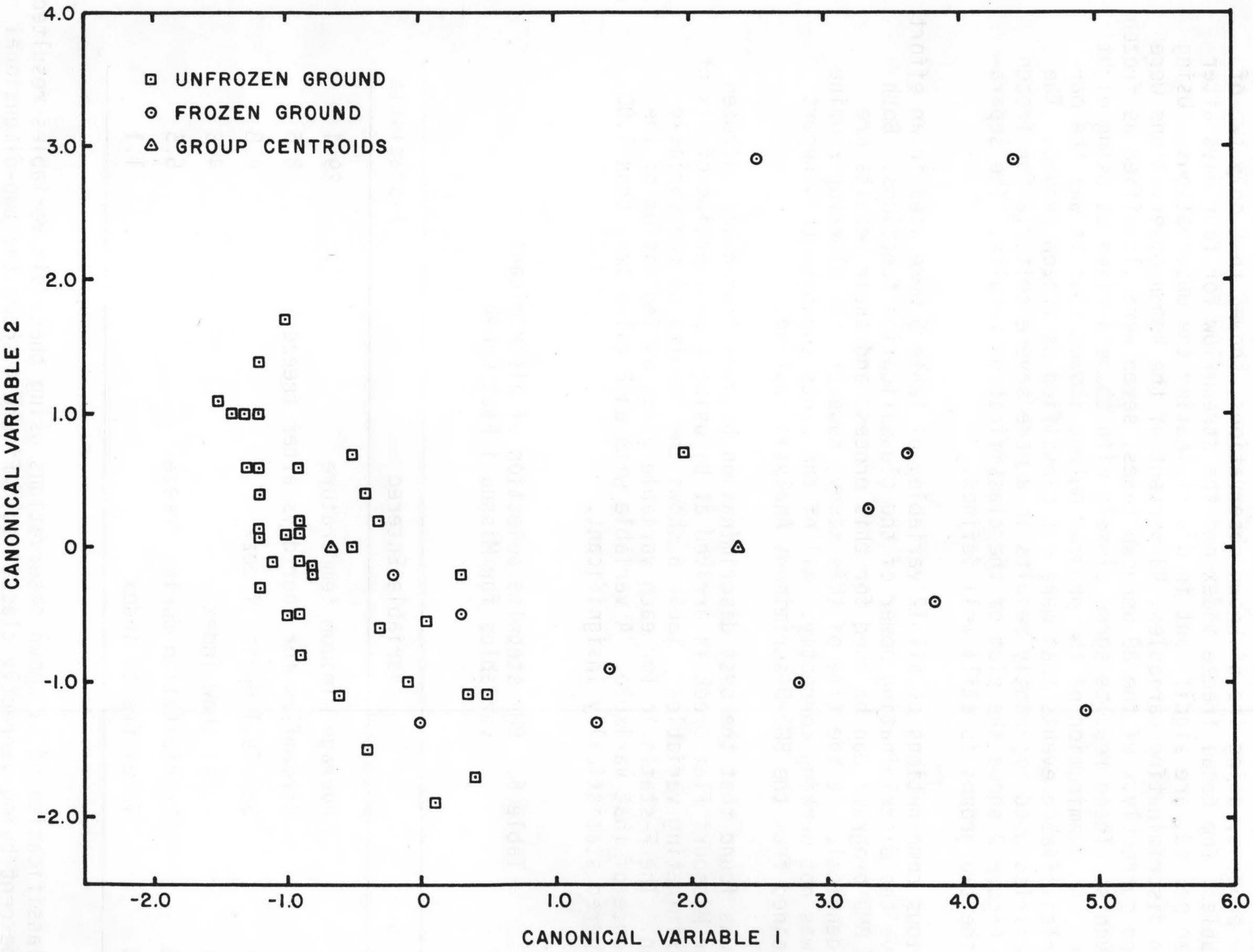

Figure 2. Classification plot using first eight variables of Table 1.

A stepwise selection of the above eight variables was made using SPSS-Discriminant Analysis and the 143 runoff events were again classified. The selection process, using the 54 known observations, showed that only two of the variables, the total freeze index and the streamflow for four days after the freeze period, are significant in discriminating the observations. Using these two discriminating variables, 93 percent of the known observations were classified correctly. Of the 89 unknown cases, seven were classified as frozen runoff events. These results agree closely with those arrived at using eight variables. An examination of the program output showed that it was the marginally classifiable events that were not classified as frozen ground. The fewer variables used apparently results in a more severe criteria for frozen ground. Figure 3 shows the plot of the classification results. The separation of the two groups is still well defined.

Various combinations of all 12 variables of Table 5 were used in an effort to improve the discriminating power of the classification functions. Both SPSS and BMD programs can be used for this process and their results are almost identical. At the time of this study, however, the plotting routine of SPSS was not working correctly. All of the plots shown in this report were obtained from the BMD-Discriminant Analysis routine.

It was found that the best discrimination between frozen and unfrozen cases for Missouri Flat Creek is arrived at by using a combination of six of the discriminating variables. Table 6 shows the results of the variable selection. The F-statistic for each variable gives an indication of the significance of that variable. A variable with an F value less than 1.00 is considered statistically insignificant.

Table 6. BMD stepwise selection of discriminant variables for Missouri Flat Creek

Step	Variable Entered	F-Statistic
1	Average minimum temperature	29.4
2	Streamflow for four days after freeze	8.6
3	Snowfall during freeze	6.8
4	Total thaw index	4.3
5	Precipitation during freeze	5.5
6	Total freeze index	1.1

Classification of 54 known observations using these six variables resulted in 98 percent being correctly classified. Figure 4 shows the two-dimensional plot of these results. The two groups are definitely well separated and distinct. It is evident that the linear combination of these six discriminating variables does adequately define a set of classification functions which

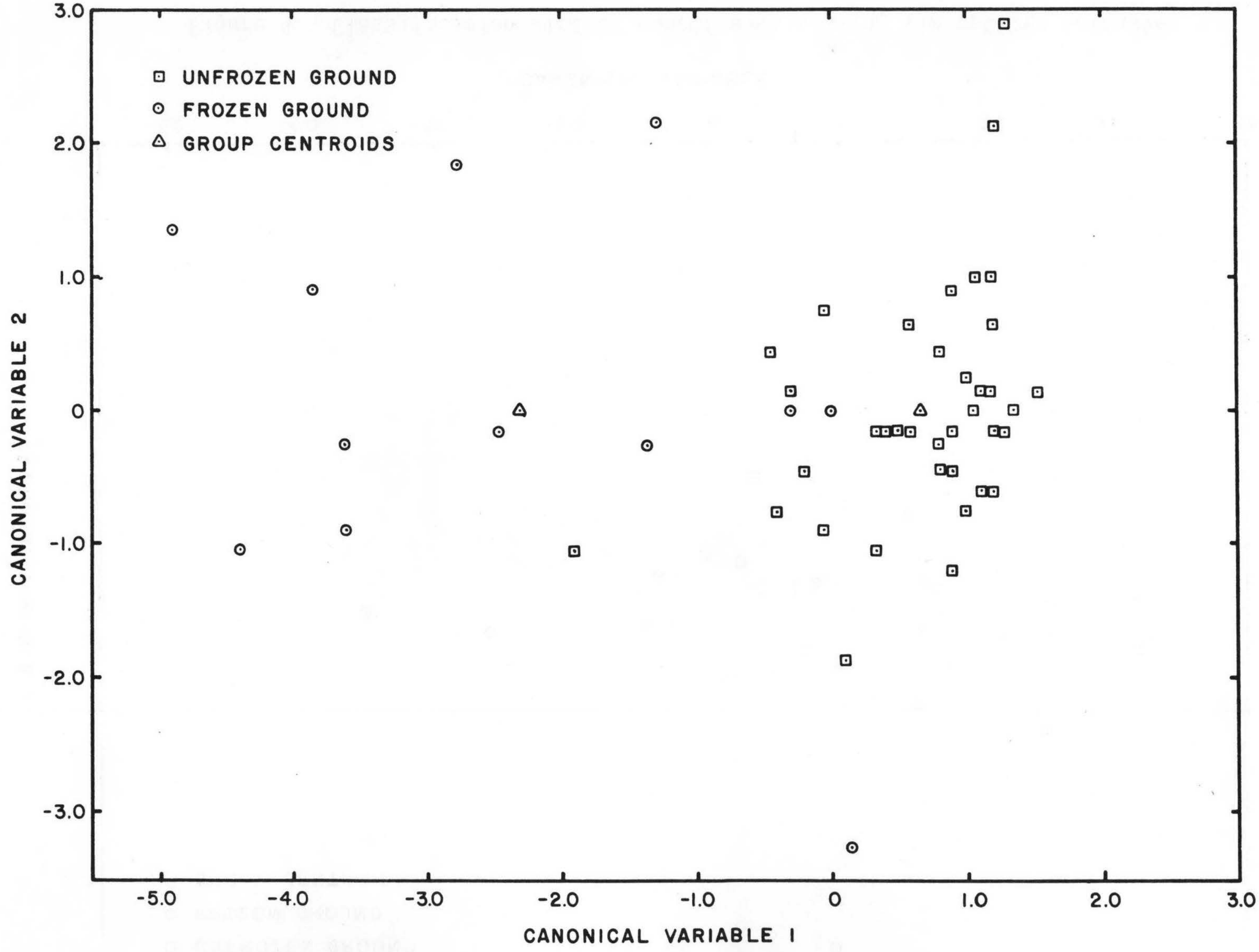

Figure 3. Classification plot using two optimum variables.

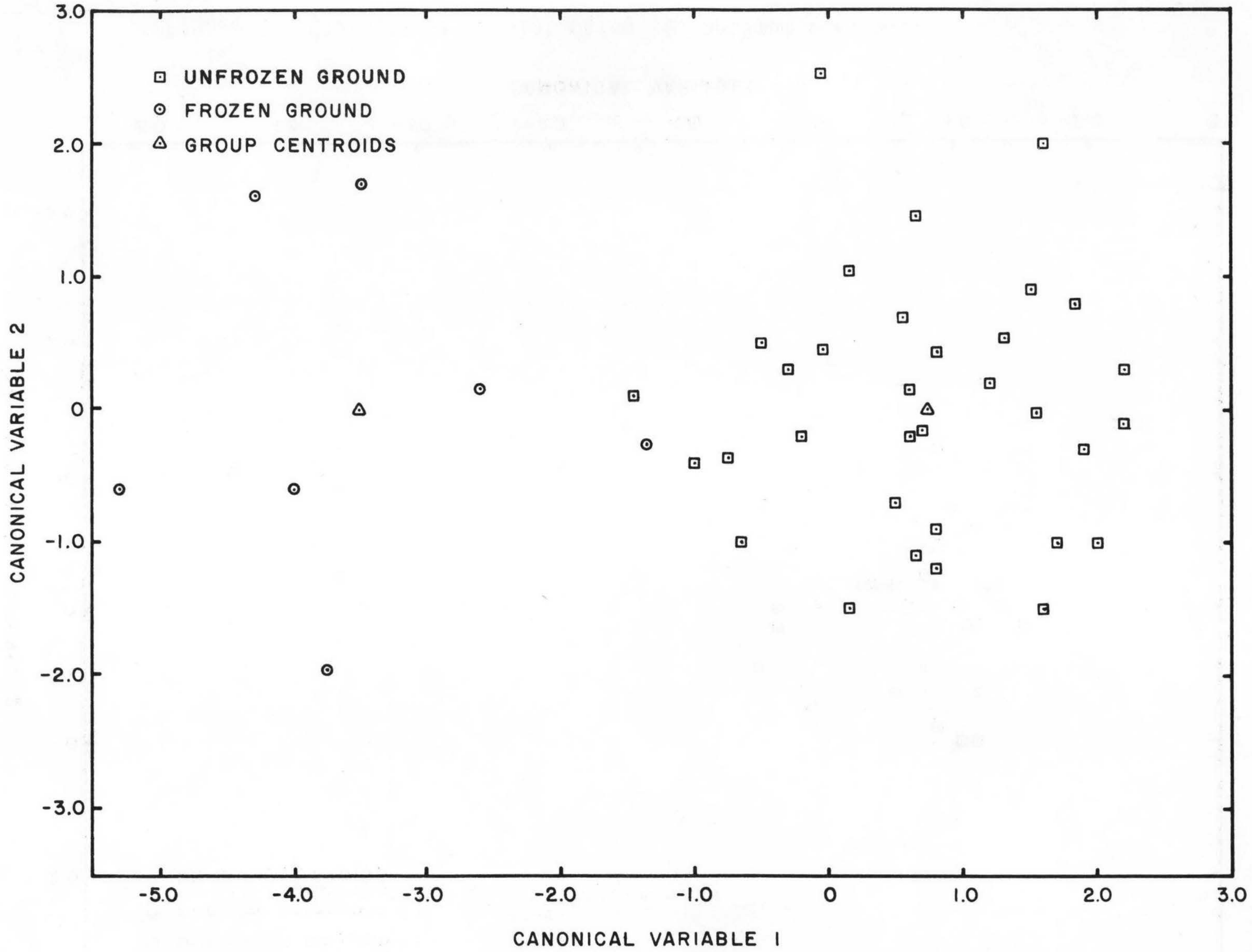

Figure 4. Classification plot of runoff events using six optimum variables.

can statistically distinguish between frozen and unfrozen runoff events for the Missouri Flat Creek watershed.

McKay Creek

In order to find if the classification functions derived for the Pullman area are applicable to other watersheds with different physical features and different weather patterns, a study of the McKay Creek basin near Pilot Rock, Oregon was undertaken. The nearest weather station is Pendleton, Oregon. A series of 70 unknown runoff events, seven previously determined to be frozen and 35 unfrozen events, were used for the analysis. These frozen ground floods were determined using rainfall-runoff relationships. The results of the classification using the Missouri Flat Creek classification functions showed that 16 of the 70 observations were classified as frozen ground events, the remaining cases being classified as unfrozen ground floods. Also, 89 percent of the known cases were correctly classified.

A classification system for the McKay Creek basin which is independent of the Pullman area should lead to a more accurate classification of runoff events. Using the known observations for the watershed, a BMD stepwise selection of variables was run along with the classification routine. This resulted in a unique set of discriminating variables being chosen for this area. Table 7 lists the results of the variable selection. It can be seen that a different set of variables than those found for Missouri Flat Creek are important in discriminating between frozen and unfrozen runoff events.

Table 7. BMD stepwise selection of discriminant variables for McKay Creek

Step	Variable Entered	F-Statistic
1	Average minimum temperature during freeze	23.8
2	Precipitation during freeze	11.0
3	Streamflow for four days after freeze	2.9
4	Precipitation from October 1 to start of freeze	2.0

The classification results using the above discriminating variables showed that 96 percent of the known observations were classified correctly.

Figure 5 shows the two-dimensional plot of the classification. Good group separation is evident and it appears that the classification procedure is successful.

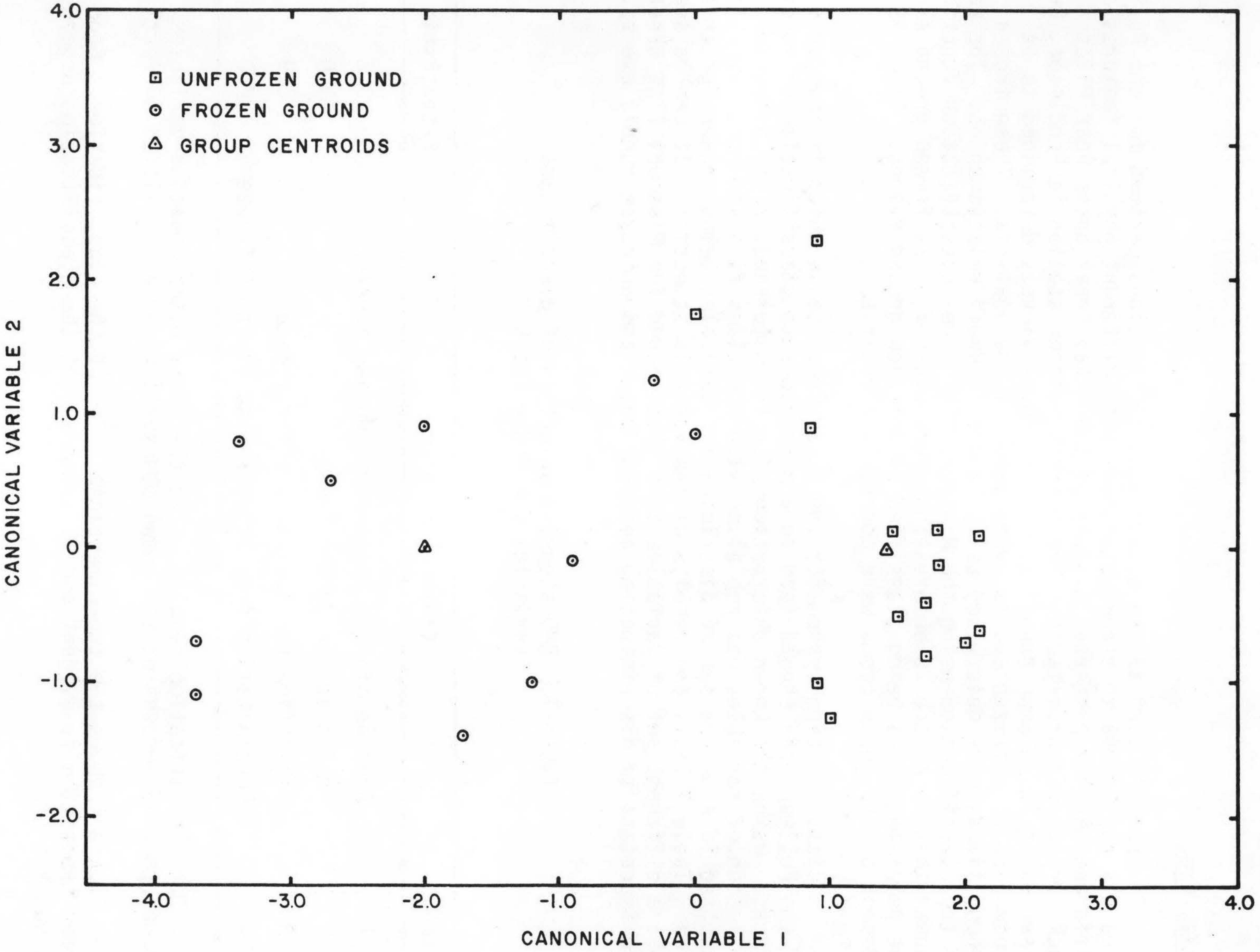

Figure 5. Classification plot of selected events for McKay Creek.

Blackfoot River

The Blackfoot River basin in southeastern Idaho differs considerably from the previous two study areas with respect to physical and climatic factors. It is a much larger watershed than either Missouri Flat Creek or McKay Creek and the area has a rather dry climate. These factors could very well affect the relationships between climatic conditions and the occurrence of frozen ground. Because of the large size of the basin, precipitation-runoff relationships were unsatisfactory for finding frozen ground runoff events. Therefore soil temperatures from the Aberdeen experiment station were used to identify 54 frozen ground cases out of 83 observations. The remaining 29 cases were assumed to be unfrozen ground. Using the variables listed in Table 5, a BMD stepwise selection of variables was run in order to define classification functions for the basin. Four variables were chosen as the best set of discriminators for classifying the runoff events. Table 8 lists the results of the variable selection.

Table 8. BMD stepwise selection of discriminant variables for Blackfoot River.

Step	Variable Entered	F-Statistic
1	Number of days below freezing	20.2
2	Number of days from October 1 to start of freeze	3.7
3	Average minimum temperature during freeze	1.5
4	Precipitation four days after freeze	1.3

The classification resulting from the use of these four variables showed that 74 percent of the known observations were correctly classified. The two-dimensional plot of the canonical variables is shown in Figure 6. There is much overlapping between the two groups and they are not well separated. These results were not satisfactory and another approach was tried.

Using soil temperature data from the Aberdeen Agricultural Experiment Station and Extension Center, 20 soil freeze dates and 21 soil thaw dates were determined. With these 42 known observations an analysis was tried in order to determine the optimum period, prior to a given event, that could be used to predict the occurrence of either frozen or unfrozen ground. Three different period lengths were used. Prior to each of the 42 chosen events, a period of 5, 10 and 30 days was studied to see if a set of discriminating variables could be found that could be used for classification purposes. For each of the three periods seven variables were computed and run through the stepwise variable selection routine. They were: the average minimum temperature for the period, the total freeze index for the period, the total thaw index for the period, the precipitation during the period, the total precipitation from October 1 to the start of the period, the snowfall during the

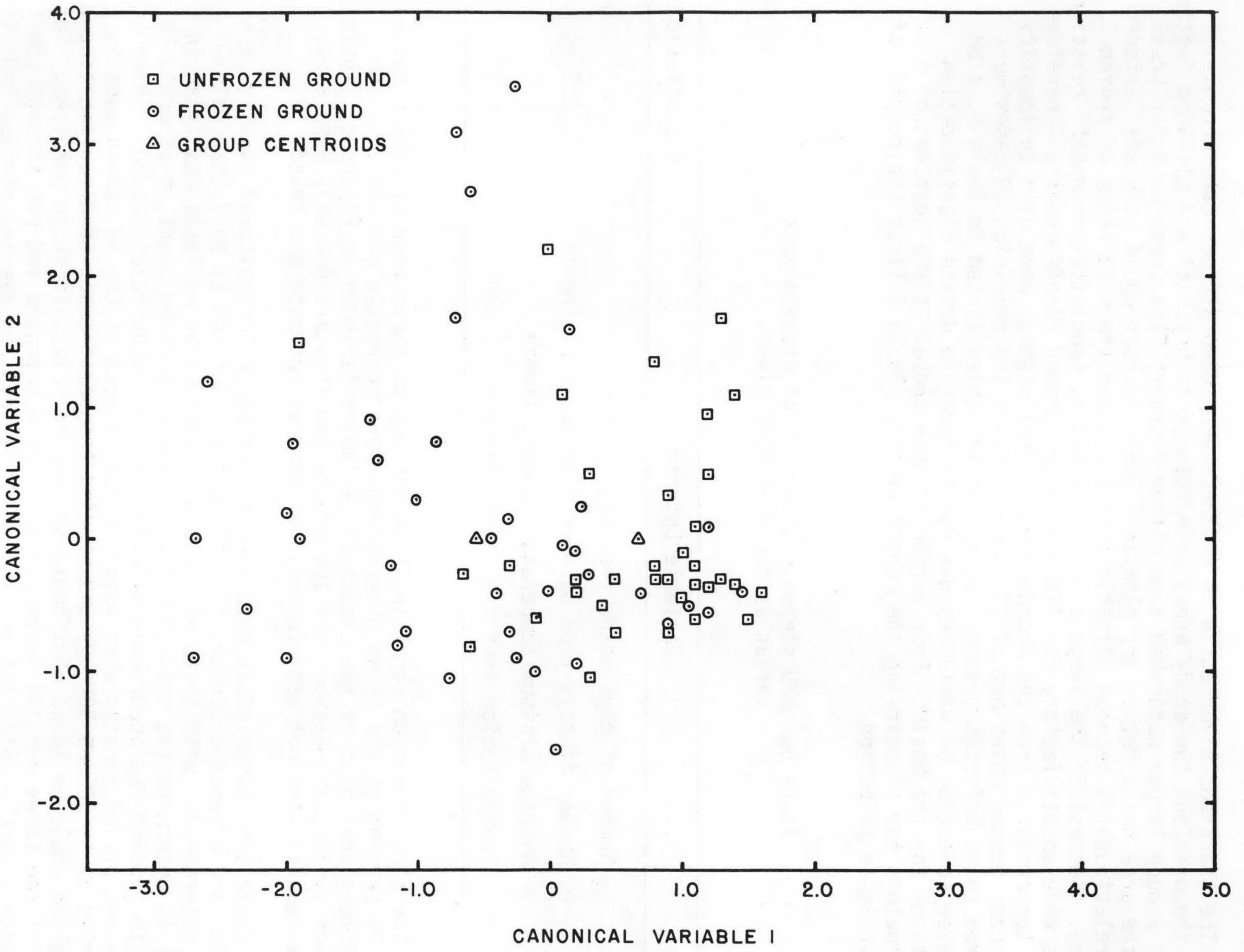

Figure 6. Classification plot of runoff events for the Blackfoot River.

period, and the streamflow for five days after the period. After the selection of variables was made, the 42 known events were classified as either frozen or unfrozen soil.

The most successful results occurred for the 10 day period prior to the freeze-thaw event. A set of three variables were chosen as the best discriminators, the freeze index, snowfall during period and streamflow for five days after the thaw; however, the classification results showed that only 71 percent of the known cases were classified correctly. The two groups do not appear well separated and distinct. It seems that the discriminant analysis procedure does not work well for this large area with few freeze-thaw cycles each year. It is also possible that Aberdeen is not a good choice for a climatic station despite the presence of soil temperature data. The prevailing weather is predominantly from the southwest. Therefore, the air masses that pass over the basin would also pass over Idaho Falls. Thus, Idaho Falls may have been a better choice of station.

Rock Creek

For the Rock Creek basin, a similar attempt was made to define a set of variables which could distinguish between frozen and unfrozen ground floods. Initially, the known frozen ground events were determined from soil temperature data at Twin Falls, Idaho. If the maximum soil temperature at a four inch depth is less than or equal to 32°F, the soil was classified as frozen. A thaw period then began when the soil temperature became greater than 32°F. This is similar to the method used for the Blackfoot River. The BMD variable selection routine was used for periods of 5, 10, and 30 days prior to each event. A list of the variables used for Rock Creek is shown in Table 9.

Table 9. Discriminating variables for Rock Creek

Variable	Unit
1. Average minimum temperature during freeze period	°F
2. Total freeze index	degree-days
3. Total thaw index	degree-days
4. Precipitation during freeze period	inches
5. Precipitation from October 1 to start of freeze period	inches
6. Snowfall during freeze period	inches
7. Streamflow for 4 days after freeze period	cfs-days

The best results were obtained for the 10 day period which showed that 59 percent of the known observations were classified correctly. Group separation was very poor and there was much overlapping between the two groups.

Another analysis was tried using new thaw periods. In this case the ground was assumed thawed when the minimum daily soil temperature at a four inch depth is greater than 32°F. This selection process resulted in somewhat different thaw periods than before. The freeze periods were the same. A variable selection process was run for 5, 10 and 30 day periods as was done earlier. The best results showed that only 65 percent of the known cases were correctly classified. These results would not be satisfactory for predicting whether an unknown observation was frozen or unfrozen.

A final attempt was made at getting a successful set of classification functions for the Rock Creek area. The same thaw dates as above were used; however, new freeze dates were chosen as occuring when the maximum four inch soil temperature is less than or equal to 31°F. The same type of analysis as used earlier was tried on the new periods. The 10 and 30 day periods did not produce significant results. For the five day period, four discriminant variables were chosen for the classification functions. These are listed in Table 10.

Table 10. BMD stepwise selection of discriminant variables for Rock Creek

Step	Variable Entered	F-Statistic
1	Snowfall during freeze period	2.62
2	Precipitation during freeze period	2.28
3	Total thaw index	1.22
4	Total freeze index	1.75

The F-value for each of the variables is quite low, indicating that none of them have much statistical significance with regard to distinguishing between frozen and unfrozen floods. The classification results using these discriminating variables showed that 62 percent of the known observations were classified correctly. Figure 7 shows the two-dimensional plot of the classification. The two groups are not well separated.

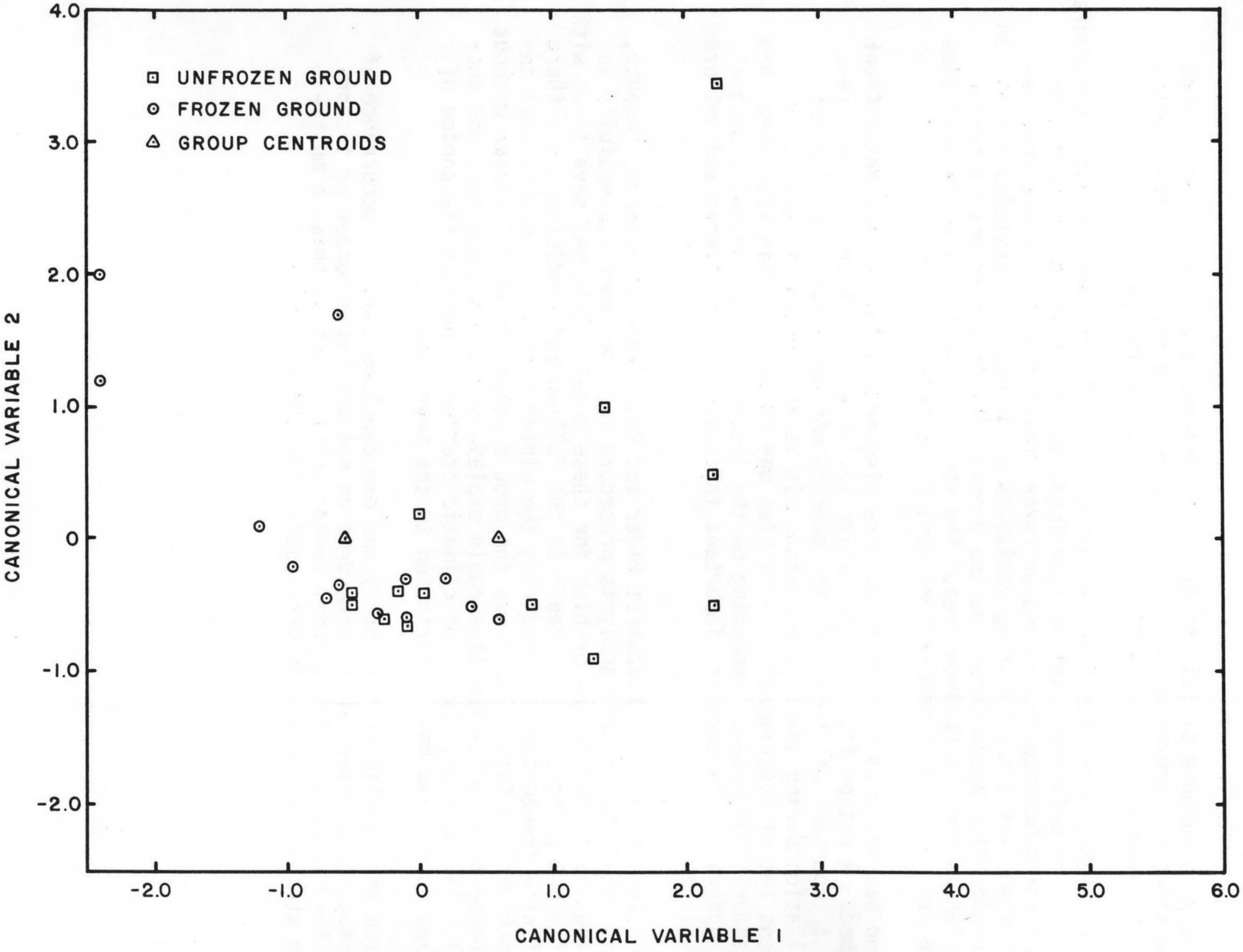

Figure 7. Classification plot of runoff events for Rock Creek.

CONCLUSION

The main purpose of this study was to introduce a discriminant method for analyzing the frozen ground flood problem. The success of this method appears to depend on the specific area to which it is applied.

For the Missouri Flat Creek watershed, the discriminant analysis procedure worked well in defining a set of hydrologic variables which are useful in discriminating between frozen and unfrozen ground floods. By the combination of these six discriminating variables a successful classification system was derived which would determine the probability of occurrence of frozen ground floods for the Pullman area. The most important of the six variables was the average minimum temperature during the freeze period.

The methods used in this study were also successful for the McKay Creek watershed. A set of four discriminating variables was chosen for the area. The most important of these were the average minimum temperature and the precipitation during the freeze period. It is interesting to note that a different set of discriminating variables was chosen for this watershed than for Missouri Flat Creek. Depending on the location of the basin, a unique set of hydrologic factors are important in distinguishing frozen and unfrozen ground floods.

The results for the Blackfoot River and Rock Creek watersheds, however, show that the discriminant analysis procedure does not work successfully in analyzing the frozen ground problem for these areas. This may have to do with the different climate of the area. In the Pullman and Pendleton areas there are definite freeze-thaw cycles during the winter months. It may be that in the Blackfoot and Twin Falls areas the ground stays frozen all winter without many freeze-thaw cycles and this could explain why the methods were not successful. In addition, choice of climatic station or perhaps the choice of variables could also have contributed to the poor results.

From the results of this study one can conclude that the occurrence of frozen soil on a watershed is dependent on not one but a number of factors interacting together. For a "real world" problem such as this, a multivariate statistical method is very useful for the analysis.

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