AN ABSTRACT OF THE DISSERTATION OF

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Julia Allen Jones

Throughout the 20th century, windthrow has affected forests in the Bull Run watershed, a 26,500 ha basin that is the principal water source for the city of Portland, Oregon. Windthrow from storms in 1973 and 1983 was mapped into a geographic information system (GIS) and compared to a 1931 windthrow pattern that had been determined through field work and photo interpretation. By relating the windthrow patterns to vegetation, topography, soils, and edges created by forest canopy openings such as lakes and clearcuts, the degree to which these factors influence the patterns was tested with a logistic regression. Distanced sampling was used to compensate for spatial autocorrelation among the data. The results showed that topographic exposure most strongly affected the 1931 windthrow patterns, while a greater number of 1973 and 1983 windthrow patches were associated with clearcut edges than other edges, and those edges were more likely to be affected when located on shallow soils with a high hazard for windthrow. All three storms were characterized by northeasterly winds, a common occurrence during winter months in the vicinity of the Columbia River Gorge. However, the particular combination of at least two-consecutive days of severe east winds, and sub-freezing temperatures, had only occurred four times between 1948 and 1994, including both the 1973 and 1983 windthrow events. Multiple approaches were taken to estimate future windthrow risk in the Bull Run that incorporated both spatial and temporal variables. Probabilistic windthrow maps showing zones of low, medium, and high risk were generated for current forest conditions, as well as conditions projected to the years 2010 and 2075. Because variables such as vegetation height and clearcut edges are ephemeral, the prediction of future risk incorporates

assumptions of vegetation succession. However, a mean return interval calculated for predicted windthrow-generating storms suggests that such events could occur as frequently as once every three years. While no model can predict the precise location of a disturbance as variable as windthrow, an understanding of the relative spatial and temporal probability of windthrow provides useful information for forest planners and managers.

Spatial and Temporal Patterns of Windthrow in the Bull Run watershed, Oregon

by

Diana Stuart Sinton

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APPROVED:

Major Professor, representing Geography

Chair of Department of Geosciences

Dean of Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Diana Stuart Sinton, Author

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CONTRIBUTION OF AUTHORS

Dr. Julia A. Jones and Dr. Frederick J. Swanson were involved in the design, analysis, and writing of the manuscripts.

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Chapter 1. Introduction to windthrow in the Bull Run watershed.

Natural disturbances such as windthrow, i.e., the wind-related uprooting of trees, are integral components of the process of forest succession (Henry and Swan 1974; White 1979; Attiwill 1994). Not only does windthrow create woody debris, mix forest soils, and alter forest composition and structure, but unlike disturbances such as fire, its occurrence cannot be readily suppressed.

Windthrow, as a pattern or a process, can be investigated at a variety of spatial and temporal scales. Windthrow patterns over landscapes have been reconstructed by Canham and Loucks 1984; Glitzenstein and Harcombe 1988; Abrams and Scott 1989; Seischab and Orwig 1991; and Boose *et al.* 1994 . At tree-level or stand-level scales, researchers evaluate the impacts of windthrow on local soil or vegetative conditions (Schaetzl *et al.* 1989; Adams and Norton 1991; Bormann 1995) or investigate gap dynamics (Spies *et al.* 1990; Alaback and Tappeiner 1991).

The factors that contribute to a windthrow pattern operate at a variety of scales as well. At the landscape level, the process of windthrow can be influenced by landforms and vegetation patterns (Foster 1988a; Swanson *et al.* 1990; Bellingham 1991; Foster and Boose 1992). Recent evidence indicates that windthrow patterns are sensitive to landscape patterns of forest fragmentation (Franklin and Forman 1987). At a smaller spatial scale, factors such as root decay or a particularly shallow rooting system can predispose trees to windthrow (Coutts 1986; Blackburn *et al.* 1988).

When an extended temporal scale is considered, multiple windthrow events can be reconstructed. In these cases, the study areas have typically been relatively small (< 10 km^2) (Henry and Swan 1974; Oliver and Stephens 1977; Deal *et al.* 1991; Foster and Zebryk 1993). Studies at larger spatial scales are restricted by the methodology of pattern reconstruction. Researchers have usually relied on historical records of windthrow location (Lorimer 1977; Frelich and Lorimer 1991; Seischab and Orwig 1991; Lorimer and Frelich 1994) or used a transect sampling technique to estimate windthrow in a large area (Dunn *et al.* 1983).

When disturbance patterns are considered on a large spatial scale, an approach involving landscape ecology may be appropriate. Two features of landscape ecology that distinguish it from other ecological sciences are its examination of pattern/process interactions and its attention to scale. For example, the influence of landform and vegetation patterns on ecological disturbances is often investigated in landscape ecology (Turner 1989; Swanson *et al.* 1990; Wiens 1992). Studies of vegetation patterns have elucidated pattern connections with interrelated processes such as successional change, fire behavior, and insect propagation (Reiners and Lang 1979; Rykiel *et al.* 1988; Morrison and Swanson 1990; Geldenhuys 1994; Powers 1995).

Scale involves the spatial resolution or the spatial and temporal ranges that set the bounds of a phenomenon, and is particularly important in studies of spatial heterogeneity (Forman and Godron 1986). It can affect all aspects of a research project, including the probability that a pattern or a process can be successfully detected, recognized, and analyzed for its causal mechanisms (Turner 1989; Wiens 1989; Levin 1992).

This landscape ecology study in the Bull Run watershed examines the effects of broad-scale ecological and geographic patterns on the process of windthrow. The natural variability of disturbance regimes suggests that most ecosystems experience a range of disturbance sizes, frequencies and severities (White 1979; Pickett and White 1985; Swanson *et al.* 1993). It is of interest to this study to consider whether the effects of forest management on the landscape may have moved the Bull Run landscape outside the range of natural variability created by historic windthrow disturbances in the area.

This dissertation is composed of four sections, each dealing with a separate issue related to the analysis of windthrow in the Bull Run watershed, Oregon. The first section, Chapter 2, introduces the history of windthrow in the Bull Run. Windthrow from storms in 1973 and 1983 was mapped with aerial photographs, and windthrow from an earlier period (1890s to 1931) was identified and mapped with both aerial photographs and field work. Patterns from three of the storms (1931, 1973 and 1983) were compared and contrasted with a multivariate statistical analysis. Chapter 3 provides information on the methods used to create the geographic information system (GIS) data layers that formed the spatial basis of this study and describes the steps followed to conduct logistic regressions with the data on windthrow and other landscape variables. Chapter 4 contains retrospective analyses of wind and other climatological data for the Bull Run watershed and vicinity. A model was developed to predict windthrow-generating storm events, and mean return intervals for such events were calculated. Chapter 5 combines information on the spatial and temporal patterns of windthrow to generate windthrow susceptibility maps for the Bull Run. The maps were tested with known windthrow patterns from the past, and depict zones of windthrow probability for current (1995) vegetation conditions, as well as predicted conditions in the years 2010 and 2075.

Chapter 2

Changes in the spatial patterns of windthrow in the Bull Run watershed, Oregon, over the past century.

Diana S. Sinton, Julia A. Jones, and Frederick J. Swanson

in preparation for journal submission

2.1 Introduction

The study of windthrow patterns has involved many approaches, covering a range of spatial and temporal scales. Efforts to map windthrow patterns have depicted single-tree gaps in studies covering areas less than 10 m^2 (Spies *et al.* 1990; Alaback and Tappeiner 1991), to patches of windthrow in landscape-level areas of 10 km^2 or greater (Foster 1988b; Glitzenstein and Harcombe 1988; Abrams and Scott 1989; Seischab and Orwig 1991).

Windthrow is associated with a number of contributing factors, including root decay, soil moisture, tree height, and topographic exposure, and these factors operate at a variety of scales as well. Few studies of windthrow in the Pacific Northwest have been published, and these primarily focus on topographic, soil, and edge factors (Ruth and Yoder 1953; Gratkowski 1956; Taylor 1990; Greene *et al.* 1992; Tang 1995, unpublished). When windthrow from a single storm event extends over a large area, it becomes more difficult to distinguish among the contributing factors. Cause-effect relationships among variables cannot be drawn with certainty from a descriptive, retrospective study such, as this one (Ramsey and Schafer, 1993 unpublished), yet statistical analyses can provide insights for interpreting spatial patterns.

This chapter evaluates windthrow patterns resulting from different storm events to estimate how vegetation and geophysical landscape factors, such as topography and forest fragmentation, have influenced the patterns of windthrow. The relative importance of soil type, aspect, elevation, slope, vegetation type, and edges (their type, location and age) is assessed from windthrow patterns reconstructed over a 100-year period. Specifically, patterns of windthrow from a pre-logging, 1931 storm are compared to the windthrow patterns from storms in 1973 and 1983.

2.2 Background

High winds associated with storms are common in the Pacific Northwest and especially in the vicinity of the Columbia River Gorge (Wells 1921; Cameron 1931b; Cameron and Carpenter 1936), and wind-related tree damage has long been a concern among foresters (Lawrence 1939; U.S.D.A. Forest Service 1987). Most windthrow in the western half of the Gorge has been associated with winds coming from the east, especially during winter storms (Cameron 1931a; Lawrence 1939; U.S.D.A. Forest Service 1987).

In the Bull Run watershed, the U. S. Forest Service began to implement a timber management plan in 1958. By 1973, 2278 ha of forest, or 10% of the forested portions of the basin, had been harvested. In January 1973, an east-wind storm crossed the basin and blew down approximately 515 ha. Later in 1973, a lawsuit was filed that eventually brought an end to a commercial timber management program in the water supply drainage of the Bull Run (Wilson 1989). Since 1973, an additional 2122 ha have been cut, primarily to salvage windthrown timber.

In December 1983, another storm with easterly winds blew down approximately 1370 ha, or 7% of the forested areas in the Bull Run. The Environmental Impact Statement prepared by the Forest Service for the salvage of 1983 windthrow stated that "about 74% of the 1983 blowdown occurred adjacent to openings and the degree of exposure to the damaging winds is a major factor influencing windthrow hazard" (U. S. D. A. Forest Service 1987, Appendix D-1). Many of these openings were clearcuts.

2.3 Methods

2.3.1 Overall approach

This study consisted of three phases: 1) identification and mapping of windthrow using photo interpretation and field work; 2) statistical analyses of windthrow patterns; and 3) a detailed analysis of one area where windthrow has been particularly severe. The analyses were conducted using a geographic information system (GIS) (Arc/Info, Versions 6.0 and 7.0.1); statistical software (SAS, Release 6.10); spreadsheet software (Excel Version 4.0); and separate C language-computer programs (described in detail in Sinton 1996b, unpublished).

2.3.2 Study site

The Bull Run watershed is a 26,500 ha basin located in the Mount Hood National Forest, just south of the Columbia River at approximately 45° 30' N latitude, 122°00' W longitude (Fig. 2.1). The climate is typical of the Pacific Northwest region with warm, dry summers and cool, wet winters. Average annual precipitation in the Bull Run watershed ranges from 2280 to 4300 mm, depending on elevation (U.S.D.A. Forest Service 1987). Both steep canyons and glacial valleys characterize the watershed; 5% of the watershed is less than 5% slope and 12% is greater than 50% slope. Elevations range from 225 m to over 1400 m . The soils are colluvial and primarily formed from glacial till overlying basalt and andesite (Harr 1980; Schulz 1980). Limited areas in the watershed have experienced landslides and other mass movement events (Schulz 1980), but as a whole, the watershed has been described as "geologically stable" (U.S.D.A. Forest Service 1979).

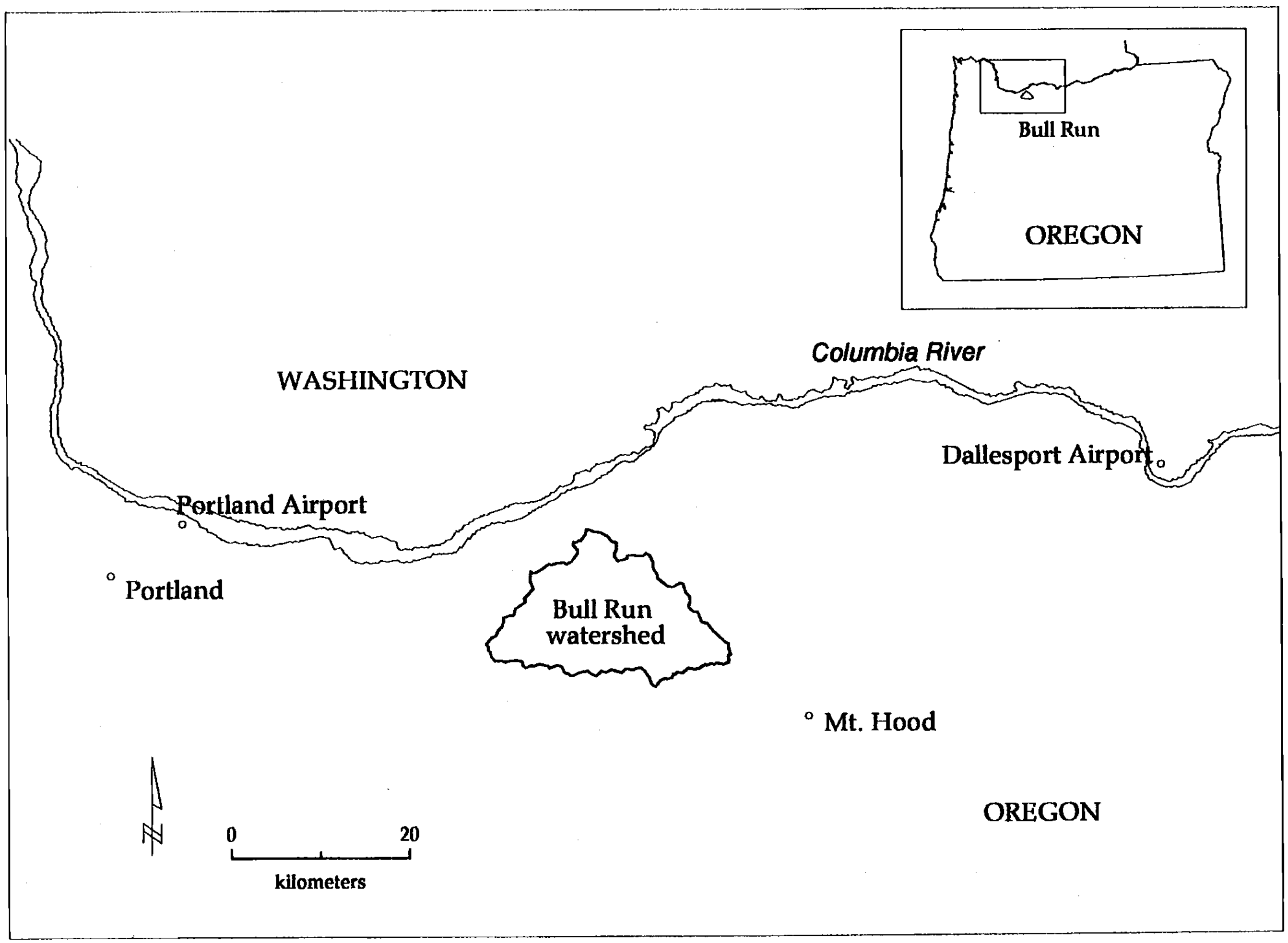
The primary vegetation in the Bull Run watershed is coniferous forest, composed principally of Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla)*, Pacific silver fir *(Abies amabilis)*, and western red cedar (*Thuja plicata*). The major deciduous species are big leaf maple (*Acer macrophyllum*) and red alder (*Alnus rubra*), found mostly near the reservoirs and in riparian zones.

The watershed has been the primary source of water for the city of Portland, Oregon, since 1895. The two reservoirs have a combined holding capacity of 17 billion gallons (Wilson 1989). The Bull Run Trespass Act of 1904 (P. L. 206), forbidding public access to the watershed, was intended to protect the quality and quantity of the water supply (U.S.D.A. Forest Service 1987; Wilson 1989), and restricted access remains in effect today.

2.3.4 Data layers in the Geographic Information System (GIS)

GIS layers depicting windthrow, topography, vegetation, soils and other data were based on aerial photography, field work, or were inherited from other sources or agencies. All data layers were extensively edited and modified in preparation for analyses. For details, see Sinton (1996b, unpublished).

Figure 2.1 Bull Run watershed study area.



Aerial photography obtained from the Mt. Hood National Forest was used to identify patches of windthrow from storm events in 1973 and 1983. Only uprooted trees were identified and mapped. Trees otherwise damaged by the wind storms, but still standing when the photographs were taken, were neither identified nor mapped.

Windthrow from a January 1973 storm was identified on a set of air photos (1:7920, true color) taken in February 1973. The location of windthrow was mapped by overlaying a 0.6 cm mylar grid onto each photo and marking a single point in the center of each grid square if windthrow were present in that area. The points were then transferred to a mylar grid overlaid on orthophotoquads (1:12000, enlarged from 1:40000) and digitized into the GIS. Each 0.6 cm mylar grid cell was equivalent to an approximate area of 75 x 75 m (0.56 ha) on the ground, based on the 1:12000 orthophotoquads. Poor photo quality, snow coverage on the ground, and oblique sun angles prohibited the mapping of 1973 windthrow by severity.

Patches of windthrow from a storm in December 1983 were interpreted from air photos (1:12000, true color) taken in July 1984. The severity of windthrow was determined by assessing the amount of tree canopy that had been blown down in each 75 x 75 m area. With the use of a hand lens, the number of boles or rootwads on the ground within each square area was estimated, as well as the number of residual standing trees. Windthrow was grouped into three severity classes: low (< 30% canopy blown down); medium (30-70% canopy blown down); and high (> 70% canopy blown down). Points of different colors (to distinguish the severity classes) were placed in the center of the 0.6 cm mylar grid that was overlaid on the air photos. These were transferred to a mylar grid over orthophotoquads and digitized to create a 1983 windthrow data layer.

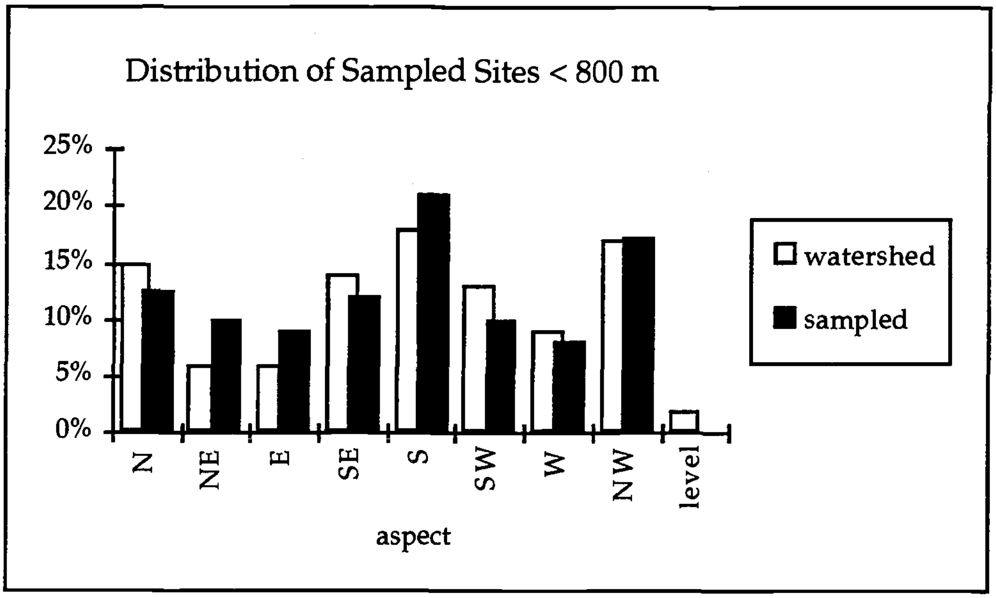
Historic windthrow (i.e., having occurred prior to 1958 when logging began) was identified indirectly using a combination of aerial photography and field work. Old-growth Douglas-fir is the tree species and age class most often affected by windthrow within the Bull Run watershed (D. Sinton, field observations). Fallen Douglas-fir trees decompose slowly (Harmon *et al.* 1986), and their trunks are readily identifiable on the ground more than one hundred years after a windthrow event. Windthrow of Douglas-fir often releases shade-tolerant, understory species, especially Pacific silver fir and western hemlock, which eventually can become the overstory dominants of a stand (Franklin 1964; Franklin and Hemstrom 1981; Alaback and Tappeiner 1991).

Air photos from July 1984 (1:12000, true color) and June 1979 (1:12000, true color) were used to locate forest stands dominated by Pacific silver fir or western hemlock. Approximately 105 stands ranging in size from 0.5 ha to 150 ha were identified using this procedure. Thirty additional sampling sites were selected, based on their elevation and aspect rather than species composition, to ensure that the field sampling was representative of the watershed as a whole (Fig. 2.2). Each of these 135 sites was visited during the summers of 1993 or 1995. Field data were collected, including the number, orientation, and species of windthrown trees (if present); current overstory and understory species composition; and the occurrence of pit and mound topography.

To determine whether a site had experienced windthrow from a single event, multiple events, or not at all, a checklist of decision criteria was developed, based on physical evidence of windthrow (Ruth and Yoder 1953; Henry and Swan 1974; Oliver and Stephens 1977; Deal *et al.* 1991), and five "Field Classes" of windthrow types were assigned to each windthrow site (Table 2.1). The most obvious indicator of windthrow in a stand was the presence of uprooted trees, lying in the same general direction and at approximately the same state of decay. The sites of primary interest in this study were the 56% of the 135 total stands visited that were identified as having experienced windthrow during one or more storm events (Field Classes 3, 4 and 5 in Table 2.1).

The date of windthrow in a stand was determined by identifying a growth release date in shade-tolerant trees that were in the canopy at the time of sampling, following Dynesius and Jonsson (1991). In each stand that had experienced windthrow, five to ten western hemlock or Pacific silver fir trees, located within approximately a 10-m radius of windthrown root wads, were selected and cored with a 16" or 20" increment borer. Trees were chosen that were likely to have been suppressed in the understory at the time of the windthrow event, based on their size and estimated age at time of sampling, and determined on a stand-by-stand basis in the field, depending on the estimated time that the windthrown trees had been on the ground. For example, to date windthrow that had occurred between approximately 1880 and 1930, hemlock or silver fir trees estimated to be between 100 and 150 years old in 1993 were selected. In total, approximately 355 tree cores were catalogued during the fall of 1993.

Figure 2.2 Distribution of sampling sites by aspect and elevation. Stands that were sampled in the Bull Run watershed during the summers of 1993 or 1994 were first selected on the basis of their species composition. Additional sites were added to ensure that the overall sampling scheme reflected the distribution of the watershed by aspect and elevation. To display the distribution of the sampling sites, both the watershed and sampling sites are divided by elevation at 800 m, approximately the median elevation of the watershed.



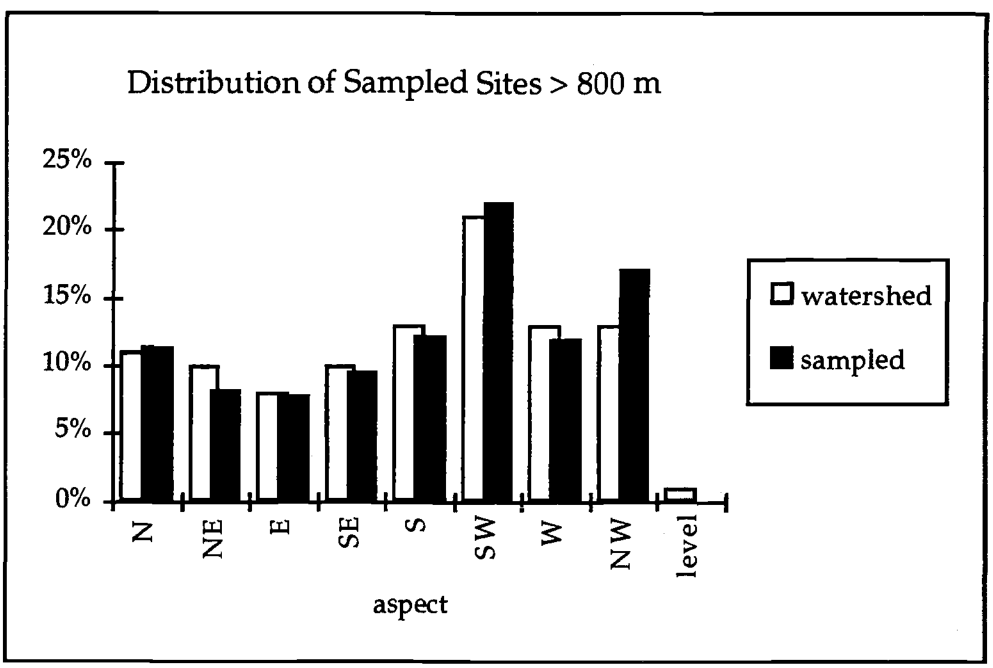


Table 2.1. Criteria used in the field to ascribe windthrow to sites in the Bull Run watershed, Oregon. Forest stands containing windthrow were divided by type of windthrow present. An "X" denotes the characteristic most frequently seen in the field. "Background level" in Classes 1 and 2 denotes the presence of wind damage to trees, though no evidence of one or more particular storm event(s), such as a single decay class or all downed trees lying in the same direction.

	Type of windthrow				
Criteria	Field Class 1 low background level	Field Class 2 high background level, chronic windy site	Field Class 3 single event, low severity	Field Class 4 single event, high severity	Field Class 5 multiple event, chronic blowdown site; low or high severity
1. trees/ha blowndown:					
< 25	X		X		
> 25		X		X	X
2. decay stages of blowndown trees:					
one			X	X	
multiple	X	X			X
3. compass orientation of blowndown trees:					
one			X	X	X
multiple	X	X			X
4. type of damage to blowndown trees:					
snapped	X	X			
uprooted	X	X	X	X	X
5. growth release of canopy trees in stand:					
none	X	X			
multiple; dates spread by > 5 years	X	X			X
single date or varied by < 5 years			X	X	
6. pit/mound topography		X			X
7. branches, tree debris on ground		X			X

Identifying a specific date for an event was not always possible. Using a hand lens, a release date was identified for a tree core if there was an increase of at least two times the width of the preceding growth rings and if the increased trend continued for at least ten years, following Henry and Swan (1974); Lorimer and Frelich (1989) and Abrams *et al.* (1995). A single date of windthrow was assigned when five or more release dates in a stand coincided, and a range of up to 3 years was attributed to a storm event when multiple release dates (> 5) fell within a three-year period.

The areas that experienced windthrow prior to 1950 were divided into two severity classes, initially based on the number of boles still visible on the ground within a stand in 1993. The "lower severity" classification was assigned to stands with less than 25 trees/ha blown down (Field Class 3 sites) and "higher severity" was assigned to areas with greater than 25 trees/ha blown down (Field Class 4 and 5 sites). The severity classifications were further refined by using the aerial photos to estimate the amount of Douglas-fir in the canopy within that stand. Areas that were classified as higher severity had less than 30% Douglas-fir in the canopy within each 75 x 75 m grid cell, as visible on 1984 aerial photographs. Field Class 5 sites had experienced windthrow from more than two distinct storm events, determined by a multiple growth release pattern in the overstory dominant tree species.

Once a stand was identified as having experienced windthrow and a date or range of dates for the event was determined, it was mapped as a set of points, each centered within 0.6 cm mylar grids, whose boundaries coincided with the Pacific silver fir or hemlock stand on the air photos and orthophotoquads. Each point was then digitized into the GIS.

An additional GIS data layer created with the 1984 aerial photography and 1989 orthophotoquads depicted perennial openings in the forest canopy created by talus slopes, meadows, shrub fields, and small lakes.

All other GIS data layers were obtained in digital format from other sources, and details related to the transfer of data and the editing of data layers can be found in Sinton (1996b, unpublished). Specifically, the GIS center of the Mt. Hood National Forest provided data on the road and hydrologic network; a DEM of the forest; the locations of all clearcuts and the date of harvest; and a map of soil types, divided by relative soil depth into windthrow hazard classes (U.S.D.A. Forest Service 1964). Two DEMs (Vancouver-e and The Dalles-w) were obtained from the U. S. Geological Survey and used to create a data layer showing the topography of the area surrounding the Bull Run watershed.

A 1988 Landsat 5 TM satellite image of the Bull Run watershed was supplied by the Forest Service's Pacific Northwest Research Station, Forestry Sciences Laboratory. The original image was classified into different vegetation cover types (Cohen *et al.* 1995), and edited with Erdas (Version 7.5) software to create distinctions between clearcut openings and other forest canopy openings, such as talus slopes, that the original classification grouped together.

2.3.5 Statistical analyses

Univariate statistics to describe windthrow patterns, such as patch size, were generated with FRAGSTATS, a computer program written by McGarigal and Marks (1995). From this output, mean and median patch sizes were calculated and the windthrow patterns from each storm could be described by their extent and magnitude.

Spatial autocorrelation (SA), or the tendency for phenomena to be similar or related as a function of distance, often characterizes ecological data (Legendre and Fortin 1989; Legendre 1993). The presence of SA precludes the use of parametric statistics as the data are not independent from one another. Several techniques were used to test for SA among the data, including calculation of Moran's I and Geary's c coefficients and construction of semivariograms. For further details, see Sinton (1996b, unpublished).

Bivariate relationships between windthrow patches and possible causal factors was examined by comparing *expected* to *observed* amounts of windthrow on different aspects, elevations, slopes, soils, vegetation types, and in buffer zones adjacent to perennial and ephemeral canopy openings. The *expected* amount of windthrow in each case was the distribution of each potential associated factor (e.g. aspect, elevation, soil) in the watershed, and can be considered a neutral value to assess whether the variable in question affected the distribution of windthrow. The predicted or expected amount of windthrow in each category was compared to the *observed* amount of windthrow. Observed and expected values could then be compared using a Chi square test of statistical significance. However, because each windthrow pattern was likely the result of multiple variables and perhaps their interactions, factors that a Chi square test cannot readily consider, the Chi square statistics were not calculated. Instead, the comparisons between expected and observed values were used for non-statistical descriptions of the landscape patterns of windthrow.

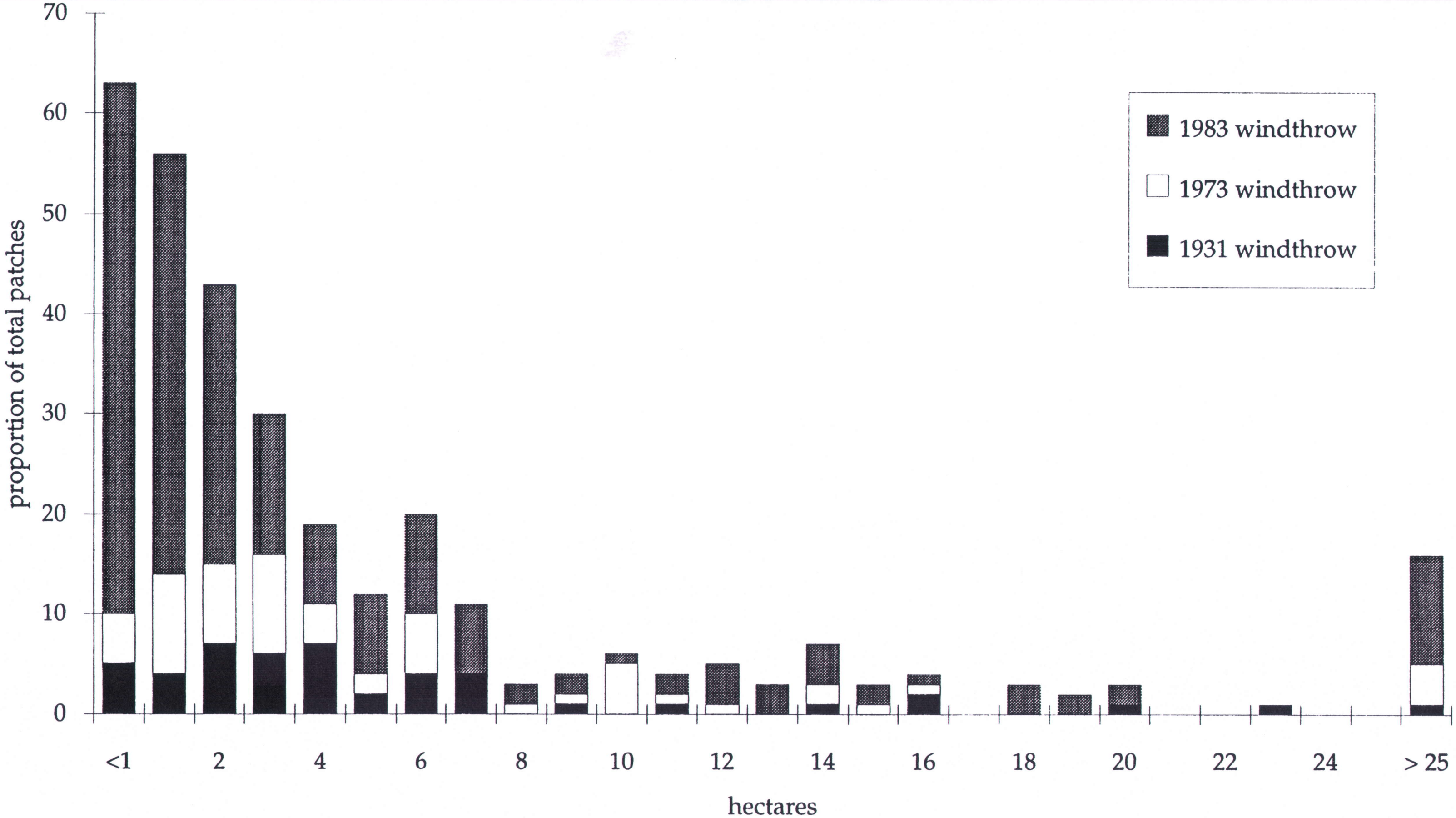
Trees that are suddenly exposed to wind as a result of a recent opening in the canopy, such as a clearcut, may be more susceptible to windthrow than trees that had grown in a chronically exposed location, such as at the edge of a talus slope. The distinction between ephemeral opening edges (clearcuts and reservoirs less than 25 years old) and perennial opening edges (lakes, meadows, talus slopes, older clearcuts and reservoirs greater than 25 years old) was made to differentiate between the effects of a recent canopy opening and a perennial opening on the location of windthrow. Reservoirs themselves are permanent openings, but for these analyses, their edges were considered as ephemeral for a 25-year period, after which they were reclassified as perennial openings.

Forest stands that had been partially harvested, rather than clearcut, were not considered in the analyses because detailed information on their location was not available. Also, narrow, linear openings, such as roads and streams, were not used in the analyses because they fell below the minimum mapping resolution of 0.56 ha. The buffer zones were defined as a 150-m-wide area surrounding each opening.

The indirect method of identifying and mapping historic windthrow probably resulted in an underestimation of smaller patches (< 2 ha) of windthrow, particularly for earlier storms, because of the difficulty of identifying small patches of Pacific silver fir or western hemlock on aerial photos. A comparison of patch sizes from each storm corroborates this theory (Fig. 2.3). To compensate for this, an additional analysis involved a "filtering" of the 1973 and 1983 windthrow layers to remove all patches less than 2 ha in size. Several of the expected to observed comparisons among windthrow patterns were then repeated.

A related analysis considered only non-clearcut edge associated windthrow from 1973 and 1983. The purpose of this analysis was to see if non-edge-related windthrow exhibited patterns similar to expected watershed values or historic patterns. The 1973 and 1983 windthrow layers were filtered to remove all windthrow that was within 150 m of a clearcut, and several comparisons with landscape variables were repeated.

Figure 2.3 Patch sizes of 1931, 1973 and 1983 windthrow in the Bull Run watershed.



A different type of spatial analyses considered linear features that may have had a spatial association with windthrow, namely the edges of openings in the forest canopy. The edge segments (arcs or lines) of the ephemeral and perennial openings were used in the GIS analyses rather than the whole openings (polygons) themselves. Within the GIS, data were attributed to the edges (arcs or lines) of the openings in order to classify them by their location relative to landscape variables, such as aspect, elevation, and windthrow-hazardous soils. The edges of ephemeral openings were also coded according to the date of their creation. For further details, see Sinton (1996b, unpublished).

Multivariate statistical analyses were conducted to examine how windthrow might be affected by multiple, interacting factors. In order to compensate for spatial autocorrelation among the data, a subsample of points was selected that met a minimum distance criterion from one another. The exact distance was determined by considering the results of the spatial autocorrelation assessment (see Sinton 1996b, unpublished).

Logistic regressions were conducted in Arc/Info and SAS (Release 6.10). In logistic regression, the dependent variable (windthrow) has a binary response, i.e., either a 1 (windthrow) or a 0 (non-windthrow). Logistic regression is the most appropriate type of analysis for this data set as windthrow cannot be measured as a continuous variable that is linear in its response (as would be the case with data for a linear regression).

The data sets used for each logistic regression contained information on the dependent variable, i.e., windthrow, and six independent variables (aspect, elevation, slope, soils, and ephemeral and perennial openings). Interaction terms were considered among all independent variables, and variables were included in the final model if they were significant at a minimum .05 alpha level. A final logistic model was generated for each storm event and odds ratios were calculated following Hosmer and Lemeshow (1989).

The odds ratio is a useful way to interpret the results of a logistic regression because it represents the probability of the occurrence of the binary variable in association with each of the explanatory factors. Furthermore, the odds ratio is the only parameter that can be estimated from this type of retrospective analysis to compare binary response outcomes for the explanatory categories (Ramsey and Schafer, 1993 unpublished). Because the sampled data, selected to meet a minimum distance criterion, represented less than 12% of the total data from each storm event, odds ratios were also calculated for the significant variables with the complete data sets from each storm to check the representativeness of the sampled data.

2.3.6 Comparison of climatic data from three storm events

Basic descriptive data (average daily and maximum wind speeds and direction, temperature and precipitation) from each storm and the 14-day, pre-storm period were compiled. Information for a 1931 storm was obtained from published records (Cameron 1931a). The National Climatic Data Center, in Asheville, North Carolina, provided data on wind speeds and directions from a site in downtown Portland. The Oregon Climate Service provided data from the Portland Airport for the 1973 and 1983 storms. Additional data regarding precipitation and temperature from a site at Reservoir #2 within the Bull Run watershed were provided by the City of Portland Water Bureau.

2.3.7 The northeastern quadrant of the Bull Run

The northeastern portion of the watershed received extensive windthrow in both the 1973 and 1983 storms, and a detailed examination was made of this area to evaluate the natural susceptibility of the area. Surrounding topography influencing the Bull Run area was considered as a factor as well as locations where landscape variables such as soil type and ephemeral openings may have interacted to contribute to severe windthrow.

2.4 Results

2.4.1 Windthrow patterns

Windthrow patterns tend to be patchy and clustered. The search for windthrow from the pre-logging period revealed a total of 76 patches, ranging in size from 0.56 ha to 157 ha, with a median patch size of 4.86 ha (Table 2.2 and Fig. 2.4). Dating of these patches identified five distinct windthrow events (Field Classes 3 and 4), several patches where multiple events occurred (Field Class 5), and additional areas where a storm date could not be determined. The use of a 3-year range for certain storm events reflects the variability associated with growth release of understory trees (Dynesius and Jonsson 1991).

The most extensive windthrow in the pre-logging period (before 1958) occurred in 1931. Not only was growth release consistent for that year, but published records indicate that a severe, east wind storm occurred locally in April, 1931 (Cameron 1931a). Because many of the patches from other pre-1950 storms were < 1 km^2 in size and too small to be sampled at the minimum distance necessary for the logistic regression, only the 1931 windthrow pattern was compared to patterns from the 1973 and 1983 storms.

The 1931 storm produced an estimated 463 ha of windthrow, or 2% of the forested area of the watershed (Table 2.2 and Fig. 2.4). Forty seven patches of 1931 windthrow were identified through photo interpretation and field observations. Seventy-three percent of the 1931 windthrow was low severity (Field Class 3) and 27% was high (Field Class 4).

From the 1973 storm, 62 patches totaling 554 ha of windthrow could be identified from aerial photos (Table 2.2 and Fig. 2.5). This represented 3% of the forested area of the watershed at that time. Windthrow in 1973 may have been underestimated due to the partial coverage of the aerial photos (only the eastern and southern parts of the watershed were included in the flight) and the snow cover and oblique sun angles on the photographs.

Approximately 1369 ha of forest was affected by windthrow in the 1983 storm, or 7% of the forested area of the watershed (Table 2.2 and Fig. 2.6). Over 200 patches of windthrow were identified. Sixty-five percent of the 1983 windthrow area was classified as low severity, 18% as medium, and 17% as high.

The methods used to classify the severity of the 1931 and 1983 windthrow were not comparable, since the quality and type of data differed between events. Without photographic coverage soon after the wind event, complete identification and mapping of the 1931 windthrow is impossible. Therefore, it was not possible to objectively compare severity between storms.

The windthrow pattern from the 1931 storm was dissimilar in its geographic distribution from the storms in 1973 and 1983 (Fig. 2.7). The 1931 windthrow was concentrated in the southern and central portions of the basin.

Table 2.2 Windthrow patch data from the 1893 - 1931, 1973, and 1983 storms in the Bull Run watershed, Oregon. Statistics for the windthrow patches are described for each storm. Statistics are summed for the four storms between 1893 and 1921 (1893-95, 1900-02, 1910-12, and 1921). The figures for patch sizes are derived from data compiled with FRAGSTATS (McGarigal and Marks 1995). The windthrow severity figure are not comparable across storms; see text for further explanation.

Windthrow characteristics	1893-1921 storms	multiple date sites and sites without known storm dates	1931 storm	1973 storm	1983 storm
total area (ha)	156	69	463	554	1369
as % of forested area	<1	<1	2	3	7
number of patches mapped	17	12	47	62	209
patch size (ha)					
minimum	0.56	0.56	0.56	0.56	0.56
maximum	37	22	157	116	104
mean	9.1	5.7	8.6	8.3	6.5
median	7.3	3.3	4.1	3.9	2.3
severity (%)					
low	85	NA	73	NA	65
medium	NA	NA	NA	NA	18
high	15	NA	27	NA	17

Figure 2.4 Windthrow in the Bull Run watershed, 1893 - 1931 storms.

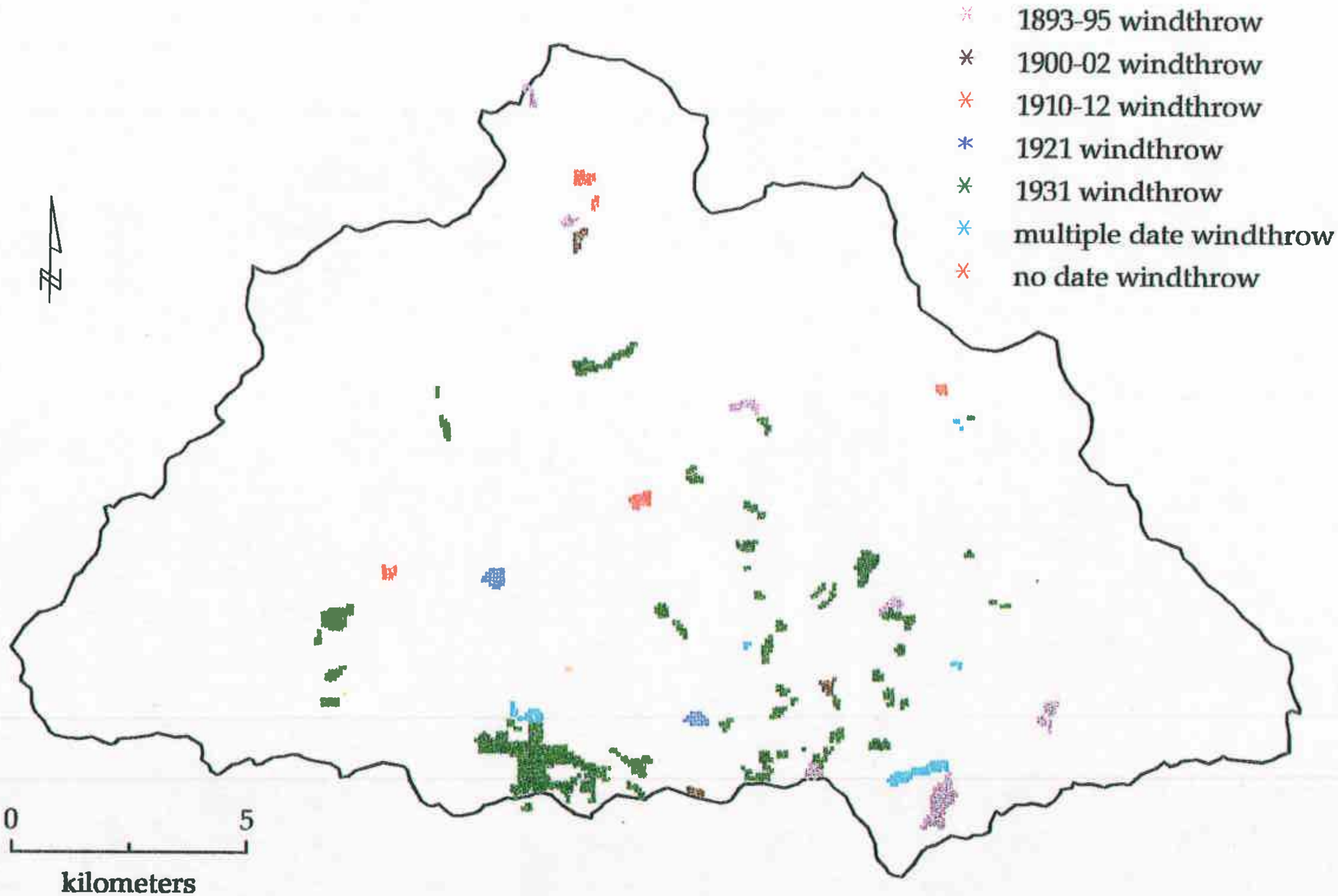


Figure 2.5 Windthrow in the Bull Run watershed, 1973 storm.

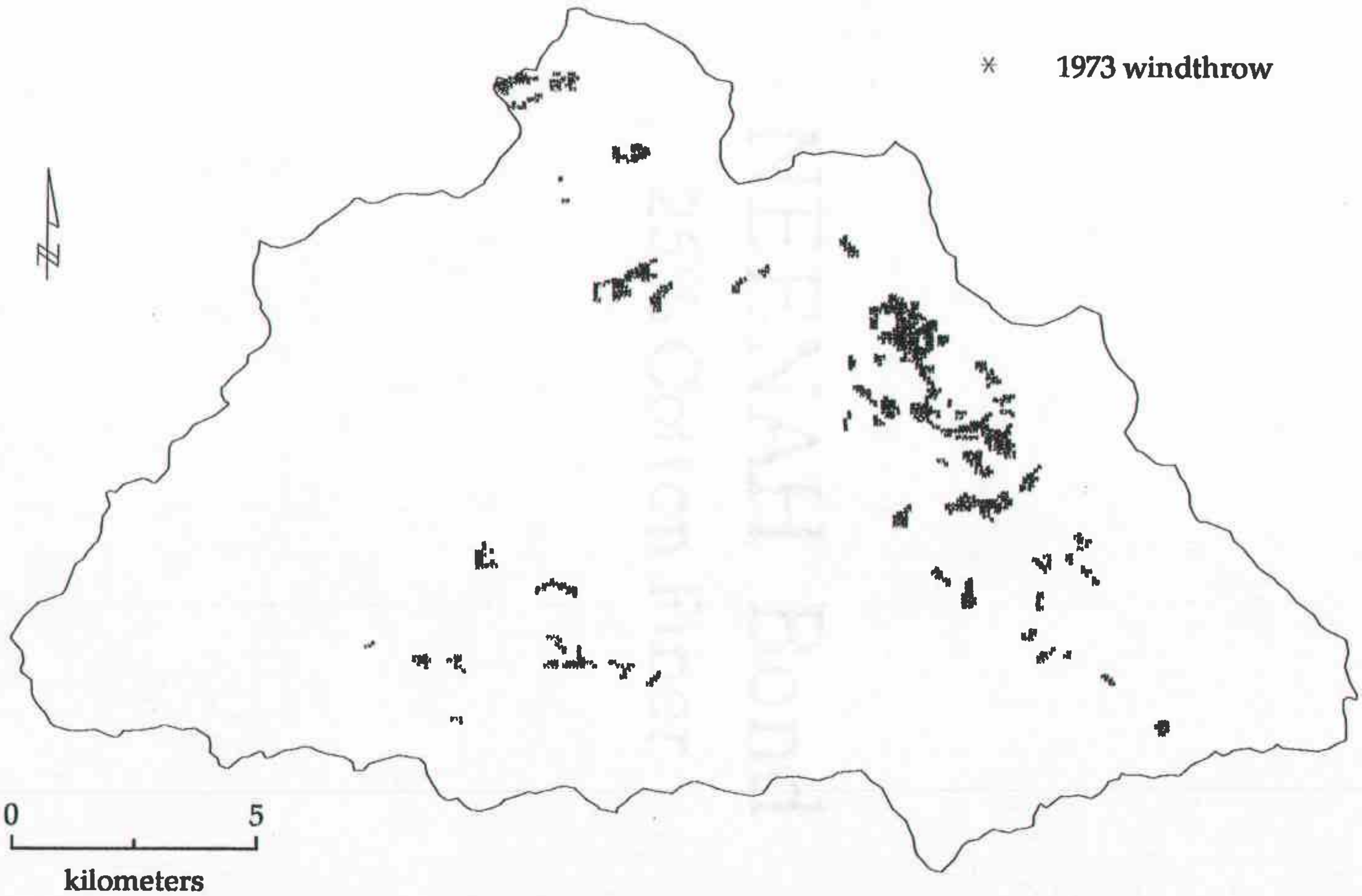


Figure 2.6 Windthrow in the Bull Run watershed, 1983 storm.

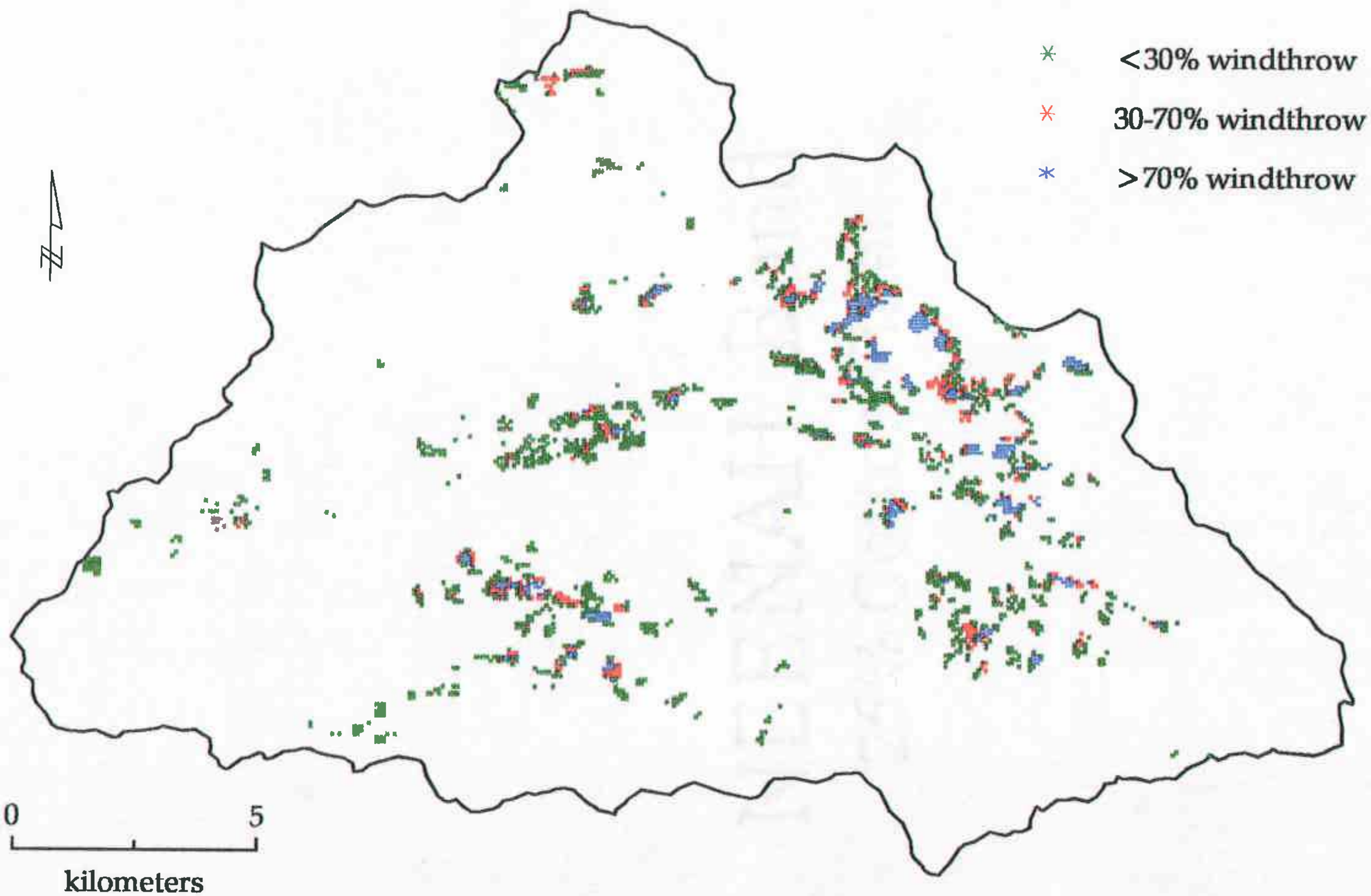
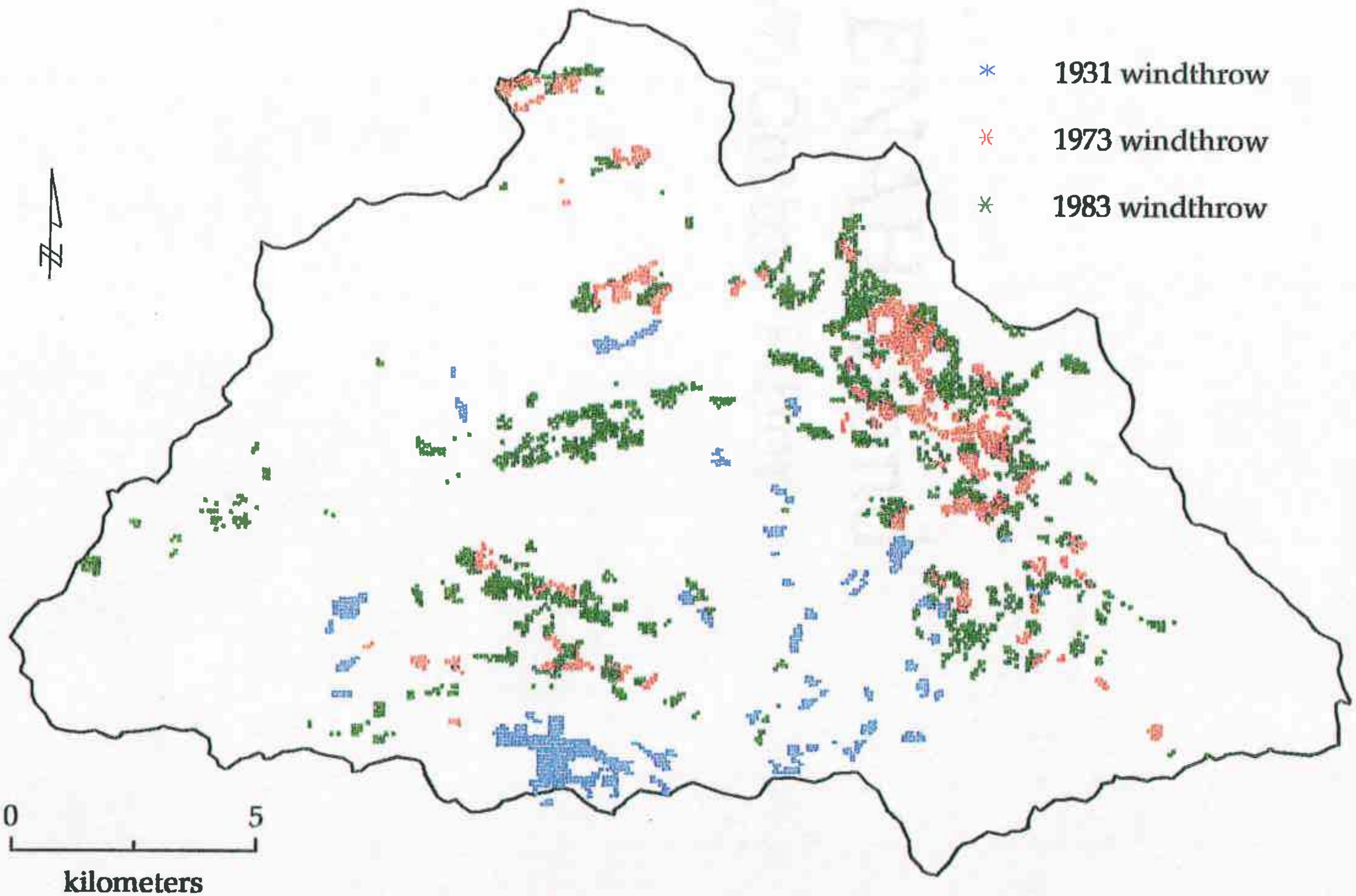


Figure 2.7 Windthrow in the Bull Run watershed, 1931, 1973 and 1983 storms.



In contrast, the 1973 windthrow was most apparent in the eastern portions of the watershed, with only a scattering of windthrow elsewhere. The 1983 windthrow was much more extensive than any earlier storm. It occurred in the central and eastern parts of the watershed, and reflected the distribution of the 1973 windthrow and its salvage logging units.

The Moran's I and Geary's c coefficients indicated that spatial autocorrelation was present among the data. The semivariograms showed that the autocorrelation was strongest at distances below 750 m to 1 km, suggesting that many patches of clustered data are smaller than this (Sinton 1996b, unpublished). To compensate for the autocorrelation, the initial sampling for the logistic regressions was done at distances greater than 750 m between points. An inadequate number of points at this distance was available from the 1931 and 1973 windthrow patterns, and those patterns were resampled at a 350 m minimum distance.

2.4.2 Factors affecting windthrow patterns

The spatial arrangement of windthrow patches from the 1931, 1973 and 1983 storms was compared to landscape patterns of aspect, elevation, slope, soil type, vegetation cover type and openings in the forest canopy (Tables 2.3 - 2.8).

In 1931 windthrow was found most frequently on northern, northeastern and eastern aspects (Table 2.3). In contrast, the concentration of windthrow in 1973 was on southern and southwestern aspects, and trees on southwestern aspects were also frequently windthrown in 1983. This distinction between the 1931 windthrow and the later storms is also evident in the elevational distribution of windthrow (Table 2.4). The majority of 1931 windthrow (67%) occurred between 800 and 1100 m in elevation, while the 1973 and 1983 storms generated windthrow at slightly lower elevations, with most windthrow in both storms occurring between 700 and 800 m. Most of the windthrow in all three storms occurred at slopes of 5 to 15 degrees slope, a relatively flat slope for mountainous terrain (Table 2.5). Surprisingly, most of the windthrow in each of the three storms occurred in areas mapped as "slight" hazard soil class, with consistently less than expected in the "moderate" class (Table 2.6). Only in 1973 and 1983 was there more windthrow in the "severe" class than was expected.

Table 2.3 Expected vs. observed percentages of windthrow by aspect for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The expected values represent the actual distribution of aspect in the watershed.

		Observed windthrow from storms in		
Aspect	Expected (%)	1931 (%)	1973 (%)	1983 (%)
north	13	29	13	17
northeast	8	15	13	11
east	7	12	6	6
southeast	12	10	7	6
south	15	9	23	16
southwest	17	5	21	21
west	11	5	10	10
northwest	15	15	7	13
level ground	2	0	0	0
total	100	100	100	100

Table 2.4 Expected vs. observed percentages of windthrow by elevation for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The expected values represent the actual distribution of elevational ranges in the watershed.

		Observed windthrow from storms in		
Elevation (m)	Expected (%)	1931 (%)	1973 (%)	1983 (%)
<300	2	0	0	0
300-399	7	0	0	5
400-499	6	1	0	6
500-599	7	2	3	8
600-699	11	13	14	15
700-799	13	6	36	29
800-899	15	14	28	18
900-999	17	35	16	12
1000-1099	12	18	2	6
1100-1199	6	8	2	2
1200-1299	2	2	0	0
1300-1399	0	0	0	0
>1400	< 1	0	0	0
total	100	100	100	100

Table 2.5 Expected vs. observed percentages of windthrow by slope angle for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The expected values represent the actual distribution of slope angles in the watershed.

		Observed windthrow from storms in		
Degrees	Expected (%)	1931 (%)	1973 (%)	1983 (%)
< 5°	12	10	15	12
5-15°	47	61	63	59
16-30°	36	26	19	27
> 30°	4	2	3	2
total	100	100	100	100

Table 2.6 Expected vs. observed percentages of windthrow by soil type for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The distinctions between soil types are based on their estimated effect on windthrow susceptibility. This was first mapped in 1964 by the Forest Service and was based on factors such as areas of perched water tables and restricted tree rooting ability (U.S.D.A. Forest Service 1964). The expected values represent the actual distribution of soil types in the watershed.

		Observed windthrow from storms in:		
Windthrow hazard of soil	Expected (%)	1931 (%)	1973 (%)	1983 (%)
none	13	3	2	6
slight	54	76	63	51
moderate	18	6	6	10
severe	15	16	30	33
total	100	100	100	100

Old-growth conifer forest was the predominant cover type affected in all three storms. The majority of windthrow from the 1931 storm affected old-growth conifer stands (58%), but younger conifer stands also were affected (Table 2.7). There was little or no windthrow associated with other cover-types, and after 1931 the younger conifer classes were not affected by windthrow. The majority of 1973 and 1983 windthrow coincided with old-growth forest. In 1983, only half the forested area (53%) was classified as old growth, but the old-growth forest experienced 90% of the windthrow. The conifer stands less than 200 years old received much smaller proportions of windthrow. The small proportions of 1973 and 1983 classified as having occurred within clearcut openings reflects mapping mis-registration, i.e., windthrow is measured as having occurred inside the opening instead of next to it.

The reclassification techniques used to create 1931, 1973, and 1983 vegetation layers may have overestimated the amount of old-growth forest. Not only were many of the openings converted only to old-growth, but the filtering process removed many of the scattered pixels of young and mature conifer. This, combined with the registration errors of edges and windthrow, suggested that the vegetation data layers were limited in their usefulness for detailed analyses. No further analyses were performed with the vegetation data layers.

In all three storms, windthrow was frequently found adjacent to openings in the forest canopy (Table 2.8). The amount of windthrow near perennial openings remained steady across all three storms with 31 - 35% of windthrow from each storm within 150 m of a perennial opening edge. In contrast, the windthrow near ephemeral openings increased from 1931 to 1983. None of the 1931 windthrow was near the only recent canopy opening at the time, Reservoir #1. Windthrow near an ephemeral opening increased from over one-half (56%) in 1973 to over three-quarters (77%) of the 1983 storm.

The use of a buffer to measure edge-related windthrow may underestimate the total amount in locations where a contiguous patch of windthrow extends from the edge of an opening to beyond the buffer. If the 150-m buffer is disregarded and all windthrow within patches located at edges is counted as edge-related, regardless of the distance away from the edge that the contiguous patch extends, there is up to 5% more edge-related windthrow from 1983 than was measured through the 150-m buffer method.

However, this same buffering technique may simultaneously overestimate edge-related windthrow in locations where ephemeral and perennial openings

Table 2.7 Expected vs. observed percentages of windthrow by vegetation type for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The expected values represent the actual distribution of vegetation type in the watershed for each storm year. Areas covered by shadow and water are not included in the table.

	Observed windthrow from storms in:					
	1931		1973		1983	
cover type classification of unshaded land cover	expected (%)	observed (%)	expected (%)	observed (%)	expected (%)	observed (%)
ephemeral openings	3	0	10	10	16	6
perennial openings	7	2	7	0	7	1
semi-open, non-conifer	2	0	3	0	4	3
closed canopy, non-conifer	<1	0	<1	0	<1	0
conifer, < 80 y.o.	7	16	8	0	8	0
conifer, > 80 & < 200 y.o.	9	23	9	0	9	0
conifer, > 200 y.o.	71	58	62	90	55	90
totals	100	100	100	100	100	100

Table 2.8 Location of windthrow with respect to opening edges for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. All ephemeral (clearcuts, reservoirs < 25 years old) and perennial (lakes, meadows, talus slopes, reservoirs > 25 years old) openings were buffered by 150 m in the GIS and windthrow that occurred within the buffered area was considered to have a spatial connection with the opening. The remaining windthrow is categorized as having occurred near no edge. Because buffers surrounding ephemeral and perennial openings sometimes overlap, both the amount of windthrow attributed to a particular opening or lack of opening, and the proportion of the landscape that the buffered areas cover, may exceed 100%.

Storm	1931	1973	1983
buffered ephemeral opening edges (<150 m from ephemeral opening edge)			
proportion of the landscape (%)	2	40	57
proportion of the windthrow (%)	0	56	77
buffered perennial opening edges (<150 m from perennial opening edge)			
proportion of the landscape (%)	36	38	38
proportion of the windthrow (%)	35	34	31
no opening edge (>150 m from any opening edge)			
proportion of the landscape (%)	61	31	20
proportion of the windthrow (%)	65	22	13

are clustered and their buffers overlap, resulting in the attribution of windthrow to both of the buffers. Most windthrow is likely to occur only downwind of an opening, in spite of the wind turbulence often associated with canopy openings. Yet there was no way to systematically attribute windthrow to only one opening or another, or to buffer only the downwind portions of openings, given the variability in wind directions influenced by local topography. This uncertainty may have resulted in scattered windthrow, located in a seemingly upwind location with respect to an opening, having been described as edge-related. The repercussions of this are discussed further in Sinton (1996b, unpublished).

Trends in 1973 and 1983 windthrow spatial patterns were not greatly altered by removing the smallest patches of windthrow, and in some cases, comparisons between expected and observed values were not affected at all (Table 2.9 and 2.10). The largest changes were seen with soil type and perennial openings: the amount of observed windthrow in 1973 and 1983, excluding small patches, more closely reflected the expected values than the patterns with all patches included. However, filtering of small 1973 and 1983 windthrow patches did not consistently liken the resulting patterns to the 1931 storm pattern.

In contrast, the patterns created by exclusion of clearcut-related 1973 and 1983 windthrow were more closely equated with expected watershed values or the 1931 windthrow pattern (Table 2.11 and 2.12). Significant changes were seen in observed windthrow on various aspects, soil types, and associations with perennial openings.

The analysis of edge factors revealed that the types of edges likely to have been windthrown differed between 1931 and 1983 (Table 2.13). The proportion of perennial edges that appear to have affected windthrow remained constant from 1931 to 1983, at < 3% of the total perennial opening edge length. The introduction of clearcuts to the landscape dramatically increased the total length of ephemeral opening edges over the fifty year period, from 16 km in 1931 to over 460 km in 1983. There was a corresponding increase in the proportion of ephemeral opening length that appeared to have influenced windthrow, from zero in 1931 to 12% of the total length in 1983.

The perennial opening edges on certain aspects were much more associated with windthrow than edges on other aspects (Table 2.14). In 1931 and 1973, there was more windthrow than expected near perennial opening edges on northern and northeastern aspects, while in 1983 there was a dramatic shift to windthrow near perennial opening edges on southwestern aspects. The

Table 2.9 Comparison of 1973 windthrow, excluding all patches less than 2 ha, and 1931 windthrow to landscape variables in the Bull Run watershed.

aspect	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, w/o small patches (%)
north	13	29	13	9
northeast	8	15	13	13
east	7	12	6	5
southeast	12	10	7	10
south	15	9	23	17
southwest	17	5	21	27
west	11	5	10	13
northwest	15	15	7	4
level ground	2	0	0	1

elevation (m)	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, w/o small patches (%)
200-599 m	22	3	3	2
600-1000 m	57	68	93	95
> 1000 m	21	29	4	3

windthrow hazard of soils	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, w/o small patches (%)
none	13	3	2	9
slight	54	76	63	62
moderate	18	6	6	12
severe	15	16	30	16

1973 ephemeral openings	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, w/o small patches (%)
< 150 m	40	0	56	67
> 150 m	56	100	44	33

1973 perennial openings	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, w/o small patches (%)
< 150 m	38	86	34	34
> 150 m	62	14	66	66

Table 2.10 Comparison of 1983 windthrow, excluding all patches less than 2 ha, and 1931 windthrow to landscape variables in the Bull Run watershed.

aspect	watershed (%)	1931 windthrow (%)	1983 windthrow, all data (%)	1983 windthrow, w/o small patches (%)
north	13	29	17	17
northeast	8	15	11	12
east	7	12	6	5
southeast	12	10	6	5
south	15	9	16	16
southwest	17	5	21	21
west	11	5	10	10
northwest	15	15	13	13
level ground	2	0	0	0
elevation (m)	**watershed (%)**	**1931 windthrow (%)**	**1983 windthrow, all data (%)**	**1983 windthrow, w/o small patches (%)**
200-599 m	22	3	19	19
600-1000 m	57	68	74	73
> 1000 m	21	29	8	8
soils	**watershed (%)**	**1931 windthrow (%)**	**1983 windthrow, all data (%)**	**1983 windthrow, w/o small patches (%)**
none	13	3	6	6
slight	54	76	51	49
moderate	18	6	10	9
severe	15	16	33	35
1983 ephemeral openings	**watershed (%)**	**1931 windthrow (%)**	**1983 windthrow, all data (%)**	**1983 windthrow, w/o small patches (%)**
< 150 m	55	0	77	53
> 150 m	45	100	23	47
1983 perennial openings	**watershed (%)**	**1931 windthrow (%)**	**1983 windthrow, all data (%)**	**1983 windthrow, w/o small patches (%)**
< 150 m	38	14	31	30
> 150 m	62	86	69	70

Table 2.11 Comparison of 1973 windthrow, excluding all windthrow < 150 m from an ephemeral edge, and 1931 windthrow to landscape variables in the Bull Run watershed.

aspect	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, > 150 m from eph. open.
north	13	29	13	16
northeast	8	15	13	17
east	7	12	6	12
southeast	12	10	7	8
south	15	9	23	17
southwest	17	5	21	14
west	11	5	10	7
northwest	15	15	7	9
level ground	2	0	0	0

elevation	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, > 150 m from eph. open.
200-599 m	22	3	3	4
600-999 m	57	68	94	91
> 1000 m	21	29	4	3

windthrow hazard of soils	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, > 150 m from eph. open.
none	13	3	2	1
slight	54	76	63	70
moderate	18	6	6	9
severe	15	16	30	20

1983 perennial openings	watershed (%)	1931 windthrow (%)	1973 windthrow, all data (%)	1973 windthrow, > 150 m from eph. open.
< 150 m	38	14	34	56
> 150 m	62	86	66	44

Table 2.12 Comparison of 1983 windthrow, excluding all windthrow < 150 m from an ephemeral edge, and 1931 windthrow to landscape variables in the Bull Run watershed.

aspect	watershed (%)	1931 windthrow (%)	1983 windthrow, all data (%)	1983 windthrow, > 150 m from eph. edge
north	13	29	17	25
northeast	8	15	11	13
east	7	12	6	13
southeast	12	10	6	7
south	15	9	16	10
southwest	17	5	21	12
west	11	5	10	10
northwest	15	15	13	10
level ground	2	0	0	0

elevation	watershed (%)	1931 windthrow (%)	1983 windthrow, all data (%)	1983 windthrow, > 150 m from eph. edge
200-599 m	22	3	19	28
600-999 m	57	68	74	36
> 1000 m	21	29	8	48

windthrow hazard of soils	watershed (%)	1931 windthrow (%)	1983 windthrow, all data (%)	1983 windthrow, > 150 m from eph. edge
none	13	3	6	10
slight	54	76	51	43
moderate	18	6	10	9
severe	15	16	33	38

1983 perennial openings	watershed (%)	1931 windthrow (%)	1983 windthrow, all data (%)	1983 windthrow, > 150 m from eph. edge
< 150 m	38	14	31	48
> 150 m	62	86	69	52

Table 2.13 Edges of ephemeral and perennial openings and their association with 1931, 1973 and 1983 windthrow. The outer edges of all ephemeral (clearcuts, reservoirs < 25 years old) and perennial (lakes, meadows, talus slopes, reservoirs > 25 years old) openings were measured, and the length of the edges that are within 150 m of windthrow are measured with the GIS and were considered to have a spatial connection with the neighboring windthrow.

	Storm event:		
	1931	1973	1983
ephemeral openings			
length of edges (km)	16	290	462
% of edges associated with windthrow	0	6	12
perennial openings			
length of edges (km)	308	326	326
% of edges associated with windthrow	1	1	3

Table 2.14 Expected vs. observed percentages of windthrown perennial opening edges by aspect for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The perennial opening edges that were within 150 m of neighboring windthrow were measured with the GIS and were considered to have a spatial connection with the windthrow. The expected values represent the actual distribution of perennial opening edges by aspect and were combined into one column as the values were similar or identical across all three years.

		Observed windthrown edges from storms in		
Aspect	Expected (%)	1931 (%)	1973 (%)	1983 (%)
north	10	17	31	13
northeast	12	24	34	15
east	10	5	14	5
southeast	11	3	10	6
south	13	14	5	25
southwest	23	15	7	14
west	10	5	0	14
northwest	11	14	0	8
level ground	0	3	0	0
totals	100	100	100	100

ephemeral opening edges on lee aspects tended to be affected more frequently than expected during the 1973 and 1983 storms (Table 2.15), and the greatest difference occurred on southwestern aspects in 1973. Ephemeral opening edges on aspects exposed directly to the winds did not experience greater amounts of windthrow than expected.

The edges on both the upwind (northern, northeastern) and downwind (southern, southwestern) sides of perennial openings had higher windthrow than expected (Table 2.16). Differences between expected and observed values were greater in the 1931 and 1973 storms than in 1983. The downwind sides of the ephemeral opening edges experienced the greatest differences in expected vs. observed proportions of windthrow in 1973 and 1983 (Table 2.17). These results may reflect the slightly different trajectories of the winds in the three storms, although each storm was characterized by winds with generally similar wind directional patterns.

There was a slight trend for perennial opening edges at higher elevations to be associated with windthrow in 1931, and lower elevations in 1973 and 1983 (Table 2.18). The ephemeral opening edges associated with windthrow in 1973 and 1983 were all concentrated between 600 and 900 m in elevation, somewhat lower than expected (Table 2.19).

Many of the perennial openings in the watershed are located where soils have been mapped as having no hazard for windthrow, yet these edges were highly associated with windthrow in all three storms (Table 2.20). This may reflect the mapping mis-registration between windthrow having occurred near an edge versus actually within the opening. In 1973 and 1983, a greater proportion than expected of perennial opening edges with a "severe" soil hazard ranking were associated with windthrow. The majority of ephemeral opening edges occur where there is a "slight" hazard for windthrow, and a correspondingly high proportion of these edges was associated with windthrow in 1973 and 1983 (Table 2.21). However, ephemeral opening edges on the "severe" hazard soil class experienced twice as much windthrow as was expected in each year.

The analysis of windthrown ephemeral opening edges by their age (i.e., the approximate date of their creation) revealed that younger edges were associated with windthrow more frequently than older edges (Table 2.22). Overall, edges greater than ten years old experienced less windthrow than

Table 2.15 Expected vs. observed percentages of windthrown ephemeral opening edges by aspect for storms in 1973 and 1983 in the Bull Run watershed, Oregon. The ephemeral opening edges that were within 150 m of windthrow were measured with the GIS and were considered to have a spatial connection with the neighboring windthrow. The expected values represent the actual distribution of ephemeral opening edges by aspect and were combined into one column as the values were similar or identical across both years. The only recent opening in 1931 (Reservoir #1) had no windthrow adjacent to it, so it is not included in the table.

		Observed windthrown edges from storms in	
Aspect	Expected (%)	1973 (%)	1983 (%)
north	9	8	9
northeast	6	10	9
east	6	2	7
southeast	14	7	7
south	20	26	20
southwest	20	32	26
west	11	11	12
northwest	13	2	10
level ground	1	1	0
totals	100	100	100

Table 2.16 Expected vs. observed percentages of windthrown perennial opening edges by edge orientation for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The perennial opening edges that were within 150 m of neighboring windthrow were measured with the GIS and were considered to have a spatial connection with the windthrow. The expected values represent the actual distribution of perennial opening edges by edge orientation and were combined into one column as the values were similar or identical across all three years. See Fig. 3.24 for a description of the classification by orientation.

		Observed windthrown edges from storms in		
Location of edge relative to the opening	Expected (%)	1931 (%)	1973 (%)	1983 (%)
north	13	20	11	19
northeast	12	2	20	9
east	12	3	1	11
southeast	13	12	4	9
south	13	27	8	10
southwest	12	18	24	14
west	12	10	22	16
northwest	14	8	9	13
totals	100	100	100	100

Table 2.17 Expected vs. observed percentages of windthrown ephemeral openings by edge orientation for storms in 1973 and 1983 in the Bull Run watershed, Oregon. The ephemeral edges that were within 150 m of windthrow were measured with the GIS and were considered to have a spatial connection with the neighboring windthrow. The expected values represent the actual distribution of ephemeral openings by edge orientation and were combined into one column as the values were similar or identical across both years. The only recent opening in 1931 (Reservoir #1) had no windthrow adjacent to it, so it is not included in the table. See Fig. 3.24 for a description of the classification by orientation.

		Observed windthrown edges from storms in	
Location of edge relative to ephemeral opening	Expected (%)	1973 (%)	1983 (%)
north	16	21	16
northeast	9	6	8
east	12	7	8
southeast	12	3	8
south	17	11	15
southwest	9	18	10
west	12	16	18
northwest	13	17	18
totals	100	100	100

Table 2.18 Expected vs. observed percentages of windthrown perennial opening edges by elevation for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The perennial opening edges that were within 150 m of neighboring windthrow were measured with the GIS and were considered to have a spatial connection with the windthrow. The expected values represesent the actual distribution of perennial opening edges by elevation for each year and were combined into one column as the values were similar or identical across all three years.

		Observed windthrown edges from storms in		
Elevation (m)	Expected (%)	1931 (%)	1973 (%)	1983 (%)
< 300	0	0	0	0
300-399	6	0	0	9
400-499	0	0	0	0
500-599	3	0	0	2
600-699	6	0	25	14
700-799	13	0	16	25
800-899	14	0	11	8
900-999	24	58	43	31
1000-1099	18	26	5	8
1100-1199	9	14	0	0
1200-1299	4	2	0	0
1300-1399	1	0	0	4
> 1400	0	0	0	0
totals	100	100	100	100

Table 2.19 Expected vs. observed percentages of windthrown ephemeral opening edges by elevation for storms in 1973 and 1983 in the Bull Run watershed, Oregon. The ephemeral edges that were within 150 m of windthrow were measured with the GIS and were considered to have a spatial connection with the neighboring windthrow. The expected values represent the actual distribution of ephemeral opening edges for each year and were combined into one column as the values were similar or identical across both years. The only recent opening in 1931 (Reservoir #1) had no windthrow adjacent to it, so it is not included in the table.

		Observed windthrown edges from storms in	
Elevation (m)	Expected (%)	1973 (%)	1983 (%)
< 300	4	0	0
300-399	8	0	5
400-499	6	0	3
500-599	11	0	6
600-699	16	16	17
700-799	15	27	32
800-899	18	49	21
900-999	14	8	12
1000-1099	6	0	2
1100-1199	2	0	2
1200-1299	0	0	0
1300-1399	0	0	0
> 1400	0	0	0
totals	100	100	100

Table 2.20 Expected vs. observed percentages of windthrown perennial opening edges by soil type for storms in 1931, 1973 and 1983 in the Bull Run watershed, Oregon. The perennial opening edges that were within 150 m of windthrow were measured with the GIS and were considered to have a spatial connection with the neighboring windthrow. The distinctions between soil types are based on their estimated effect on windthrow susceptibility. This was first mapped in 1964 by the Forest Service and was based on such factors as areas of perched water tables and restricted tree rooting ability (U.S.D.A. Forest Service 1964). The expected values represent the actual distribution of perennial opening edges for each year and were combined into one column as the values were similar or identical across all three years.

		Observed windthrown edges from storms in		
Windthrow hazard of soil	Expected (%)	1931 (%)	1973 (%)	1983 (%)
none	66	66	51	58
slight	16	32	27	15
moderate	11	0	5	14
severe	7	2	17	14
totals	100	100	100	100

Table 2.21 Expected vs. observed percentages of windthrown ephemeral opening edges by soil type for storms in 1973 and 1983 in the Bull Run watershed, Oregon. The ephemeral openings that were within 150 m of windthrow were measured with the GIS and were considered to have a spatial connection with the neighboring windthrow. The distinctions between soil types are based on their estimated effect on windthrow susceptibility. This was first mapped in 1964 by the Forest Service and based on such factors as areas of perched water tables and restricted tree rooting ability (U.S.D.A. Forest Service 1964). The expected values represent the actual distribution of ephemeral opening edges for each year and were combined into one column as the values were similar or identical across both years. The only recent opening in 1931 (Reservoir #1) had no windthrow adjacent to it, so it is not included in the table.

		Observed windthrown edges from storms in	
Windthrow hazard of soil	Expected (%)	1973 (%)	1983 (%)
none	7	1	4
slight	68	61	59
moderate	10	5	6
severe	15	32	31
totals	100	100	100

Table 2.22 Expected vs. observed percentages of windthrown ephemeral opening edges by edge age for storms in 1973 and 1983 in the Bull Run watershed, Oregon. The ephemeral edges that were within 150 m of windthrow were measured with the GIS and were considered to have a spatial connection with the neighboring windthrow. The age is the year that the clearcut or reservoir was made. Ephemeral openings made between 1973 and 1977 are distinguished by which clearcuts were salvage of the 1973 windthrow and which were not. The expected values represent the actual distribution of ephemeral opening edges by edge age. The only recent opening in 1931 (Reservoir #1) had no windthrow adjacent to it, so it is not included in the table.

Storm	1973		1983	
Date edge created	Expected (%)	Observed (%)	Expected (%)	Observed (%)
1957-62	27	14	17	5
1963-67	46	46	29	10
1968-72	26	41	16	9
1973-77; non-salvage			15	19
1973-77; salvage			16	52
1978-83			6	5
totals	100	100	100	100

younger edges. The strongest association was between windthrown 1983 edges and the edges created by 1973 salvage operations.

2.4.3 Interactions among factors affecting windthrow

Aspect and soil type explained most of the 1931 windthrow pattern (Table 2.23), and the interaction between aspect and soils was not significant. Windthrow on northeastern aspects was more than twice as likely as on northwestern aspects. The odds ratio for soil susceptibility, based on the sample, suggested that windthrow was more likely on severe hazard soils than others, yet the results from the regression run on the entire population of 1931 windthrow points revealed that the significance assigned to soil type is due instead to the unusually high proportion of windthrow that occurred on slight hazard soils.

Aspect and the interactions between soil type and ephemeral openings were significant as independent variables in the logistic regression for the 1973 windthrow pattern (Table 2.24). Windthrow on northeastern and southwestern aspects was more likely than on northwest aspects. Where ephemeral openings existed, windthrow on severe hazard soils was over ten times more likely than on low hazard soils. Areas mapped as having no soil hazard for windthrow were excluded from the regression due to incomplete representation in certain combinations with other independent variables. These 1973 statistical results generally corroborated with the regression results generated with the entire population of 1973 windthrow. The positive interaction between ephemeral openings, severe hazard soils and 1973 windthrow was found to be over three times as likely than similar areas without ephemeral openings, but not as high as the random sample suggested.

Soils and ephemeral openings were the two significant independent variables used to predict the 1983 windthrow pattern (Table 2.25). Based on the sample results, more than twice as much 1983 windthrow occurred on severe hazard soils as expected, and windthrow on severe hazard soils was three times more likely than on slight hazard soils. Over three-quarters of the 1983 windthrow was within 150 m of an ephemeral opening, and windthrow within

Table 2.23 Results from the logistic regression of 1931 windthrow. Windthrow was tested against six independent variables (aspect, elevation, slope, soils, ephemeral and perennial openings) in a logistic regression in SAS. The odds ratios were based on a reference class from each variable, designated by an odds ratio of 1.0; the other odds ratios are with respect to that class.

Final Model:

variable	n	DF	ChiSquare	Pr > Chi
aspect	174	3	14.84	0.002
soils	174	3	25.19	0.0001

Odds Ratios:

	aspect				
windthrow	NE	SE	SW	NW	totals
yes	35	17	14	21	87
no	18	15	29	25	87
total	53	32	43	46	174
estimate (b)	1.041	0.447	-0.67	0.0	
stnd. error	0.457	0.512	0.466		
odds ratio (e^b)	2.82	1.56	0.51	1.0	

	windthrow hazard of soils				
windthrow	none	slight	moderate	severe	totals
yes	3	60	5	19	87
no	14	47	18	8	87
total	17	107	23	27	174
estimate (b)	-2.154	0.0	-1.74	0.509	
stnd. error	0.698		0.568	0.486	
odds ratio (e^b)	0.116	1.0	0.175	1.664	

Table 2.24 Results from the logistic regression of 1973 windthrow. Windthrow was tested against six independent variables (aspect, elevation, slope, soils, ephemeral and perennial openings) in a logistic regression in SAS. The odds ratios were based on a reference class from each variable, designated by an odds ratio of 1.0; the other odds ratios are with respect to that class. Soil Class 1 (areas with no hazard of windthrow) were excluded from the regression due to irregular representation in certain combinations with other variables; therefore the totals for windthrow and non-windthrow points are no longer even.

Final Model:

variable	n	DF	ChiSquare	Pr > Chi
aspect	189	3	8.4027	0.0384
soils*ephemeral openings	189	2	10.1752	0.0062

Odds Ratios:

	aspect				
windthrow	NE	SE	SW	NW	totals
yes	31	10	42	19	102
no	16	19	30	22	87
total	47	29	72	41	189
estimate	1.069	-0.186	0.561	0.0	
stnd. error	0.475	0.525	0.43		
odds ratio	2.91	0.83	1.75	1.0	

ephemeral openings yes	windthrow hazard of soils			
windthrow	slight	moderate	severe	totals
yes	30	4	20	54
no	31	5	3	39
totals	61	9	23	93
estimate	0.0	-0.344	2.314	
stnd. error		2.626	1.519	
odds ratio	1.0	0.71	10.12	

ephemeral openings no	windthrow hazard of soils			
windthrow	slight	moderate	severe	totals
yes	32	5	11	48
no	25	12	11	48
totals	57	17	22	96
estimate	0.0	-1.286	-0.371	
stnd. error		0.945	0.854	
odds ratio	1.0	0.276	0.69	

Table 2.25 Results from the logistic regression of 1983 windthrow. Windthrow was tested against six independent variables (aspect, elevation, slope, soils, ephemeral and perennial openings) in a logistic regression in SAS. The odds ratios were based on a reference class from each variable, designated by an odds ratio of 1.0; the other odds ratios are with respect to that class.

Final Model:

variable	n	DF	ChiSquare	Pr > Chi
ephemeral openings	230	1	10.312	0.0013
soils	230	3	17.456	0.0006

Odds Ratios:

	ephemeral openings		
windthrow	yes	no	totals
yes	87	28	115
no	64	51	115
total	151	79	230
estimate	0.964	0	
stnd. error	0.306		
odds ratio	2.62	1.0	

	windthrow hazard of soils				
windthrow	none	slight	moderate	severe	totals
yes	5	59	13	38	115
no	13	63	24	15	115
total	18	122	37	53	230
estimate	-0.765	0.0	-0.365	1.153	
stnd. error	0.569		0.402	0.37	
odds ratio	0.465	1.0	0.694	3.168	

150-m of an ephemeral opening was 2.6 times more likely than at distances further away.

The interaction between soils and ephemeral openings was not significant with the sampled data, but it was found to be statistically significant when the full data set of 1983 windthrow was tested. The odds ratios calculated for the interaction with the full data set suggests that the soils mapped as having no hazard for windthrow are highly correlated with areas both covered and not covered with ephemeral openings. Such a result highlights the highly volatile nature of statistical analyses performed on only a small percentage of the data.

2.4.4 Storm comparison

The storm events of April 1931, January 1973 and December 1983 were roughly comparable in terms of wind speed and direction, based on available data from the Portland area (Table 2.26). In the three storm events, winds were from the north, northeast or east directions. Peak wind speeds, recorded in Portland, reached above 30 mph in each of the three storms. This is not a particularly high wind speed, yet when the period 1948-1994 is considered, the 1973 and 1983 storm speeds are in the top 1% of all wind speeds from 1948 - 1994, based on maximum and average daily wind speeds at the Portland Airport (Sinton 1996c, unpublished).

While no wind data are available from within the watershed during the storm periods, it is likely that the measurements taken near sea level at the Portland Airport (1973, 1983) and in downtown Portland (1931) underestimate the actual wind speeds that occurred in the Bull Run. Wind speed increases with elevation and in mountainous terrain (Oke 1978; Oliver and Larson 1990), and the Forest Service reports that winds gusting up to 90 m.p.h. were characteristic of the 1983 storm (U.S.D.A. Forest Service 1987). Furthermore, wind directions recorded for a daily maximum wind speed in Portland do not necessarily represent the true wind directions encountered within the watershed. Topography can significantly redirect and alter wind directions experienced locally. No systematic analyses were performed to determine the directions which downed trees were lying on the 1973 or 1984 air photos, but they appear to be primarily oriented with canopies towards the west and southwest, suggesting

Table 2.26 Weather data from the 1931, 1973 and 1983 storms. Wind data from 1931 were recorded at a weather station in downtown Portland, Oregon, approximately forty miles west of the Bull Run watershed. Wind data from the 1973 and 1983 storms were recorded at the Portland International Airport, approximately thirty miles west of the Bull Run. Both data sets were obtained from the National Data Climate Center, North Carolina. No information was published about the duration of recorded wind speeds or the methods of collecting the data. Given the distances between the data collection sites and the watershed, the wind data do not necessarily represent conditions in the Bull Run during the storm events. Temperature and precipitation data were recorded within the Bull Run watershed at Reservoir #1.

storms	max. wind speed (mph) of day	dir. of max. wind speed	avg. wind speed (mph) of day	maximum temp (F°) of day	precipitation on day (inches)	cumulative precip. during 14 days prior (inches)
1931						
21-Apr-31	34	north	20	80	0.0	1.07
22-Apr-31	27	east	18	69	0.0	1.07
23-Apr-31	37	east	15	64	0.0	1.07
1973						
8-Jan-73	31	east	28	26	0.0	3.87
9-Jan-73	35	east	31	31	0.0	3.87
1983						
23-Dec-83	35	east	24	19	0.0	3.34
24-Dec-83	39	east	34	18	0.09	3.16
25-Dec-83	33	east	24	31	0.21	2.0

an east or northeast wind. The field work conducted to identify and map windthrown trees from the earlier period found virtually all downed trees to be lying with the top of the trees oriented between 190° and 260° degrees (south and southwest), and the average orientation among all historically windthrown trees was towards 220° (southwest). This is generally consistent with the data available from downtown Portland for the 1931 storm event.

The 1973 and 1983 storms were characterized by cold temperatures. The maximum daily temperatures, recorded within the watershed at Reservoir #2, failed to reach above the freezing level throughout the two to three day duration of either storm event.

2.4.5 The northeastern quadrant

Certain combinations of variables coincide in the northeastern quadrant of the Bull Run watershed that appear to have predisposed the area to extensive windthrow in 1973 and 1983 (Fig. 2.8). Winds from the north and east can be funneled through topographic channels to the area. Much of the windthrow occurs not at the ridgeline itself but further down the lee slope, suggesting that the turbulent lee effect of wind over a ridgeline may have been critical.

In each of the 1973 and 1983 logistic regressions, soils and ephemeral openings are significant variables either on their own or interacting. By 1982, numerous clearcuts were concentrated in the northeastern quadrant where soils have been mapped as having a high hazard for windthrow (Fig. 2.9).

2.5 Discussion

2.5.1 Pattern and storm comparison

The landscape patterns of windthrow from the 1931 (pre-logging) storm and the later events are remarkably dissimilar in their geographic distribution. Several factors may explain these pattern differences, including: 1) the interaction

Figure 2.8 Northeastern quadrant of the Bull Run watershed.

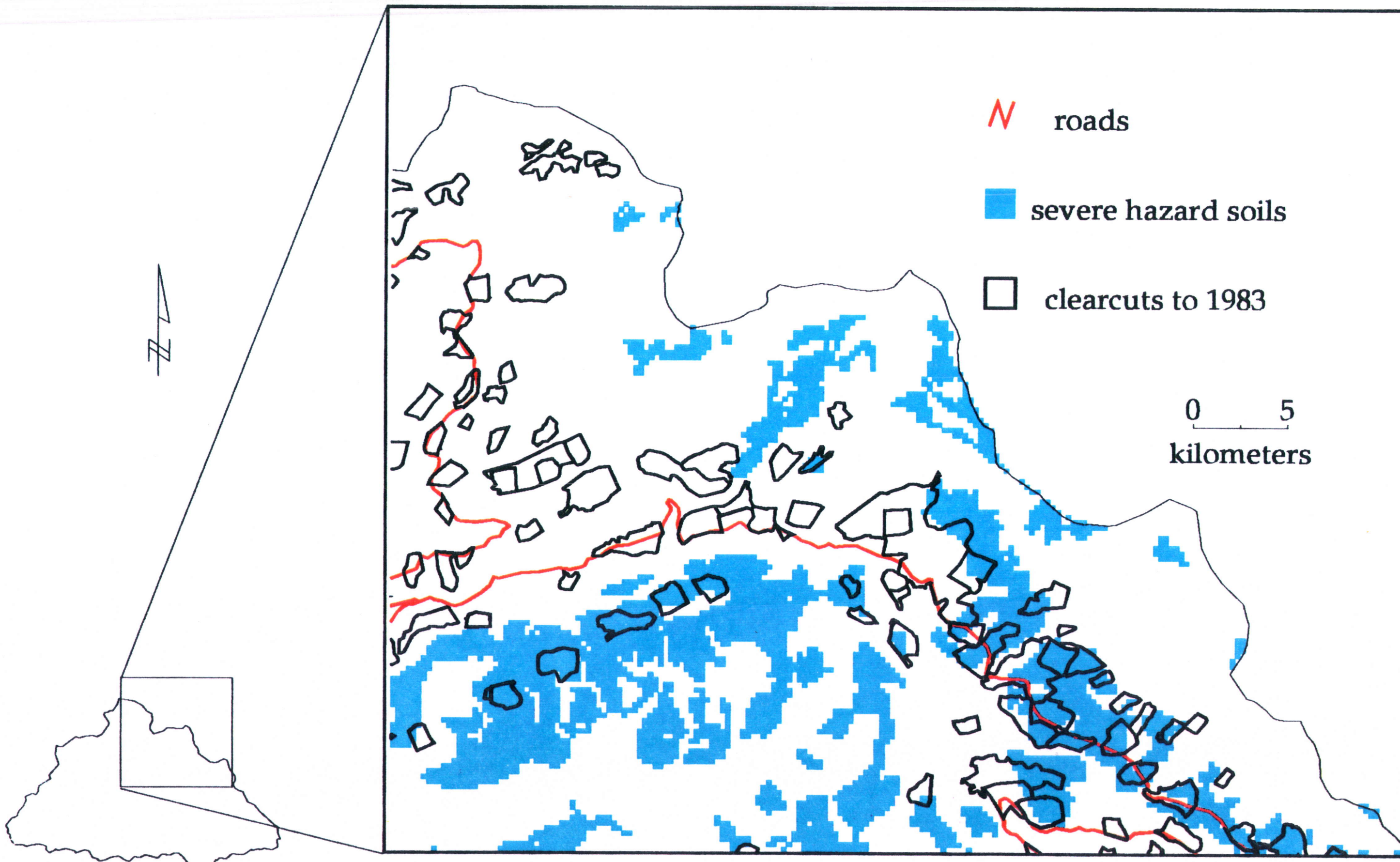
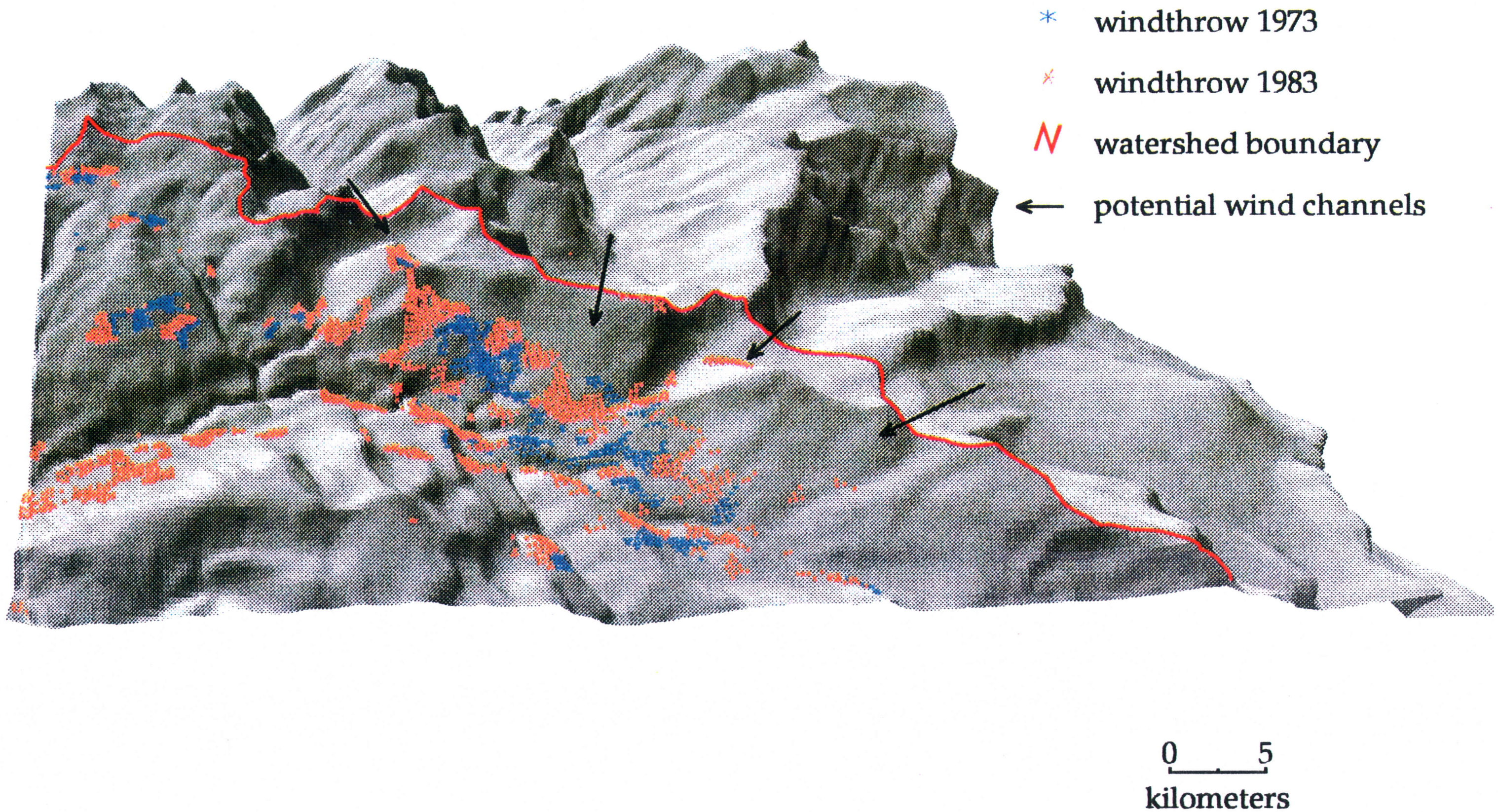


Figure 2.9 Northeastern quadrant of the Bull Run watershed, topographic exposure looking northeasterly.



of slightly different wind trajectories in each storm with the local and broader-scale topography; 2) forest stand conditions at the time of each storm; 3) the sub-freezing temperatures characteristic of the 1973 and 1983 storms; and 4) the existence of new, clearcut edges prior to each of the 1973 and 1983 events.

2.5.2 Topographic and vegetation factors

Windthrow from the 1931 storm was most strongly influenced by topographic variables. Topographic exposure to winds from a northeasterly storm would directly expose the northern, northeastern, and eastern aspects of the watershed, and this explains the predominantly northeast facing location of 1931 windthrow. Moreover, once the clearcut-related windthrow had been excluded from the 1973 and 1983 patterns, the remaining windthrow from those northeasterly storms also exhibited higher than expected values on directly exposed, northeastern aspects.

Windthrow can also affect the lee side of a ridge (Ruth and Yoder 1953; Gratkowski 1956; Oliver and Larson 1990; Stathers *et al.* 1994). Northeasterly winds would create a lee effect on southwestern aspects, where much of the 1973 and 1983 windthrow was found. Furthermore, by 1972 clearcuts in the Bull Run were clustered at low- to mid-elevations and on southern and southwestern aspects, where old-growth forest was concentrated (Table 2.27). The high amount of 1973 windthrow found on lee aspects at mid-elevations may be attributed to both to a lee slope, turbulent wind effect and the concentration of clearcuts in those locations.

The fire history of the watershed may also explain differences in the distribution of windthrow. Fires in the Bull Run tend to burn into the watershed from outside the basin, thus greatly affecting the perimeter of the watershed, and in the 1870s and 1880s, fires occurred primarily at mid- to lower elevations along the southern, western and northern watershed boundary (Table 2.27) (Krusemark *et al.* 1996). Stands affected by those fires may not have been sufficiently revegetated by conifers tall enough to have experienced windthrow again by 1973 or 1983.

Table 2.27 A comparison of interrelated site variables in the Bull Run to 1973 windthrow, based on aspect and elevation. All numbers under each sub-category sum to 100%. Numbers of particular interest are highlighted in bold.

WHOLE WATERSHED	N (%)	NE (%)	E (%)	SE (%)	S (%)	SW (%)	W (%)	NW (%)
low elev. (< 600 m)	4	1	1	4	4	2	2	4
medium elev. (600-1000 m)	7	5	5	6	8	10	6	8
high elev. (>1000 m)	2	2	1	2	3	5	3	3
FIRES 1873-1928								
low elev. (< 600 m)	9	2	3	8	6	3	4	10
medium elev. (600-1000 m)	2	3	6	8	6	5	3	4
high elev. (>1000 m)	2	2	2	3	3	3	2	3
OLD-GROWTH FOREST								
low elev. (< 600 m)	4	1	1	3	4	2	2	4
medium elev. (600-1000 m)	9	5	4	5	**9**	**11**	7	10
high elev. (>1000 m)	2	2	1	1	2	4	3	3
CLEARCUTS to 1972								
low elev. (< 600 m)	4	1	3	8	**10**	3	2	6
medium elev. (600-1000 m)	5	2	4	7	**11**	**13**	6	8
high elev. (>1000 m)	1	1	1	1	0	1	1	1
SEVERE HAZARD SOILS								
low elev. (< 600 m)	3	1	0	0	0	0	1	4
medium elev. (600-1000 m)	10	6	6	4	6	**15**	8	14
high elev. (>1000 m)	3	2	1	1	2	4	4	4
WINDTHROW 1973								
low elev. (< 600 m)	0	1	1	0	0	0	0	0
medium elev. (600-1000 m)	**12**	**11**	6	7	**22**	**21**	9	6
high elev. (>1000 m)	1	1	0	0	0	0	1	0

2.5.3 Soils and climatic factors of storms

Soil type is a significant variable in each of the three spatial pattern analyses. A high proportion of windthrow in 1973 and 1983 windthrow occurred on "severe" hazard soils, where perched water tables may restrict tree rooting. Yet the majority of the windthrow during all three storm events occurred on "slight" windthrow hazard areas, the assigned classification for the majority of the soils in the Bull Run watershed. This result is initially counter-intuitive, and suggests there may be inherent flaws in the soil hazard mapping designations. However, not only are soils maps covering large areas notoriously inaccurate, but the Bull Run Soil Survey itself states that "extremely high and gusty wind conditions" may render the soil hazard classification inadequate for prediction of windthrow (U.S.D.A. 1964). Therefore it is not surprising that with storms as extreme as the 1973 and 1983 events, so much windthrow occurred in the "slight" hazard areas.

Qualities of the storms themselves may explain part of the windthrow patterns. In the 1973 and 1983 storms, a contributing mechanism to windthrow susceptibility may have been temperature. Both storms were characterized by day-time temperatures that failed to warm above the freezing point. Exposure of wood to sub-freezing air temperatures results in a decreased modulus of elasticity and an overall increase in strength properties (Comben 1964; U.S.D.A. Forest Service 1972). The bending strength of green wood can increase as much as 100% at sub-freezing temperatures (Gerhards 1982). This mechanical change in wood could have affected the magnitude of the windthrow, particularly during the 1983 storm which was one of the coldest storms near the Columbia Gorge during this century. Trees that were stiffened by cold functioned as levers, forgoing their natural ability to bend with the wind. Instead they may have uprooted en masse, particularly in areas where shallow soils and perched water tables had already compromised the stabilizing effects of root systems.

This hypothesis is contingent on the theory that the boles of the trees, rather than the roots and soil, were affected by the cold temperatures. If the soil itself were frozen, tree roots would have been anchored, resulting in a greater number of snapped tree boles than was evident. However, it is unlikely that soils were frozen following a single cold snap, and roots surrounded by insulating soil would not have been affected by only three days of sub-freezing temperatures.

The Environmental Impact Statement prepared by the Forest Service for the salvage of 1983 windthrow stated that the soils were in an "unfrozen and saturated" condition (U.S.D.A. Forest Service 1987).

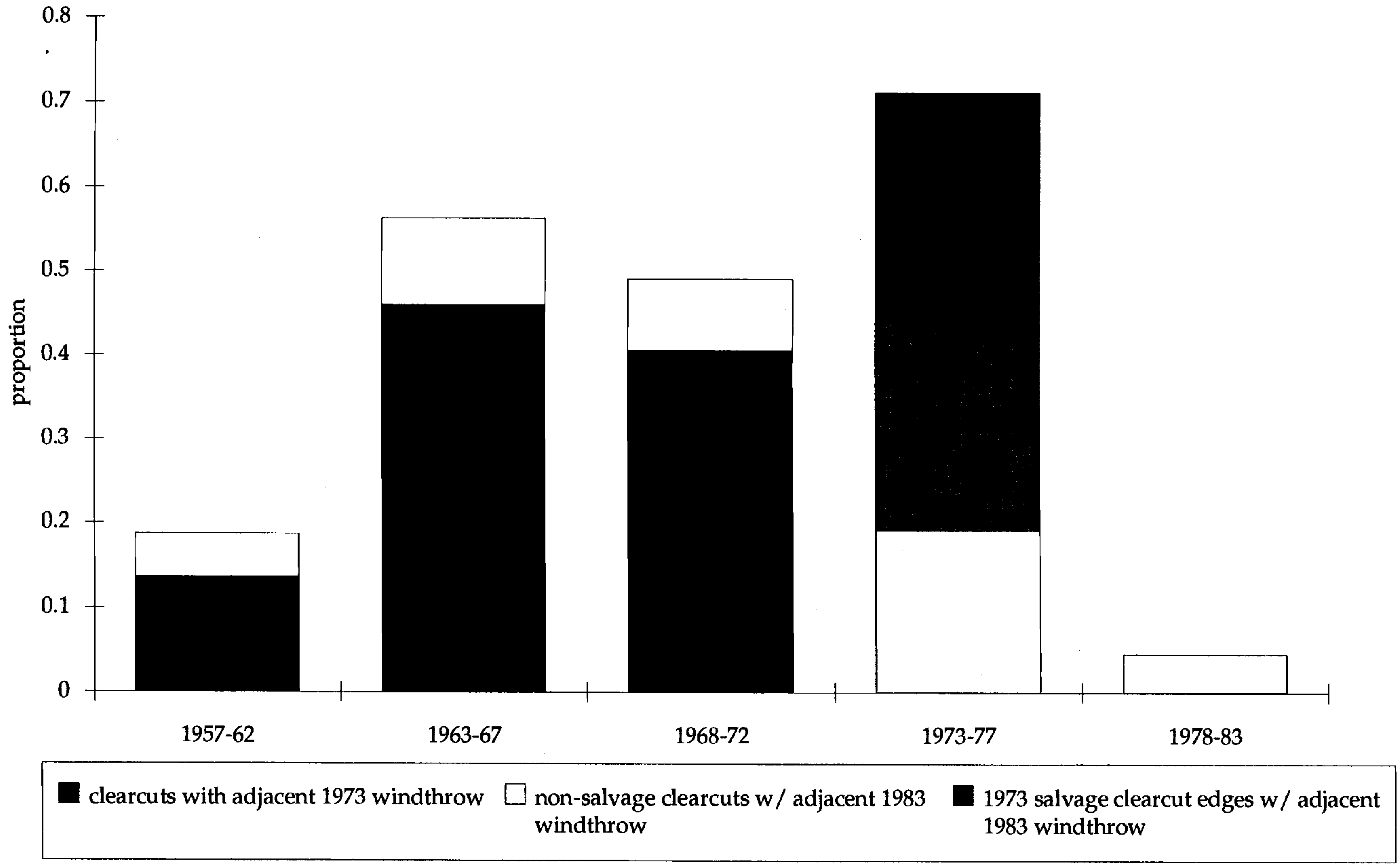
A secondary explanation for the interaction between cold temperatures and windthrow is the effect of rime ice, a type of ice that forms when moisture-laden air, such as fog, is blown against a cold surface. The Bull Run watershed is known for its extensive fog (Harr 1982), and it is possible that rime ice could have formed in the canopies of trees during the 1973 and 1983 storm events. Ice in a tree canopy would decrease its ability to streamline itself in the wind, increasing the drag force and leading to a greater windthrow potential.

2.5.4 Edge exposure

The edges of clearcuts are ephemeral; they lose vulnerability to windthrow over time as revegetation occurs within the cut, the distinctive height difference between forest and opening gradually diminishes, and any particularly weak or vulnerable trees at the edge of the adjacent stand are culled. Thus the aging of clearcut edges mitigates their windthrow risk (Fig. 2.10). However, all recently created canopy openings did not experience significant windthrow. Reservoir #1 had been in place for only four years at the time of the 1931 storm event, yet there was no 1931 windthrow found in its immediate vicinity. Reservoir #2 was a 1964 addition to the watershed, but there was little windthrow in close proximity following the 1973 storm.

Several reasons exist for why trees at these opening edges were less susceptible to windthrow. The 1873 fire swept across much of the area later covered by Reservoir #2 (Krusemark *et al*. 1996), so the forests there may have lacked the stand structure or height to make them particularly vulnerable to 1973 or 1983 windthrow. Additionally, the areas currently surrounding both reservoirs are characterized by a high proportion of non-conifer tree species as well as non-forested areas associated with the management of the reservoirs themselves. The absence of historic windthrow evidence could reflect the more rapid decay rates associated with deciduous tree species. Furthermore, windthrow and limb pruning of particularly vulnerable trees along ephemeral opening edges are likely to occur during mild to moderate storm events. If this

Figure 2.10 Age of clearcut edges affected by 1973 and 1983 windthrow in the Bull Run watershed.



culling occurred prior to the next severe wind storm, the remaining trees may have adjusted to the increased amount of exposure, resulting in fewer windthrown trees.

At least one-third of the windthrow in 1931, 1973 and 1983 occurred near perennial openings. Trees at these edges are presumed to have a greater inherent "windfirmness" than trees located elsewhere, as they have grown under chronic wind exposure and tend to have wind-pruned canopies and a stable rooting system. However, under extreme wind conditions these factors may prove inadequate to protect the tree from windthrow, as was likely the case with the 1973 and 1983 storm.

2.5.5 Pattern and process interactions

On a species basis, Douglas-fir is considered more windfirm than either western hemlock or Pacific silver fir (Minore 1979). Yet Douglas-fir trees achieve greater height than the other species, and in the Bull Run watershed, Douglas-fir was the most frequently windthrown tree found from storms since the 1890s (D. Sinton, field observations). In old-growth forests where a mixed-age and multi-story canopy is typical, the relative height of a tree may be more important than its rooting characteristics in evaluating its susceptibility to windthrow.

Stands affected by severe fires and windthrow from the late 1800s through the 1920s were not sufficiently revegetated by conifers tall enough to have experienced windthrow again by 1973 or 1983. However, as these stands continue to grow, the probability of future windthrow increases. In other sections of the watershed, clearcuts made in the last twenty years have removed the threat of extensive windthrow from those areas for many decades to come, by removing the trees themselves. The pattern and timing of vegetation succession interacts with the return interval of windthrow-generating storm events in determining the likelihood of windthrow at any given location and time.

Fire suppression creates vegetation patterns that interact with windthrow, by affecting stand age and height (Sinton 1996d, unpublished). In the Bull Run, windthrow affects old-growth vegetation more frequently than younger conifer classes. With effective fire suppression and no further harvesting activities, the younger conifer stands, regenerating from fires since the 1870s and clearcuts since the 1950s, will become increasingly susceptible to windthrow as they age and reach a more prominent height.

2.5.6 The northeastern quadrant

The area of the watershed that experienced the greatest amount of windthrow during the 1973 and 1983 storm was the northeastern quadrant. On southwestern slopes, forests downwind of a recent clearcut edge were as much as five times more likely to have experienced windthrow than in other forested areas. Moreover, the area is characterized by southwestern slopes at mid-elevations, where both clearcutting and severe windthrow hazard soils dominate (Table 2.27).

Little windthrow from the pre-logging period was found in the northeastern quadrant, and several explanations are possible. Fires occurred in the northern section of the watershed in 1881 and 1923 (Krusemark *et al.* 1996), and it is possible that the evidence of older windthrow (e.g., from the mid-1800s, or earlier) was then obliterated. However, given the high soil moisture typical of much of this area, the fires would have had to have been severe to erase all historical evidence of windthrow.

A second explanation is that inherent factors, such as wet and shallow soils, created a moderately susceptible windthrow hazard area, but the topographic protection from direct, easterly winds had historically prevented extensive windthrow from occurring. However, once the closed canopy forest was opened with clearcuts in the early 1960s, local factors (fresh forest edges) overcame the broader topographic factors that had previously limited windthrow. Few clearcuts existed in the area prior to the 1973 storm, but the majority of those were associated with windthrow in 1973, and 1973 windthrow in the area was removed by creating more clearcuts and associated edges. Ten years later, over half of the 1983 windthrow was near the edges of 1973 windthrow salvage clearcuts.

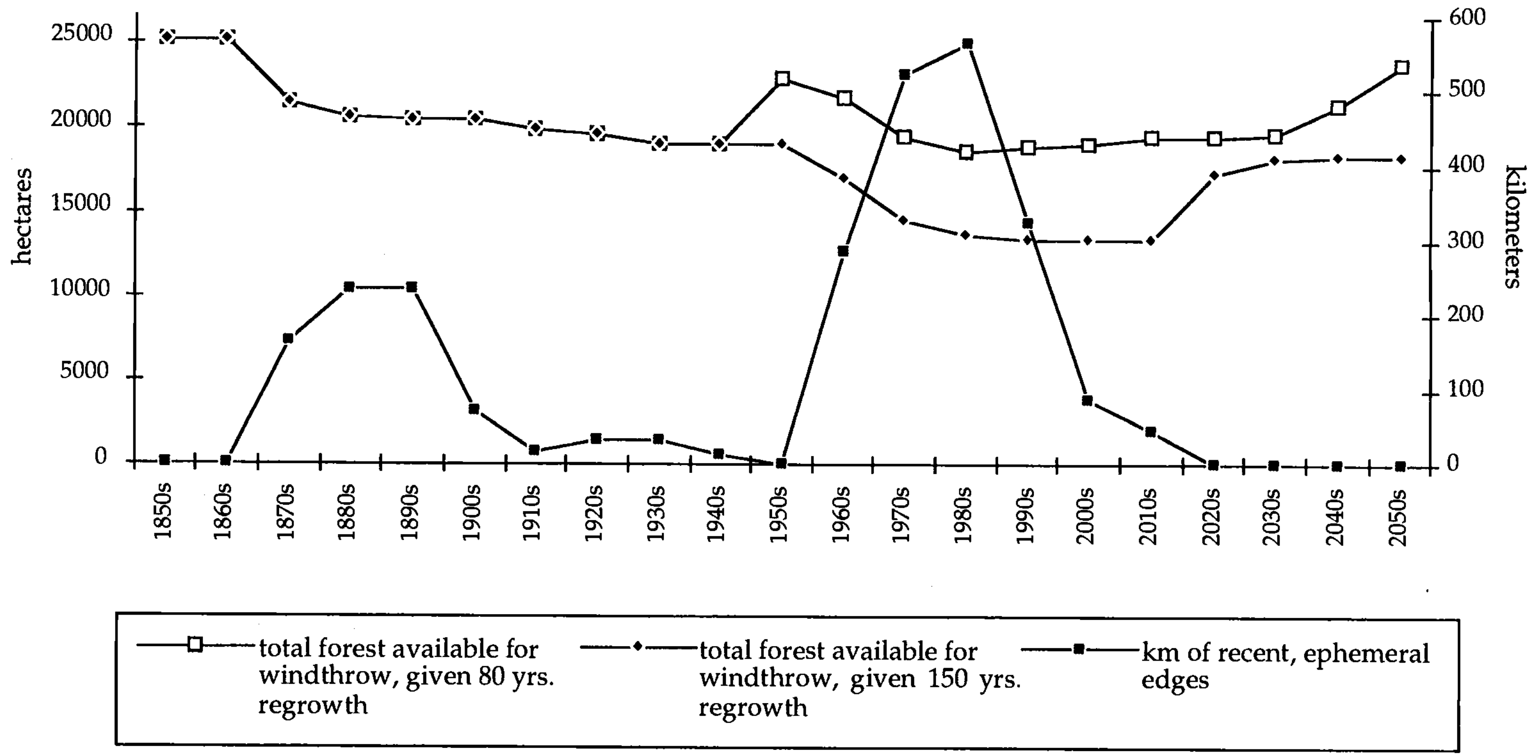
Furthermore, the northeastern quadrant has a concentration of perennial, elongate openings, primarily talus slopes and shrub fields, that are oriented in a northeastern-southwestern direction. These openings may have channeled wind downslope and into the forest below where some 1973 and 1983 windthrow occurred. Windthrow from 1973 that may have been originally influenced by these perennial openings was salvaged by clearcutting, and the salvage clearcuts later influenced the 1983 windthrow. In some locations, however, the 1983 windthrow is downwind from both a perennial opening and a clearcut. Particularly in areas where ephemeral and perennial openings are in close proximity and a positive upwind/downwind distinction is not possible, there is no straight-forward or systematic method to determine which of the openings, ephemeral or perennial, may have played a greater role in influencing windthrow.

Shallow soils in an area with perched water tables represent an inherent threat to tree stability. Field examination of sites where 1983 windthrow was salvaged revealed that even in late summer, standing water was present. The positive interaction between aspect, edge orientation, and edge age, combined with the presence of perennial openings and saturated soil conditions, created edges that were particularly unstable and susceptible to the wind conditions in 1983. Extremely cold temperatures may have exacerbated the situation.

2.5.7 The range of natural variability

Disturbance regimes characterized by a range of frequencies, sizes, and severities of events are a reflection of the natural variability of an ecosystem (Swanson *et al.* 1993). The 1983 windthrow event exceeded, in size and severity, all other windthrow events that occurred since the late 1800s in the Bull Run. Its spatial arrangement was altered by the disturbance regime imposed by clearcuts, one that does not reflect the natural variability of landscape structure created by other types of natural disturbances (Franklin and Forman 1987; Swanson *et al.* 1993). In particular, clearcut edge density increased steadily between the 1950s and the 1980s (Fig. 2.11), a landscape feature that has strongly influenced windthrow patterns. However, while the 1983 windthrow often occurred near the edges of 1973 salvage clearcuts, those salvage clearcuts themselves were the result of both edge- and non-edge-related 1973 windthrow. Locations with direct links between clearcut edge-related 1973 windthrow and subsequent clearcut-edge related 1983 windthrow, based on aerial photo and map interpretation, are evident only in certain portions of the watershed, such as the places in the

Figure 2.11 Amount of forest available to be windthrown and the total length of recent fire and clearcut edges by decade, 1850-2050. The forest proportions vary by decade depending on the area removed from windthrow risk by fire, clearcutting, or windthrow itself. The assumptions on which this model is based are described in Table 5.6.



northeast quadrant, where other topographic or soil variables contributed to windthrow as well.

It is not possible to say definitively whether the windthrow regime in the Bull Run has been significantly altered by forest management. The sample of storm events identified since the 1890s is not necessarily representative of the variation within the natural windthrow disturbance regime. That is, without a longer period of record, it is impossible to say whether the 1983 storm event represented a 50-, 100-, or 500-year event.

Moreover, because windthrow patterns are linked with dynamic features of the landscape such as vegetation patterns, the regimes themselves are dynamic. For example, the amount of windthrow that can occur in the landscape at any given time is not only a function of the amount of old-growth conifers located in exposed places. The overall proportion of mature and old-growth forest in the Bull Run has declined since the 1870s, yet as edge density increased, the amount of forest windthrown also increased.

The findings from this study suggest that salvage of future windthrow by clearcutting may exacerbate subsequent windthrow events in the near future, particularly in the northeastern quadrant of the Bull Run. Alternatively, the continual aging of clearcut edges may have already substantially reduced the effects of ephemeral edges on future patterns. Based on interpretation of wind and climate data, storms that were likely to have generated windthrow in the Bull Run occurred in both 1989 and 1996, and no measurable windthrow was detected in either case (Sinton 1996d, unpublished). With continued fire suppression and a cessation of harvesting activities, edge density will decrease as forests age, and future windthrow may increasingly resemble pre-logging patterns.

2.6 Conclusions

Storms created windthrow in the Bull Run watershed throughout the 20th century, and undoubtedly before. Multivariate analyses suggested that certain combinations of factors led to a higher likelihood of windthrow in predictable locations. On a broad, geographic scale, easterly winds channeled down the Columbia River Gorge funnel winds directly into the watershed, exposing trees both on windward (north and northeast facing) and lee (south and southwest facing) slopes. Persistently wet soils, resulting from perched water tables, created local zones of high windthrow risk, although the existing windthrow-hazard soils map may inadequately represent those zones. On a more local scale, clearcutting in the late 1950s through the 1970s created many new edges along which trees were highly likely to be windthrown, and salvage logging of windthrown trees from 1973 and 1983 storms established a dynamic legacy of susceptible forest edges across the landscape. However, storms since the mid-1980s have not generated significant windthrow, and trees at ephemeral opening edges may have begun to lose their vulnerability.

Broad patterns may be generalized at the landscape level, but it is not as straightforward to identify all causal factors that operate at smaller spatial scales. Unexplored factors, such as root decay, are a part of the natural variability that contributes to the overall pattern, but a study at this large spatial scale prohibits the full understanding of these factors. Moreover, linear or network canopy openings, such as those associated with streams and roads, were not considered because they fell below the minimum mapping resolution, and partial cuts, which could not be accurately mapped, may be another confounding factor.

The reconstruction of windthrow patterns over the last 100 years in the Bull Run watershed has shown that the windthrow disturbance regime is characterized by a range of event frequencies, sizes, and magnitudes. The patterns have been related to both landscape features, such as landforms, and canopy openings. However, the windthrow patterns as well as the disturbance regime itself will vary over time as many of the contributing factors are dynamic in nature.

Chapter 3

The use of GIS and spatial statistics to analyze a forest disturbance pattern

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in preparation for journal submission

3.1 Introduction

Geographic information systems (GIS) can be a useful tool for considering ecological questions on a landscape scale (Boose *et al.* 1994; Gonzalez *et al.* 1995; Powers 1995). On a basic level, a GIS enables researchers to assess the correlation among layers of digital data. A GIS can also be used to organize and prepare data for use with other software or statistical packages, a necessary step for certain analytical procedures (Goodchild *et al.* 1992a).

One particular advantage that a GIS provides for ecological analysis is its ability to maintain a georeferenced spatial data base. Many forms of ecological data are characterized by spatial autocorrelation, or the tendency for variables to be more or less similar as a function of distance (Legendre 1993). GIS-based knowledge of the geographic location of data can be used to identify and control for the presence of spatial autocorrelation among the data.

A GIS is, however, not a panacea for ecological analyses (Fotheringham and Rogerson 1993). Its generalized representation of spatial data may omit detail and dilute heterogeneity. GIS functions, such as buffering, may actually propagate errors in an analysis (Veregin 1994). Moreover, it is often the case that little is known about the source and accuracy of the data layers introduced to a GIS, and a "garbage-in, garbage-out" rule applies to any system.

This chapter describes the use of a GIS and spatial statistics to explore forest disturbance patterns. The objectives are to describe the way in which the GIS data layers were created, how it was used to provide data for both spatial and parametric statistical analyses, and how spatial statistics were utilized to assess spatial autocorrelation of the data. Detailed results from the pattern analysis are not provided in this chapter, but can be found in Sinton (1996a, unpublished).

3.2 Methods

3.2.1 Overall approach

GIS and spatial statistics were used to analyze patches of windthrow in an old-growth forest in western Oregon. The location of windthrow was mapped into a GIS and analyzed for its spatial arrangement in relation to other GIS data layers. The data were tested for spatial autocorrelation with several techniques, and later subjected to two versions of logistic regression to evaluate the importance of different landscape variables in influencing the spatial pattern of windthrow.

3.2.2 Study site

The Bull Run watershed is a 26,500 ha basin located in the northwestern corner of the Mt. Hood National Forest, in north-central Oregon at approximately 45° 30' N latitude, 122° 00' W longitude (Fig. 3.1). The watershed is the primary source of water for the city of Portland, Oregon.

3.2.3 Creation of the GIS data layers

The procedures taken to edit and modify the various data layers for the spatial analyses are shown in Fig. 3.2. Data layers were obtained from multiple sources and edited for use in univariate, bivariate, and multivariate analyses. Details on the editing of data layers and statistical procedures are described below.

Figure 3.1 Bull Run watershed study area.

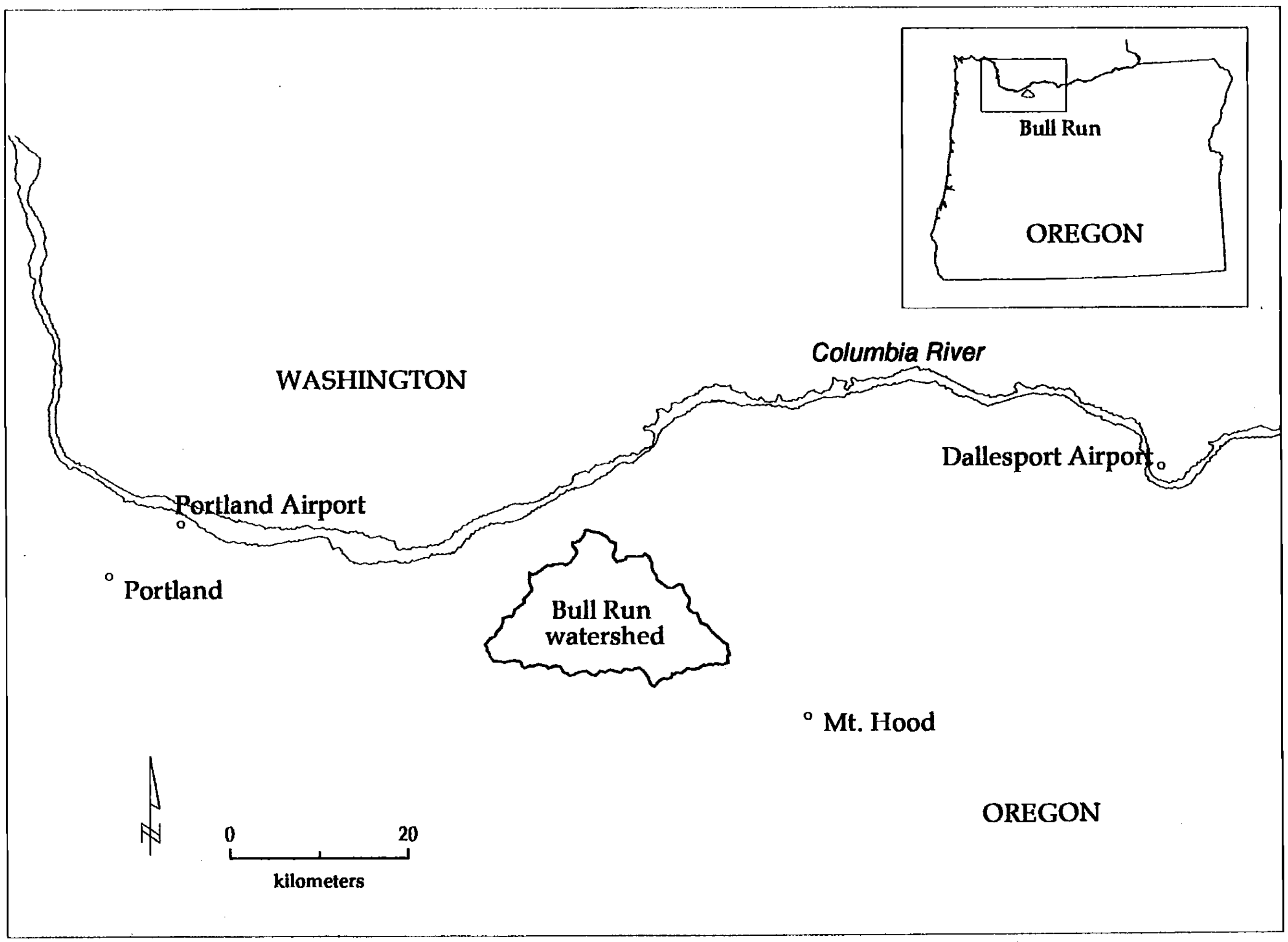


Figure 3.2 Stages in the creation of a GIS for spatial analysis in of the Bull Run watershed, Oregon.

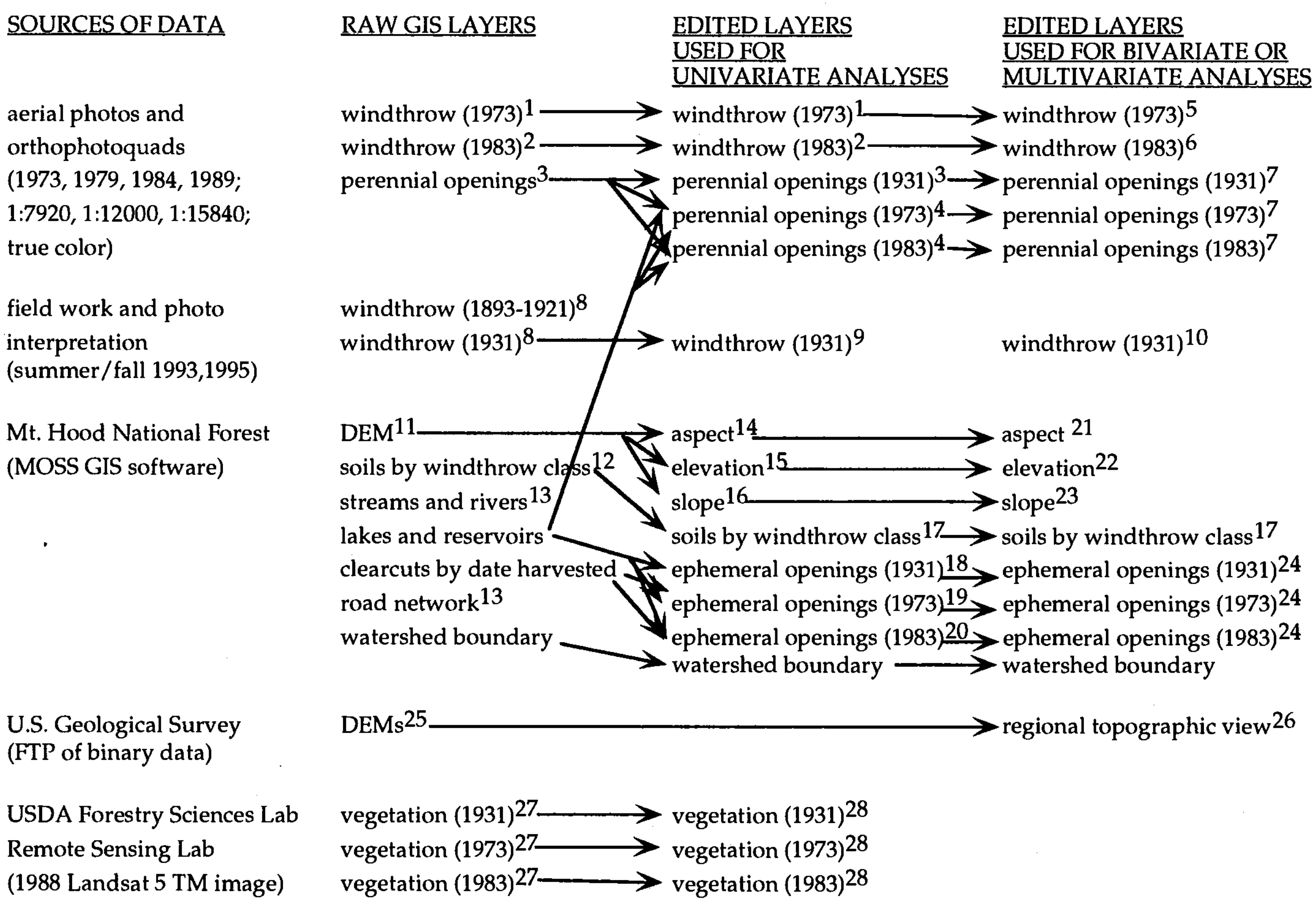


Figure 3.2 (continued) Footnotes

1 no distinction made of severity classes; mapped as points centered within a 75 m grid cell.

2 low, medium, and high severity classes; mapped as points centered within a 75 m grid cell.

3 polygons of meadows and shrub fields, talus slopes, lakes; coded as binary data (either opening or not); arcs attributed with data.

4 polygons of both perennial openings (1931) and Reservoir #1; coded as binary data (either opening or not); arcs attributed with data.

5 converted to grid cells at 75m resolution.

6 distinctions between severity removed; converted to grid cells at 75 m resolution.

7 polygons converted to grid cells at 75 m resolution.

8 mapped as points centered within a 75 m grid cell; layers not used for further analysis.

9 lower and higher severity classes; mapped as points within a 75m grid cell.

10 distinctions between severity removed; converted to grid cells at 75m resolution.

11 DEM at 30 m resolution.

12 polygons separated into four windthrow hazard classes (none, slight, moderate, severe).

13 linear coverage with features below minimum mapping unit of 75m grid cells; layer not used for further analysis.

14 nine classes (8 cardinal directions with 45° sections, plus level ground); converted to 75m resolution.

15 hundred meter intervals; converted to 75 m resolution.

16 four classes (<5°, 5-15°, 15-30°, >30°); converted to 75 m resolution.

17 all polygons converted to grid cells at 75 m resolution; cells remain separated into four windthrow hazard classes.

18 Reservoir #1; arcs attributed with data.

19 clearcuts made through 1972 plus Reservoir #2; arcs attributed with data.

20 clearcuts made through 1983 plus Reservoir #2; arcs attributed with data.

21 four classes of 90° each (NE, SE, SW, NW) still at 75 m resolution.

22 three classes of low, medium, high elevational ranges (< 700 m, 700-1000 m, > 1000 m); still at 75 m resolution.

23 two classes (< 15° or > 15°); still at 75 m resolution.

24 all polygons buffered by 150 m and then converted to grid cells at 75 m resolution; coded as binary data (either opening or not).

25 DEM of Vancouver-e and The Dalles-w, Oregon and Washington; at XX m resolution.

26 DEM of areas surrounding Bull Run watershed; approximately 75 km^2 at 75 m resolution.

27 Landsat 5 TM data of 1988 image at 25 m resolution; classified by W. Cohen; nine original classes (water; ice/snow; shadow; open (< 30% cover); semi-open (30-85% cover, non-conifer); closed canopy (> 85% cover, non-conifer); young conifer (< 80 y.o.); mature c onifer (80-200 y.o.); old-growth conifer (> 200 y.o.).

28 reclassified by D. Sinton at 75 m resolution; nine updated classes (water; clearcuts; shadow; perennial openings; semi-open and non-conifer; closed canopy and non-conifer; young conifer; mature conifer; and old-growth conifer).

3.2.3.1 Hardware/software used

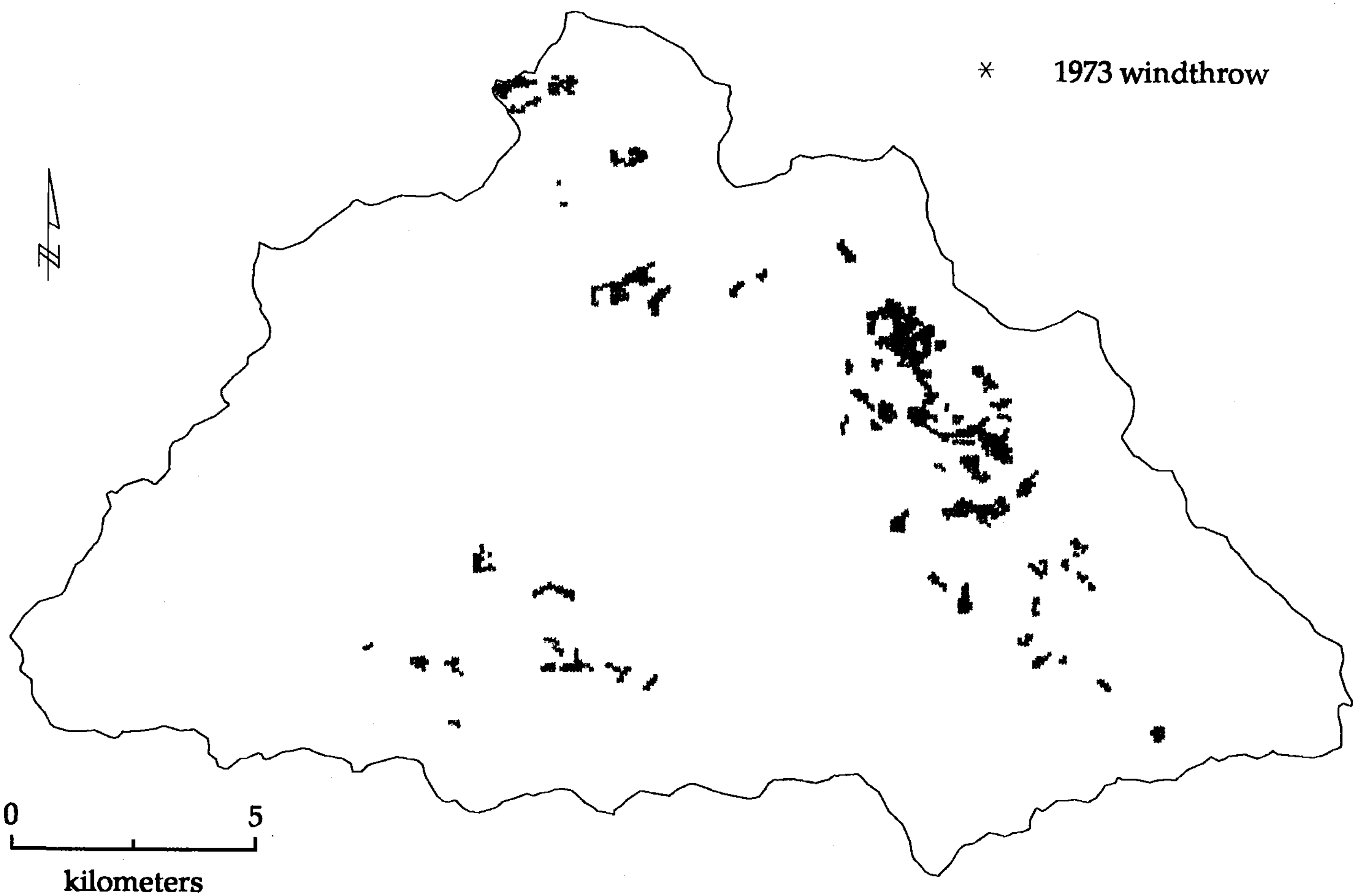
Arc/Info (Versions 6.0 and 7.0.1) and ERDAS (Version 7.5) were used on SUN SPARC workstations at the U. S. Forest Service's Pacific Northwest Research Forestry Sciences Laboratory (FSL) in Corvallis, Oregon. Computer programs written in C language (FRAGSTATS, Vgram, and Distance; each to be described in detail later) were used in a UNIX system on the same SUN workstations. Excel (versions 3.0 and 4.0) was used on Macintosh personal computers for spreadsheet analysis and production of tables, and figures. Additional figures were produced with Canvas (version 3.5.3), and with Arc/Info. For the statistical analysis, SAS (Release 6.10) was used on an IBM compatible personal computer at FSL.

3.2.3.2 Layers derived from aerial photo interpretation

The location of windthrow from a January 1973 storm was mapped with the use of air photos (1:7920, true color) taken in February 1973. A 0.6 cm mylar grid was overlaid on each photo, and a single point was marked in the center of the grid-cell if windthrow were present in that area. Each point was later marked onto mylar over orthophotoquads (1:12000, enlarged from 1:40000 photography) and digitized to create a 1973 windthrow data layer (Fig. 3.3). Each point represents what would be approximately a 75 x 75 m (0.56 ha) area on the ground, based on the 1:12000 scale orthophotoquads. The 1973 windthrow was not classified by severity because snow coverage and oblique sun angles on the aerial photos limited the accuracy with which the windthrow could be mapped.

Patches of windthrow from a storm in December 1983 were interpreted from air photos (1:12000, true color) taken in July 1984. The severity of windthrow was determined by assessing the amount of tree canopy that had been removed in each 75 x 75 m area. Windthrow was grouped into three severity classes: low (< 30% canopy removed); medium (30-70% canopy removed); and high (> 70% canopy removed). Points of different colors (to distinguish the severity classes) were marked in the center of the 0.6 cm mylar grid that was overlaid on the air photos. These were transferred to mylar over

Figure 3.3 Windthrow in the Bull Run watershed, 1973 storm.



the orthophotoquads and digitized to create a 1983 windthrow data layer (Fig. 3.4).

A third GIS data layer that was created with aerial photographs depicted naturally-occurring, perennial openings in the forest canopy, such as meadows, shrub fields, talus slopes, and lakes. Two versions were created, one to represent the perennial openings in 1931 (Fig. 3.5), and one that covered both 1973 and 1983 (Fig. 3.6). All openings that were known to be at least 25-years-old were included in this data layer. For example, Reservoir #1, created in 1927, was marked as a perennial opening on the 1973 and 1983 versions, but not on the 1931. All openings were traced onto mylar over the orthophotoquads and digitized into the GIS.

3.2.3.3 Layers derived from aerial photo interpretation and field work

Windthrow that occurred prior to the 1970s was identified indirectly. Air photos from July 1984 (1:12000, true color) and June 1979 (1:15840, true color) were used to locate stands dominated by certain tree species (western hemlock, *Tsuga heterophylla*; and Pacific silver fir, *Abies amabilis*) in the overstory canopy that are regularly found as understory, shade tolerant trees. Their presence in the overstory can be the result of a disturbance that removed the previous overstory canopy. Verification of a windthrow disturbance was made only after each stand was visited and the presence or absence of windthrown trees, lying in the same direction and usually decay-resistant Douglas-fir (*Pseudotsuga menziesii*), was observed.

To determine the date of the windthrow event, cores were extracted from current overstory trees and examined for a pattern of abrupt and sustained increase in the width of the annual rings. A growth release often indicates the year in which the tree suddenly experienced a change in the light regime and growing conditions, i.e. the year when the wind storm removed the shading effects of the taller overstory. Windthrow was attributed to a particular year, or a range of up to 3 years, when one single year could not be determined.

Once a stand was identified as having experienced windthrow and a date or range of possible dates for the event was determined, it was mapped into the GIS with the grid-cell method described above. Patches of windthrow from pre-

Figure 3.4 Windthrow in the Bull Run watershed, 1983 storm.

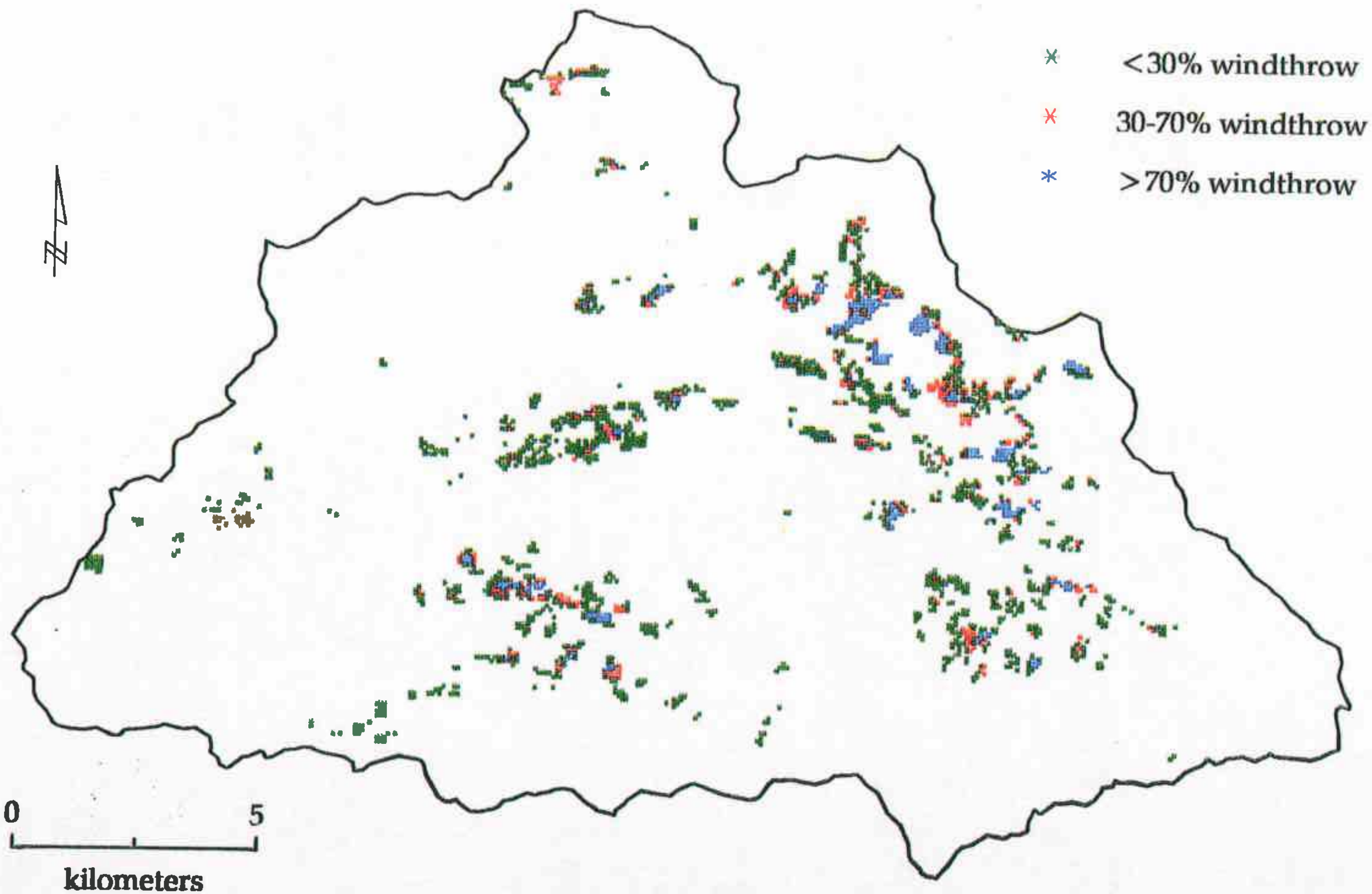


Figure 3.5 Perennial openings in the Bull Run watershed, 1931.

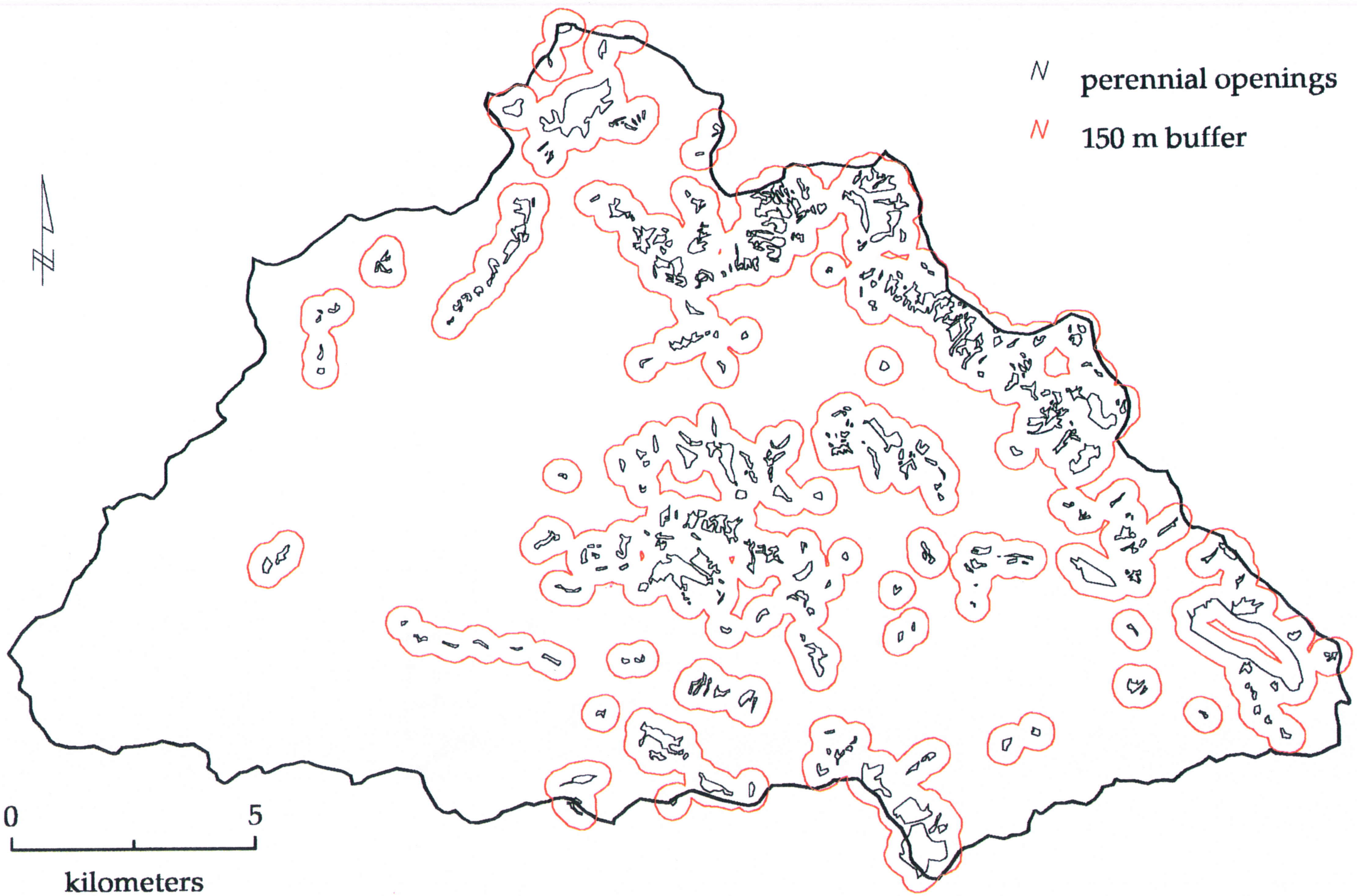
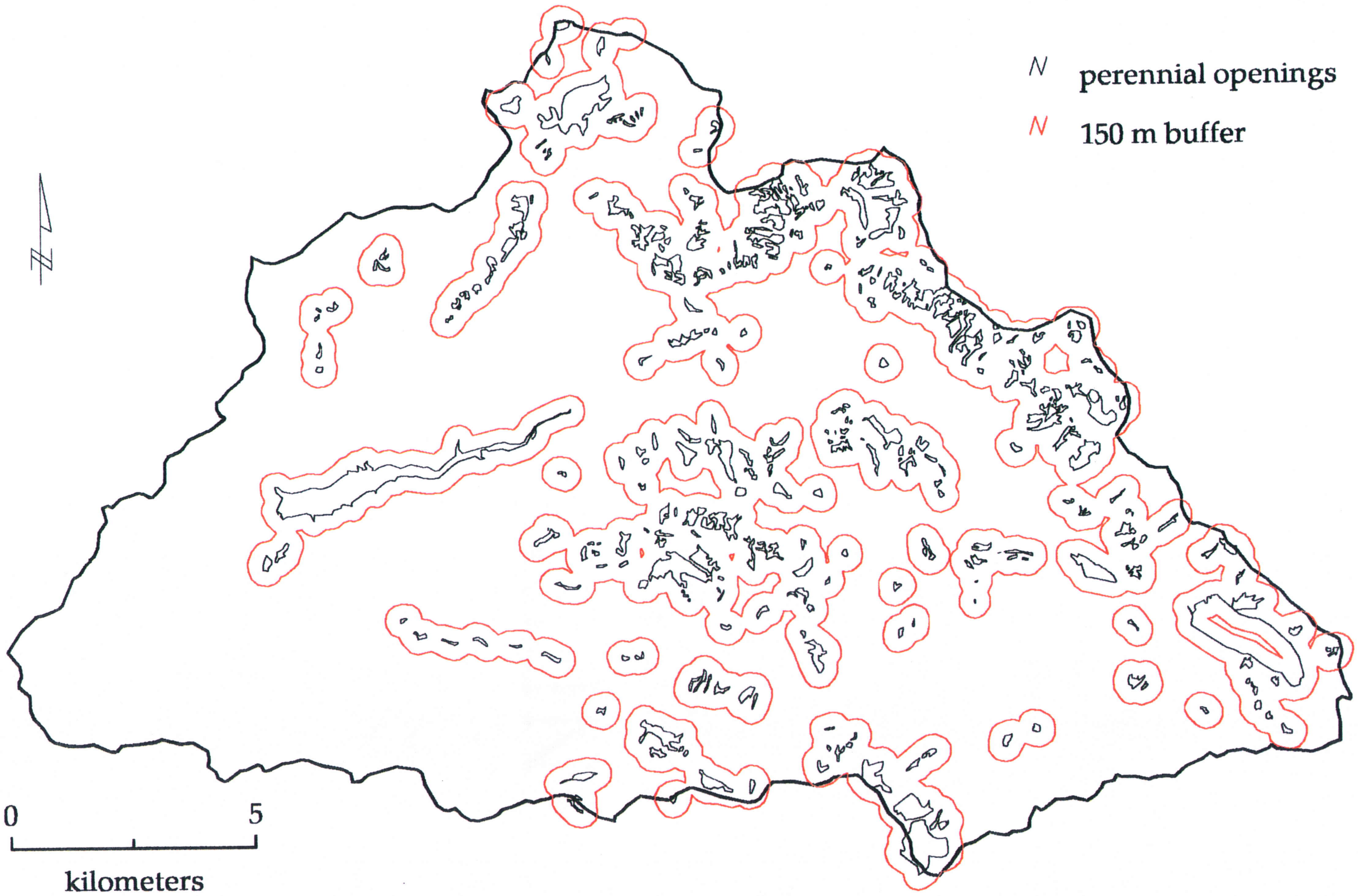


Figure 3.6 Perennial openings in the Bull Run watershed, 1973 and 1983.



1970s' storms were mapped to correspond with the geographical extent of the pacific silver fir or hemlock stand, as seen on the air photos and orthophotoquads (Fig. 3.7).

3.2.3.4 Layers inherited from other sources

The Mt. Hood National Forest (MHNF) provided digital data from their GIS. The data had been generated with MOSS software and was converted for use with Arc/Info. For analytical and display purposes, only the area within the physical drainage basin of the Bull Run watershed was used, although data covering the entire Mt. Hood National Forest was provided. The layers received from the MHNF included:

1) a DEM of the Mt. Hood National Forest at 30-m resolution;
2) the road network (Fig. 3.8);
3) the hydrologic network (Fig. 3.9);
4) the clearcuts and the years in which they were cut (Fig. 3.10);
5) the soils classified by "windthrow hazard" (Fig. 3.11);
6) the watershed boundary.

File transfer protocol (FTP) was used to obtain digital DEM data of two quadrangles (Vancouver-east and The Dalles-west) from the U. S. Geological Survey. The data were converted to GRID coverages in Arc/Info. These were used to generate a data layer showing a topographic view of the region surrounding the Bull Run watershed (Fig. 3.12).

The PNW Forestry Sciences Lab in Corvallis, Oregon, provided a 1988 TM satellite image of western Oregon that had been analyzed and classified with Erdas (Version 7.5) software (Cohen *et al.* 1995). This image covered the Bull Run watershed at 25-m resolution.

Figure 3.7 Windthrow in the Bull Run watershed, 1890 - 1931 storms.

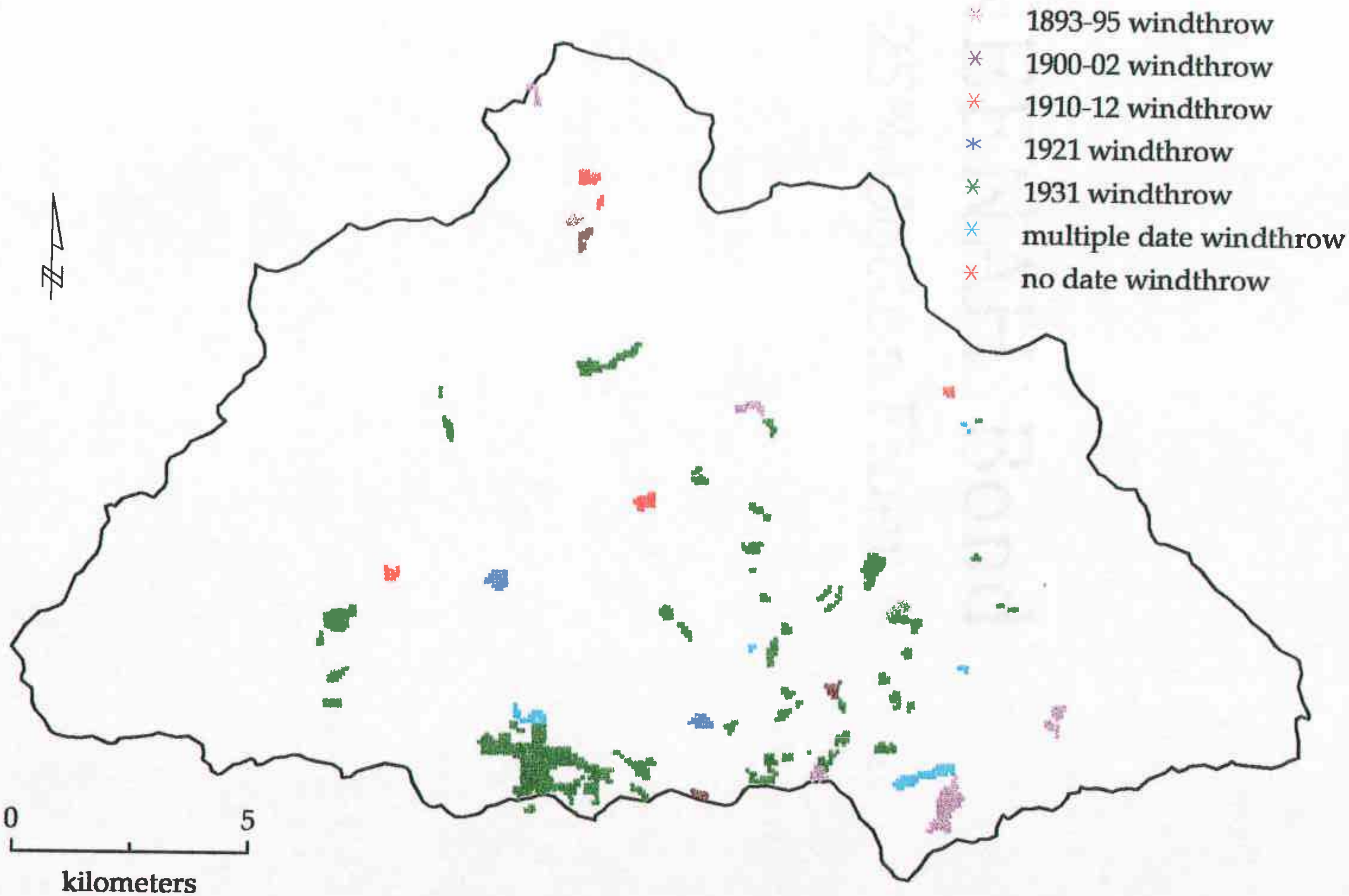


Figure 3.8 Road network in the Bull Run watershed.

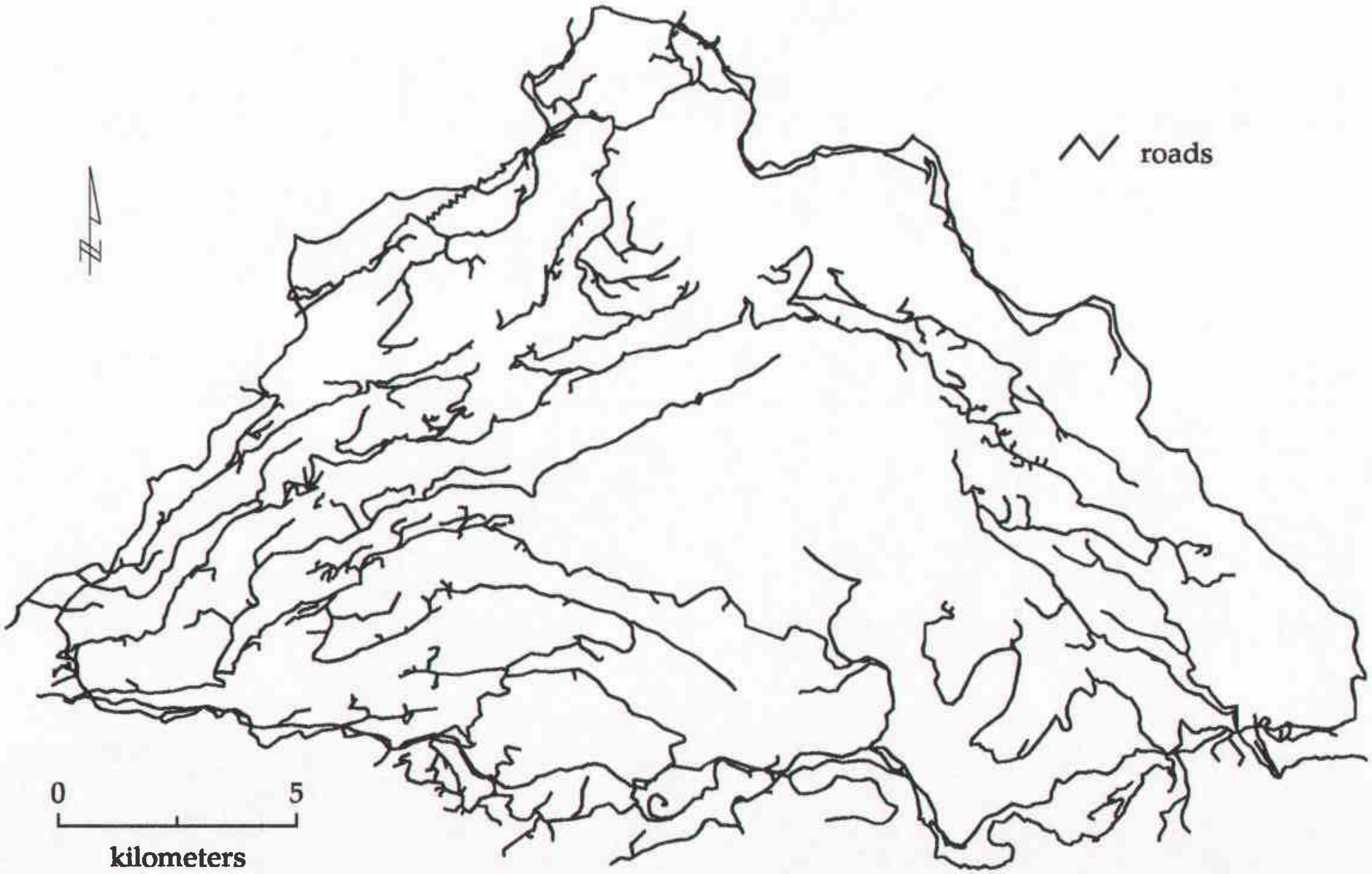


Figure 3.9 Hydrologic network in the Bull Run watershed.

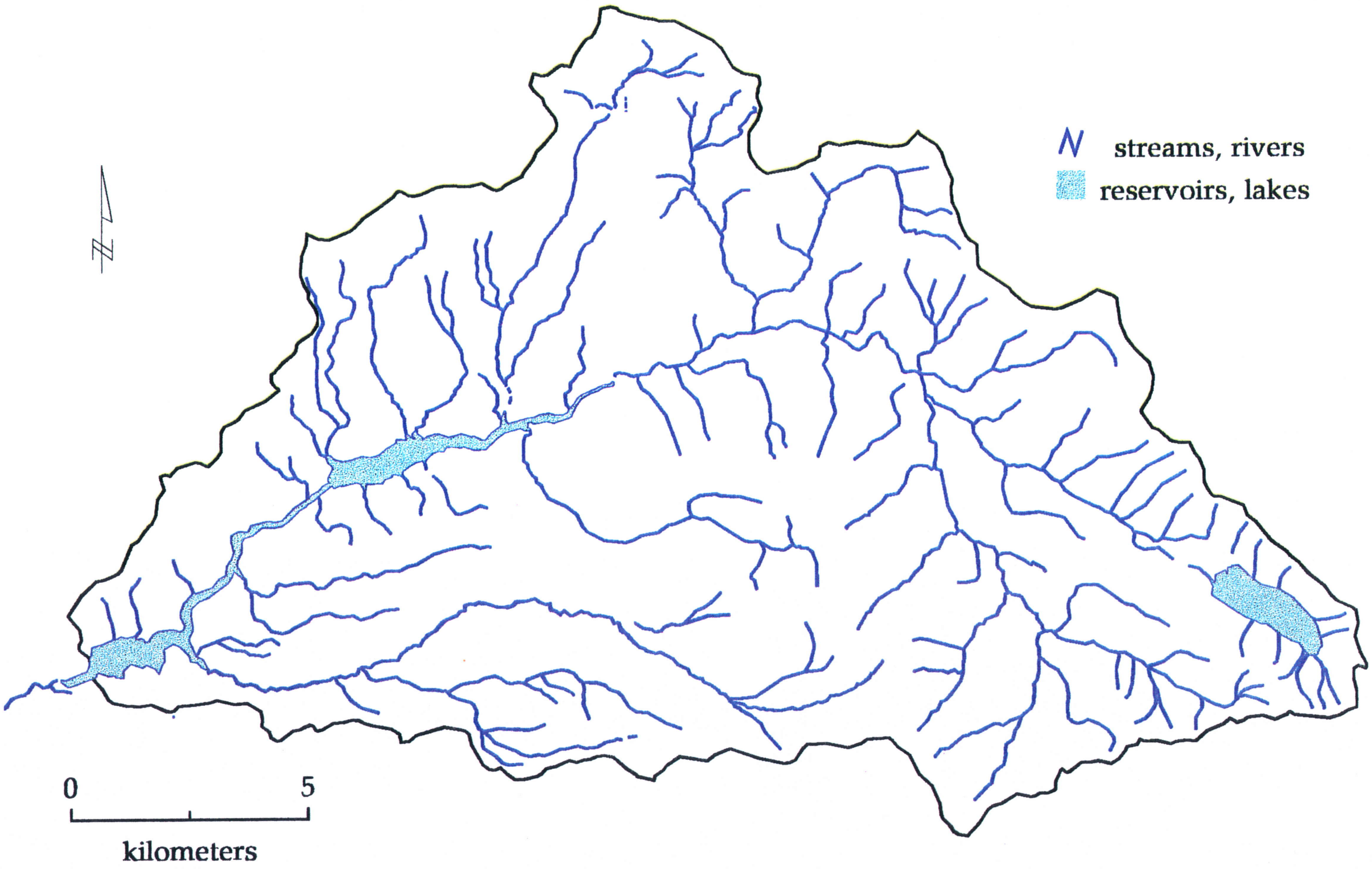


Figure 3.10 Clearcuts in the Bull Run watershed, 1958 - 1993.

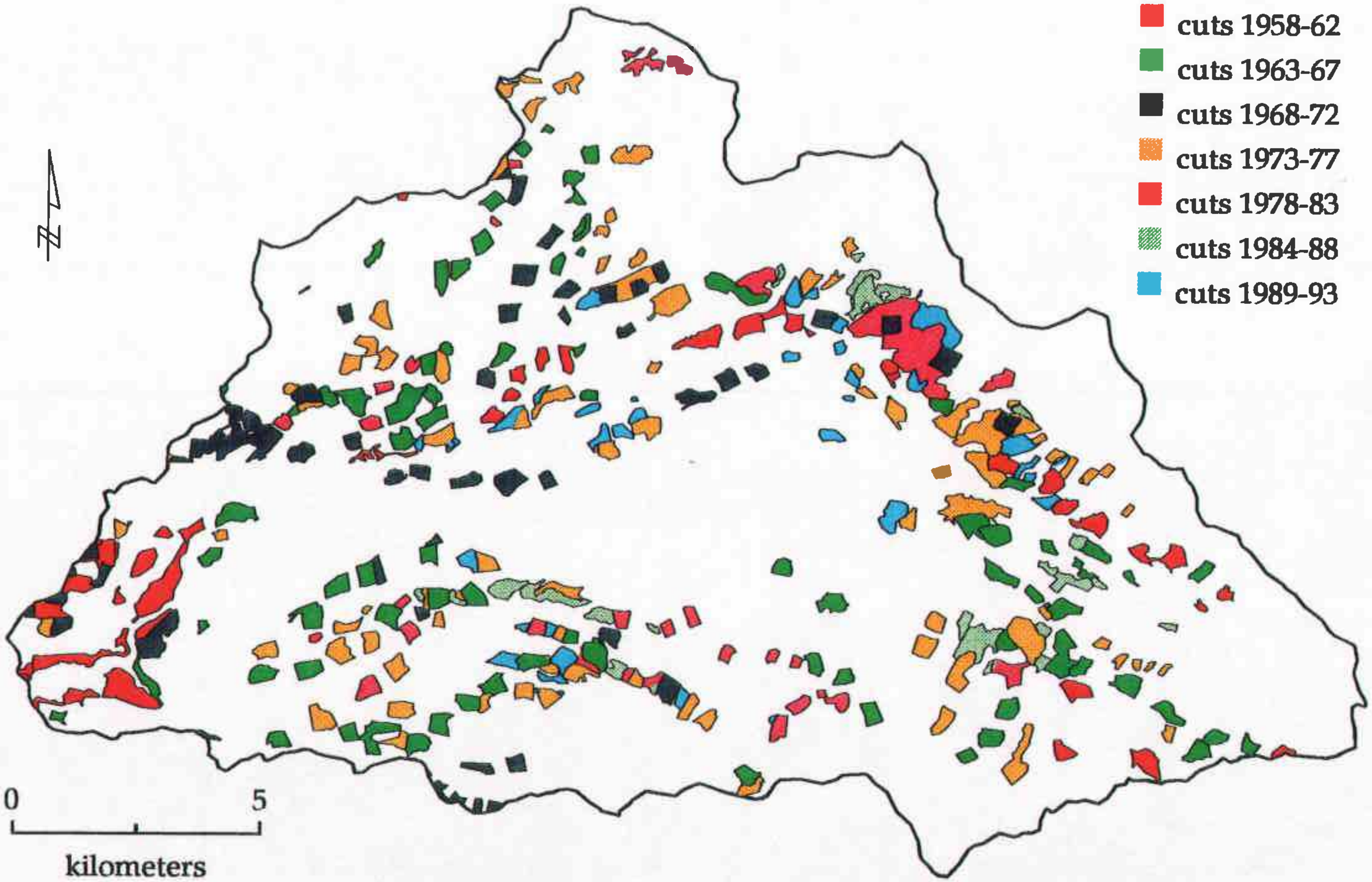


Figure 3.11 Windthrow hazard of soils in the Bull Run watershed.

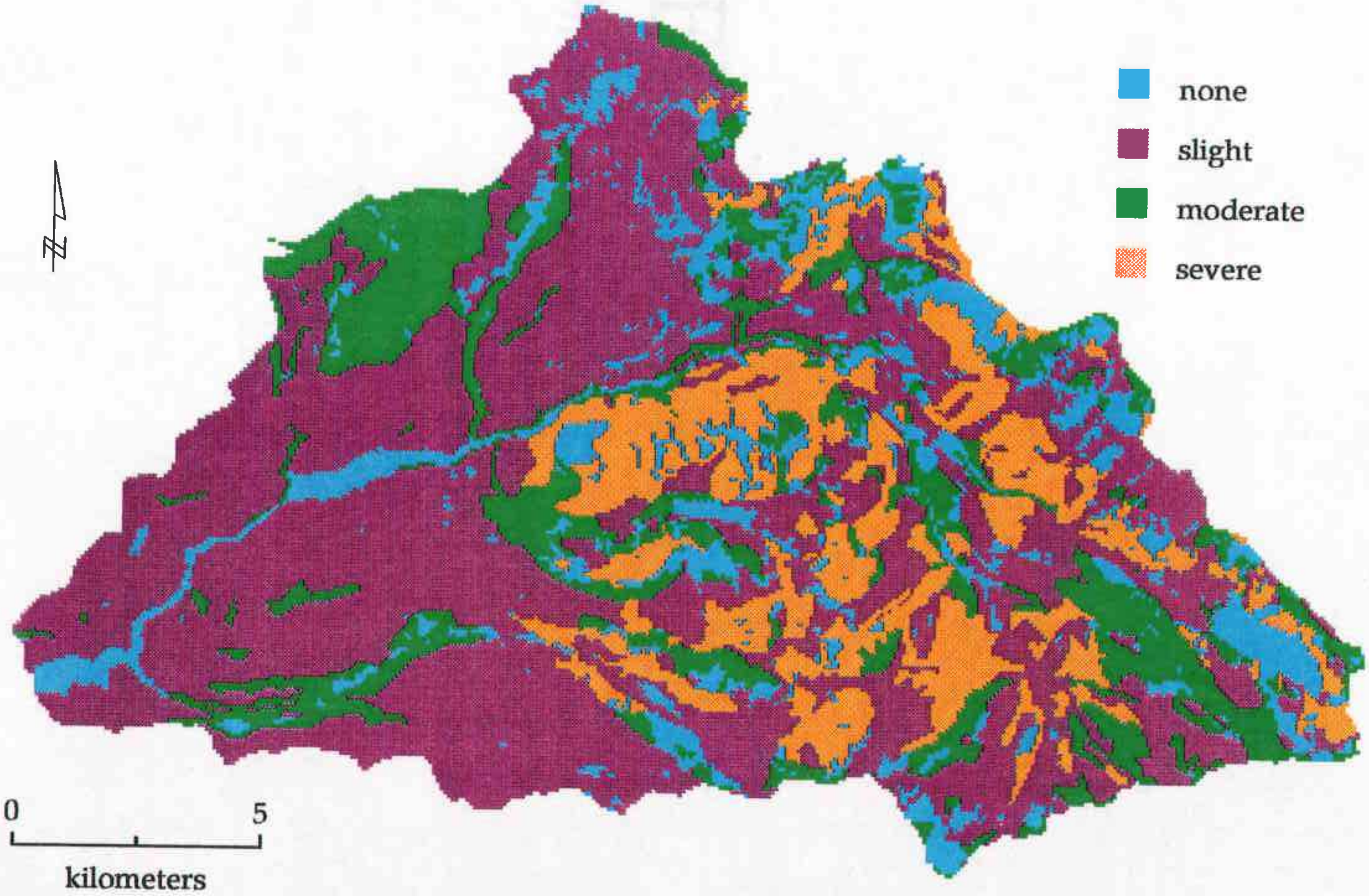
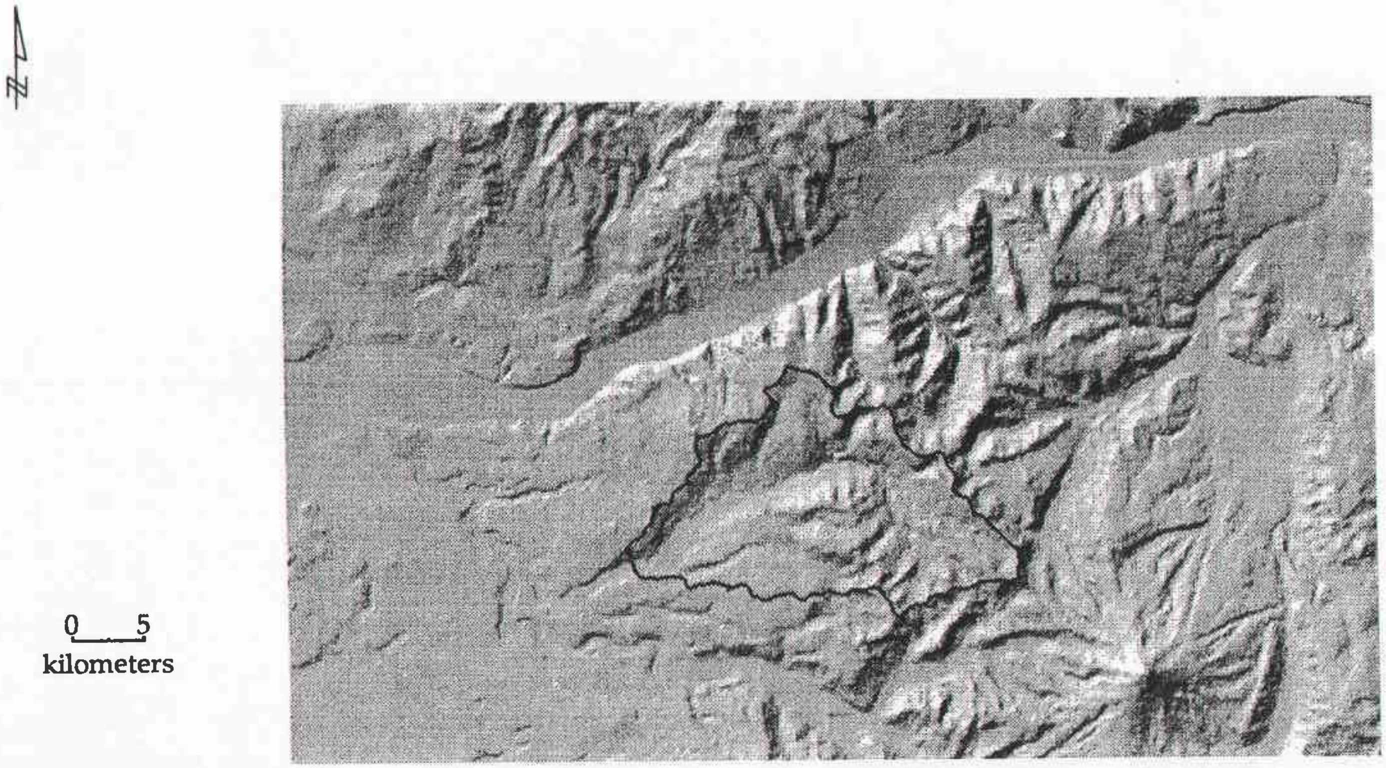


Figure 3.12 Regional topography surrounding the Bull Run watershed.



3.2.4 Procedures used to edit data layers

3.2.4.1 windthrow layers

For statistical analyses, the point coverages of windthrow from 1973, 1983, and the pre-1970s were converted to grid coverages at 75-m resolution. From the pre-1970s data, the 1931 windthrow pattern was selected for comparison with the later storm patterns as it was the most extensive storm from the pre-logging period. When creating grid coverages, the 1931 and 1983 windthrow severity classes were disregarded so that windthrow could be considered a binary response variable (windthrow or not) for the logistic regressions.

3.2.4.1 aspect/elevation/slope layers

In Arc/Info's GRID, the DEM from the Mt. Hood was degraded from 30 m to 75 m resolution to correspond with the windthrow resolution. The DEM was then used as input to create data layers showing the Bull Run watershed divided by aspect into eight cardinal directions (Fig. 3.13); elevation at 100-m intervals (Fig. 3.14); and slope angle in degrees (Fig. 3.15).

For the logistic regressions only, the aspect, elevation and slope angle data layers were collapsed to create fewer categories of data and maximize the available degrees of freedom. The aspect data layer was recalculated from eight 45° groups (N, NE, E, SE, etc.) into four 90° groups (NE, SE, SW, and NW). The elevation layer was converted from 13 classes of 100 m each (200 m to > 1400 m) to three classes 200-599 m, 600-999m, and > 1000 m). The slope data layer was changed from four classes (< 5°, 5-15°, 15-30°, and > 30°) to two classes (<= 15° and > 15°).

Figure 3.13 Aspect in the Bull Run watershed.

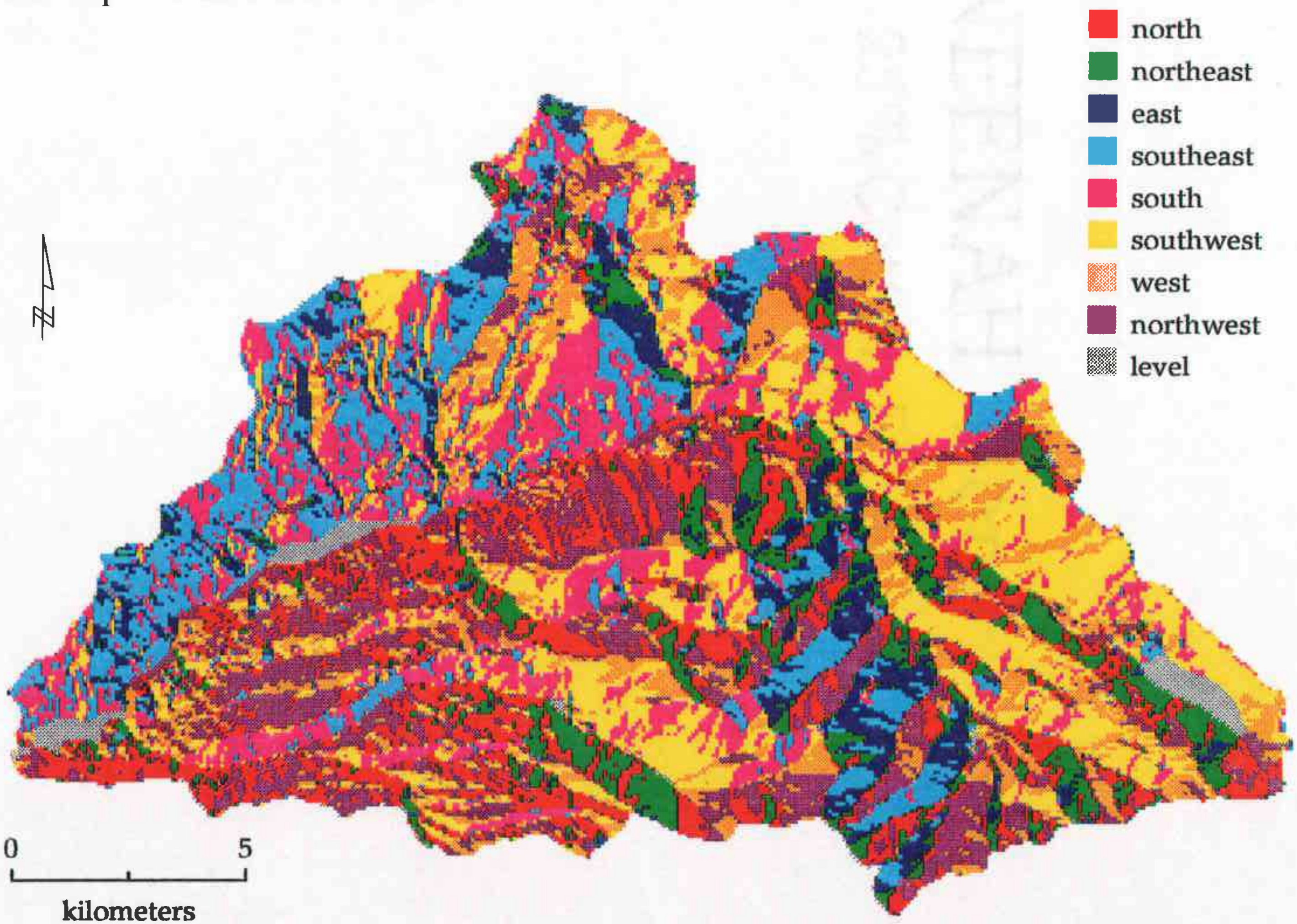


Figure 3.14 Elevation in the Bull Run watershed.

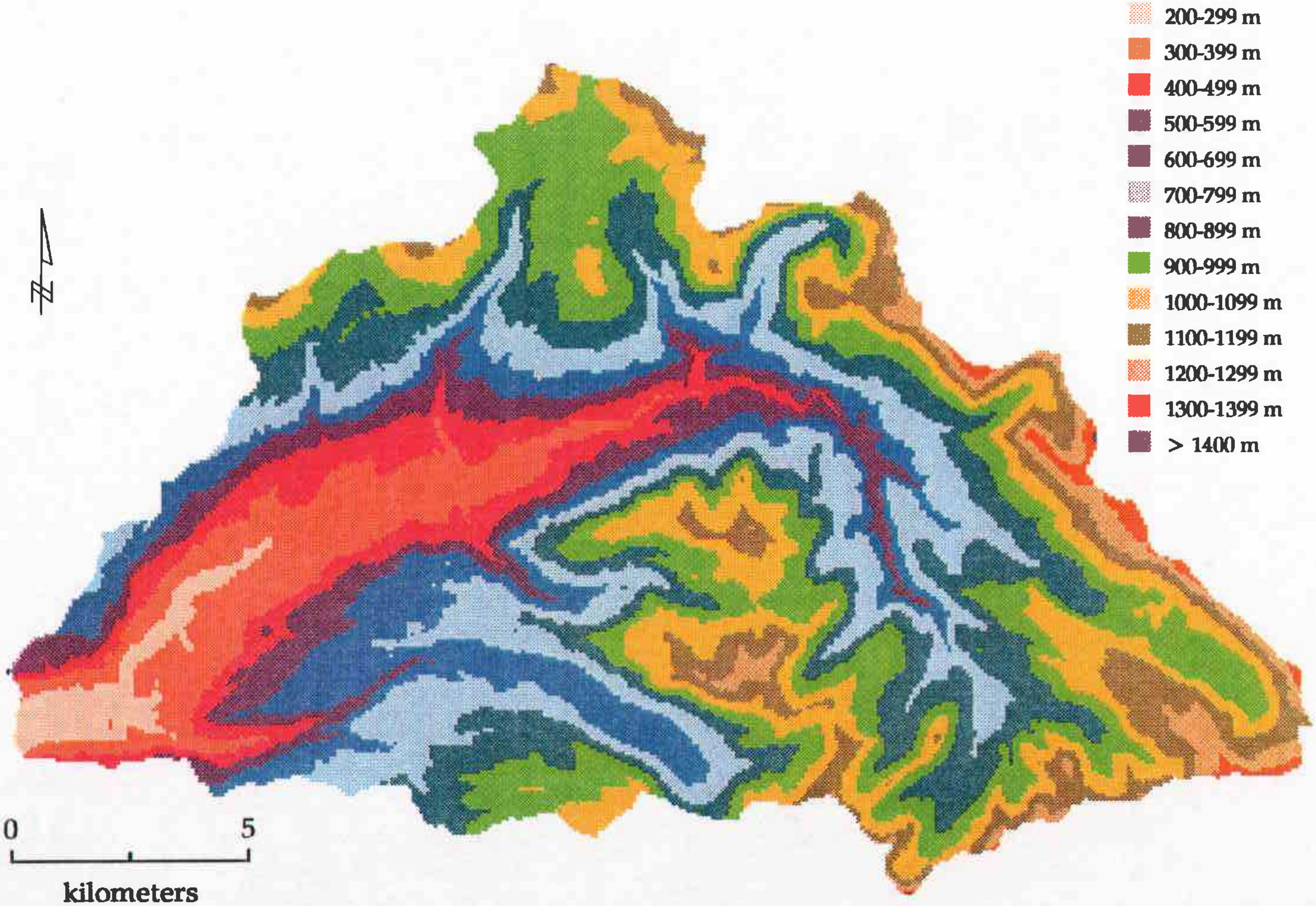
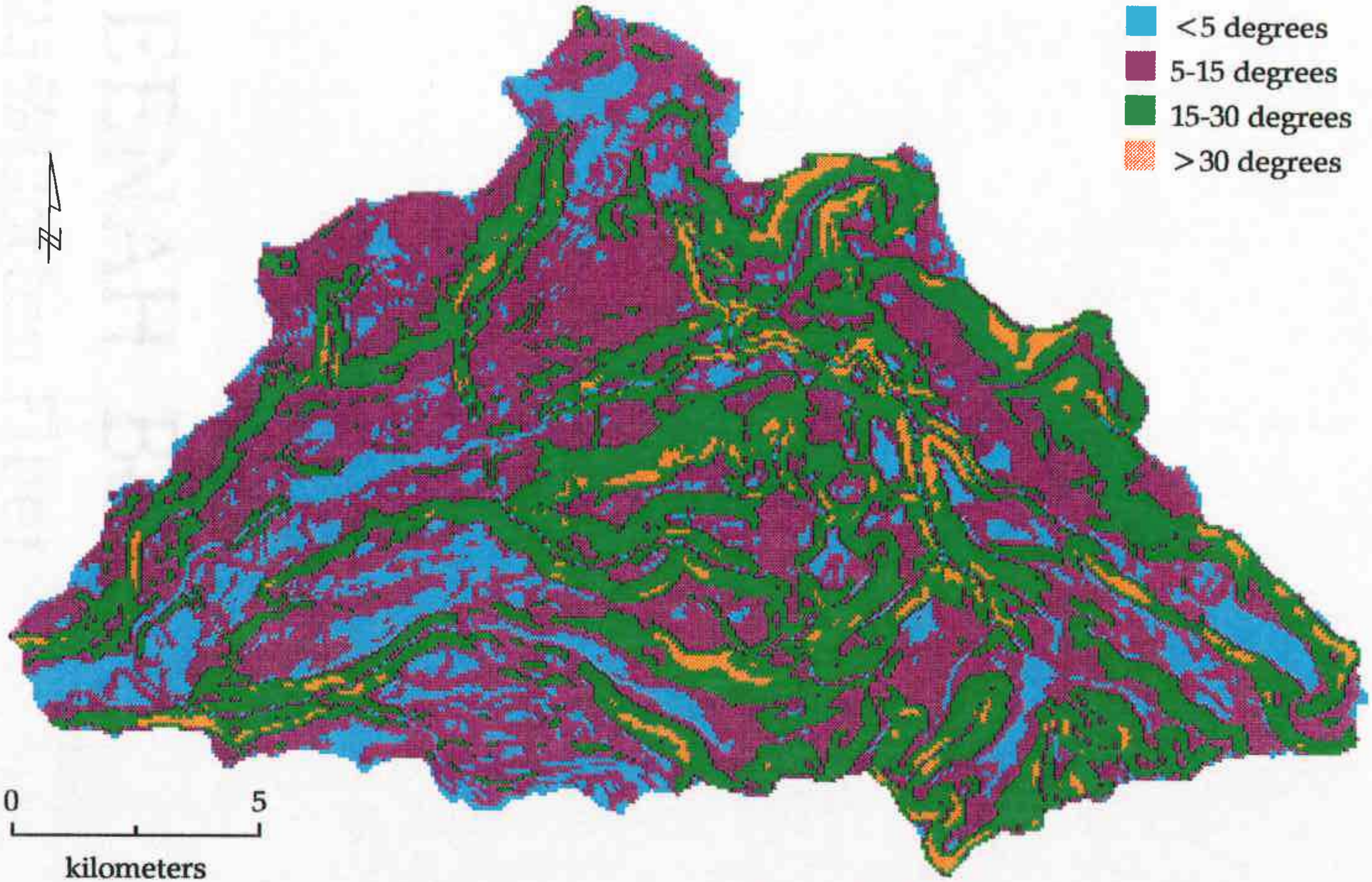


Figure 3.15 Slope angle in the Bull Run watershed.



3.2.4.2 soils layer

The polygon layer showing windthrow hazard in four classes (none, slight, moderate and severe) was converted to a grid coverage at 75-m resolution. No changes were made to the classification itself, which was based on soil characteristics that would influence a tree's rooting ability (U.S.D.A. Forest Service 1964).

3.2.4.3 vegetation layers

The nine vegetation classes originally designated by Cohen *et al.* (1995) were altered to correspond better with information needed for a spatial analysis of windthrow (Fig. 3.16). Several classes of data were eliminated (ice/snow, open < 30% cover) and others were introduced (perennial openings, clearcut openings). From the original 1988 classified image, data layers were created that were representative of vegetative conditions prior to the three storm events. For example, to change the original 1988 image to represent 1983 conditions, clearcuts made in the intervening years were "regrown." A polygon image of clearcuts dating prior to December 1983, obtained from the Mt. Hood National Forest, was overlaid on the 1988 vegetation layer using Erdas's DISPOL and cell values were changed, with GISEDIT, to old-growth. A 3x3-window-type filtering process (Erdas SCAN) smoothed the final image. This procedure used the majority value for the nine cells and replaced the central cell with that value. Once the reclassification and smoothing was complete, the 1983 vegetation layer was converted from Erdas format to an Arc/Info grid coverage for display and analysis (Fig. 3.17).

These procedures were repeated to generate 1931 and 1973 vegetation layers (Figs. 3.18 and 3.19). For the 1931 layer, the area currently covered by Reservoir #2 (created in 1964) was reclassified as old-growth, as were all clearcut openings for both the 1931 and 1973 vegetation layers. An additional change to the 1931 vegetation layer involved reclassifying some areas of mature conifer as young conifer, reflecting the location of fire events known to have occurred between 1870 and 1930 (Krusemark *et al.* 1996).

Figure 3.16. Changes made to a 1988 Landsat 5 TM satellite image to create vegetation data layers for 1931, 1973 and 1983 conditions.

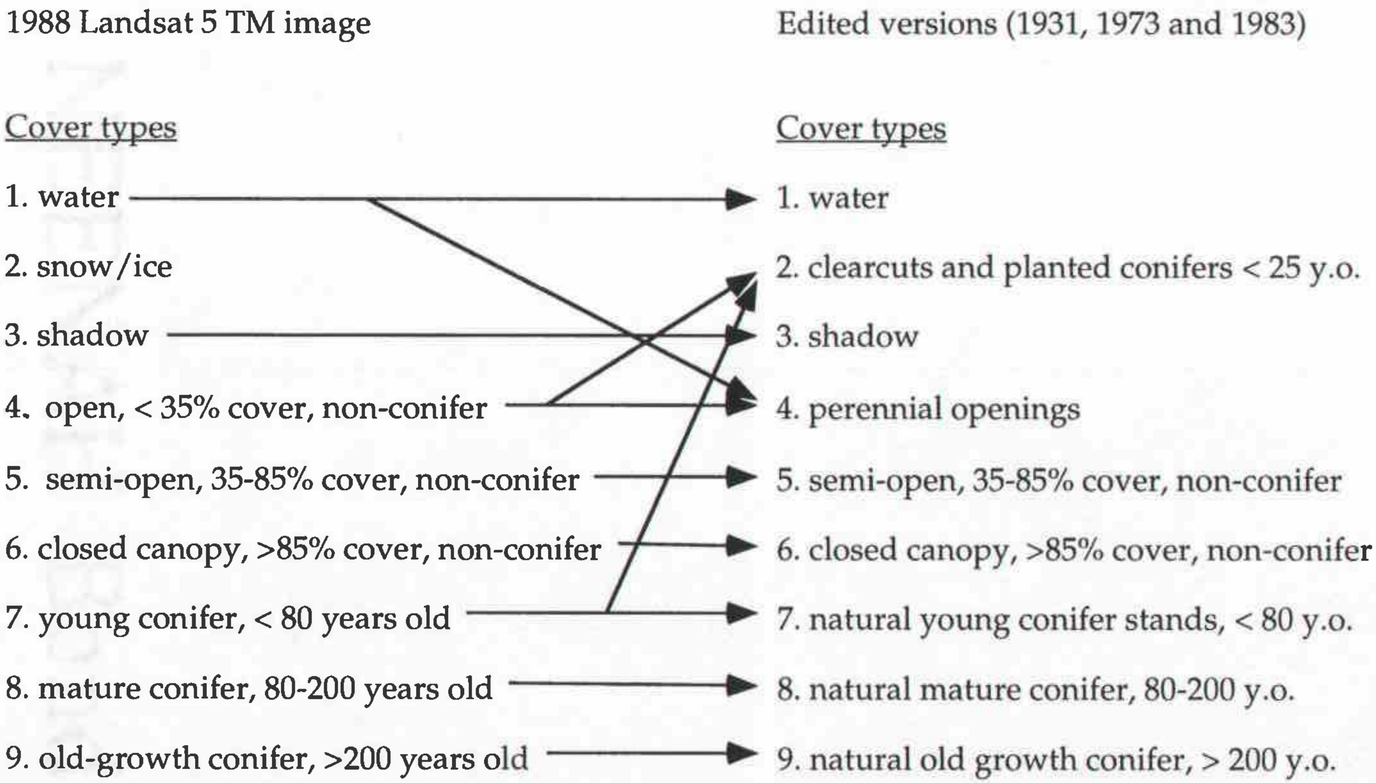


Figure 3.17 Vegetation in the Bull Run watershed, 1983.

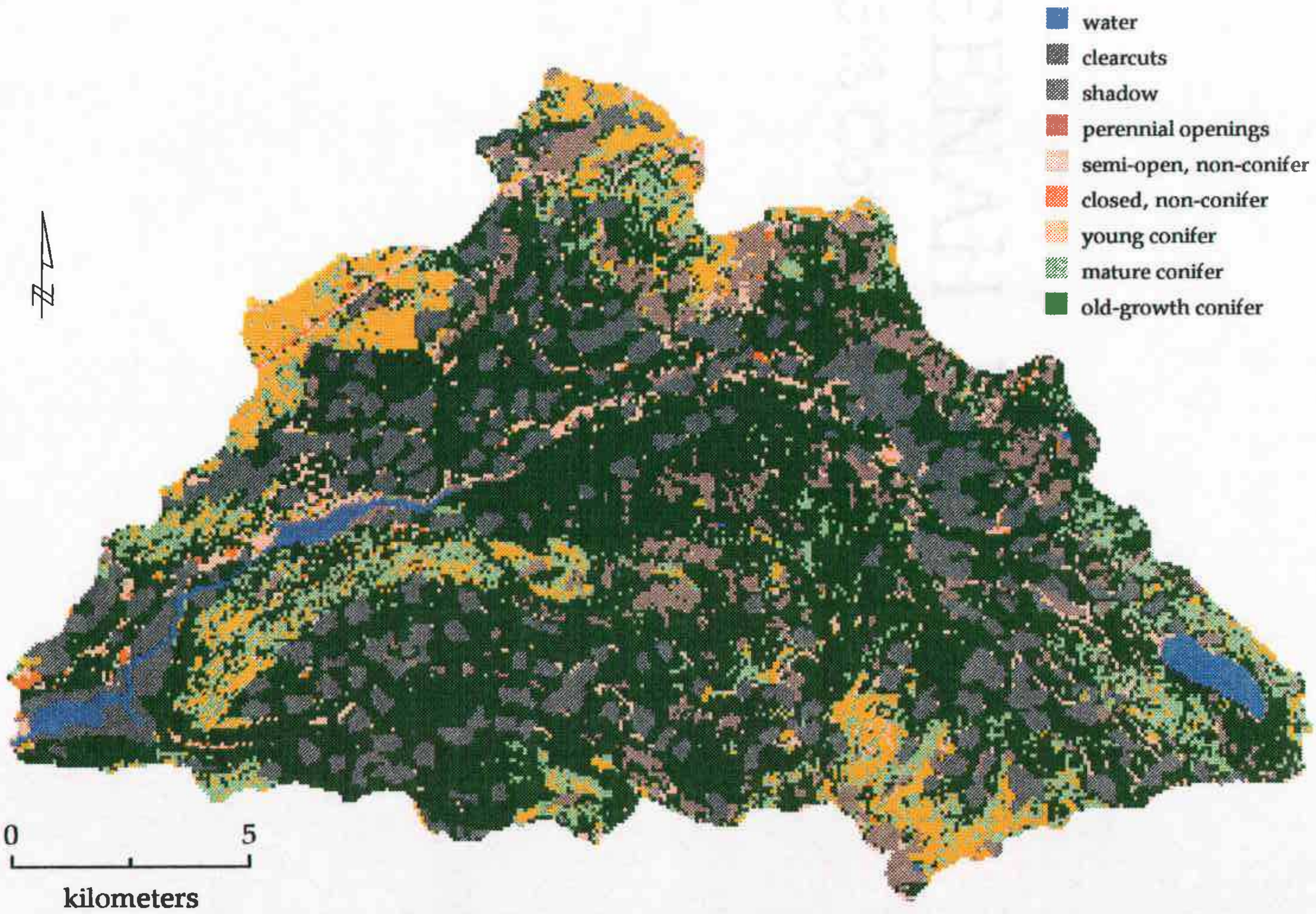


Figure 3.18 Vegetation in the Bull Run watershed, 1931.

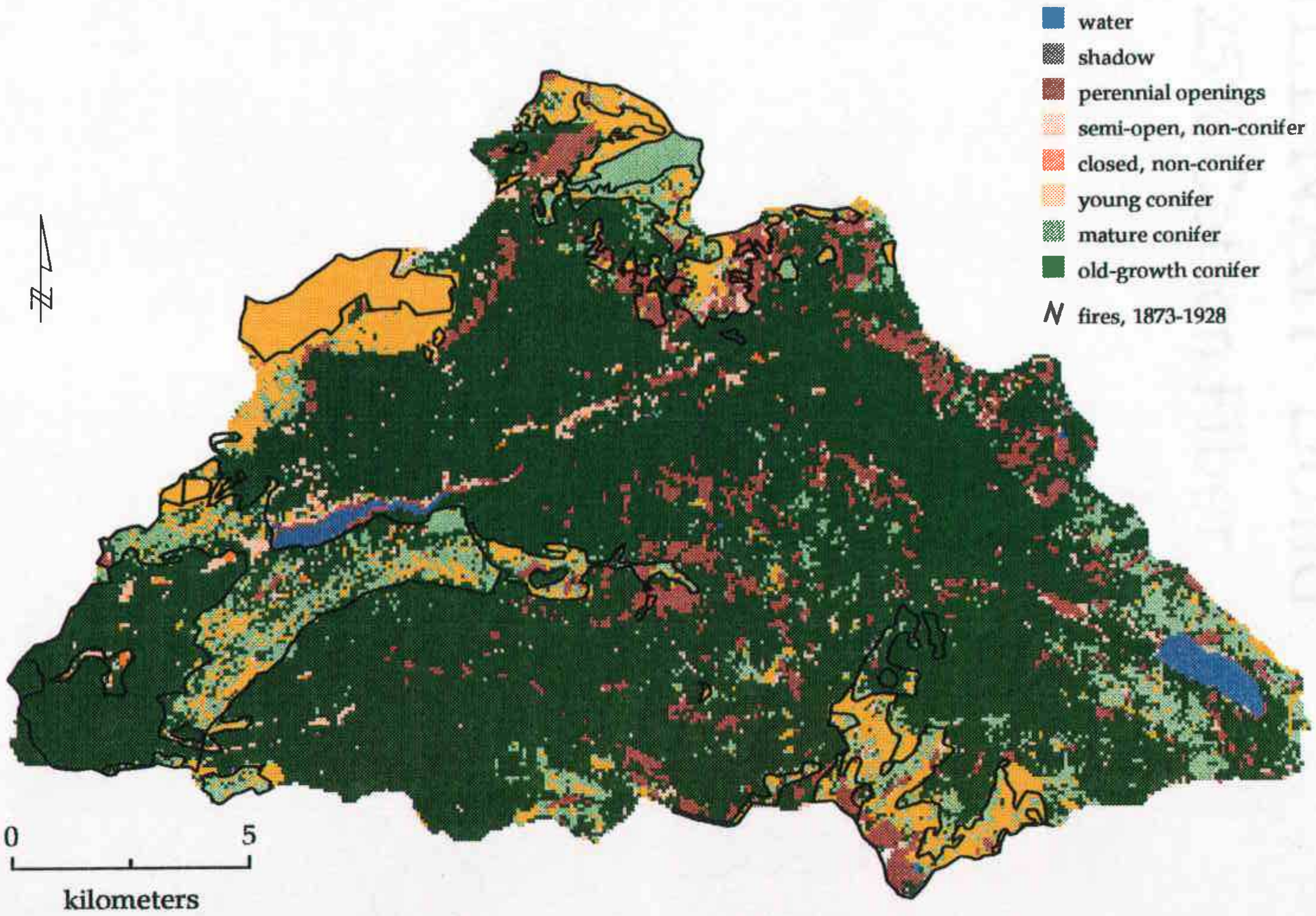
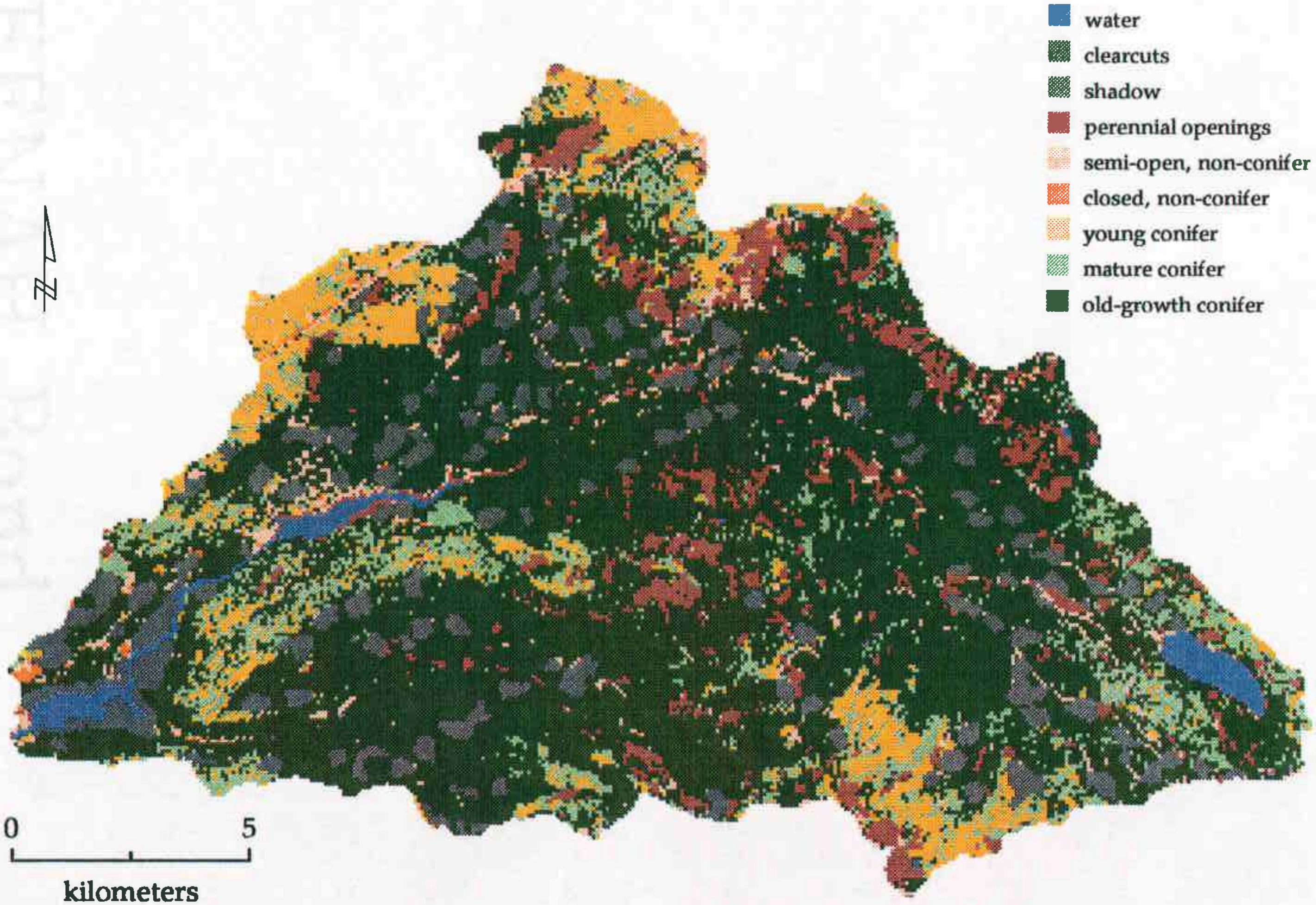


Figure 3.19 Vegetation in the Bull Run watershed, 1973.



In GRID, the vegetation data layers were degraded from 25 m to 75 m resolution to correspond with the windthrow resolution.

3.2.4.4 ephemeral and perennial openings layers

To evaluate the role of patch-type openings in influencing the distribution of windthrow, all openings were divided into two types: ephemeral (clearcuts and reservoirs, all less than 25 years old) and perennial (meadows, lakes, talus slopes, reservoirs and clearcuts > 25 years old, etc.) (Table 3.1). This step was repeated for each storm year: 1931, 1973 and 1983. The ephemeral openings layers are shown in Figs. 3.20-3.22, and perennial opening layers were described and shown earlier. The 75-m resolution for all grid-based data layers precluded the use of linear openings, such as streams or roads, in an analysis.

For the bivariate and multivariate analyses, all ephemeral and perennial opening edges were buffered by 150 m, and the resulting polygon coverages were converted to grid coverages at 75-m resolution. Windthrow that fell within the buffered zone was considered to have been affected or influenced by the edge. Different buffer widths were considered, and 150 m was selected as the best width for estimating edge-related windthrow.

To buffer openings, the edges of openings were selected and buffered as lines (arcs), rather than the opening as a whole (polygon), in order to mitigate the displacement errors associated with point features (windthrow) that fell along one or another side of a linear feature (the edge of an opening). This technique compensated both for windthrow that had been inadvertently mapped as located slightly inside the opening, as well as mapping errors associated with subjective digitizing of clearcut edges.

3.2.5 Univariate spatial pattern analysis procedures

To ascertain if the data layers were spatially autocorrelated, each gridded-format data layer was run through the following GRID programs: 1) Geary, to calculate the Geary's c coefficient; 2) Moran, to calculate the Moran's I coefficient;

Table 3.1 Distinctions between ephemeral and perennial patch openings in the Bull Run watershed. All openings in the forest canopy are divided into two classes: ephemeral and perennial, based on their age. Ephemeral openings are 25 years old or less; perennial openings are more than 25 years old. This distinction is made to evaluate the amount of time that trees near the openings would have been exposed to wind. The classifications are shown for the three years in which windthrow was analyzed (1931, 1973 and 1983).

openings	ephemeral	perennial
Reservoir #1 (1927)	1931	1973, 1983
Reservoir #2 (1964)	1973, 1983	
clearcuts (1958-72)	1973, 1983	
clearcuts (1973-83)	1983	
meadows		1931, 1973, 1983
talus slopes		1931, 1973, 1983
shrub fields		1931, 1973, 1983
lakes		1931, 1973, 1983

Figure 3.20 Ephemeral openings in the Bull Run watershed, 1931.

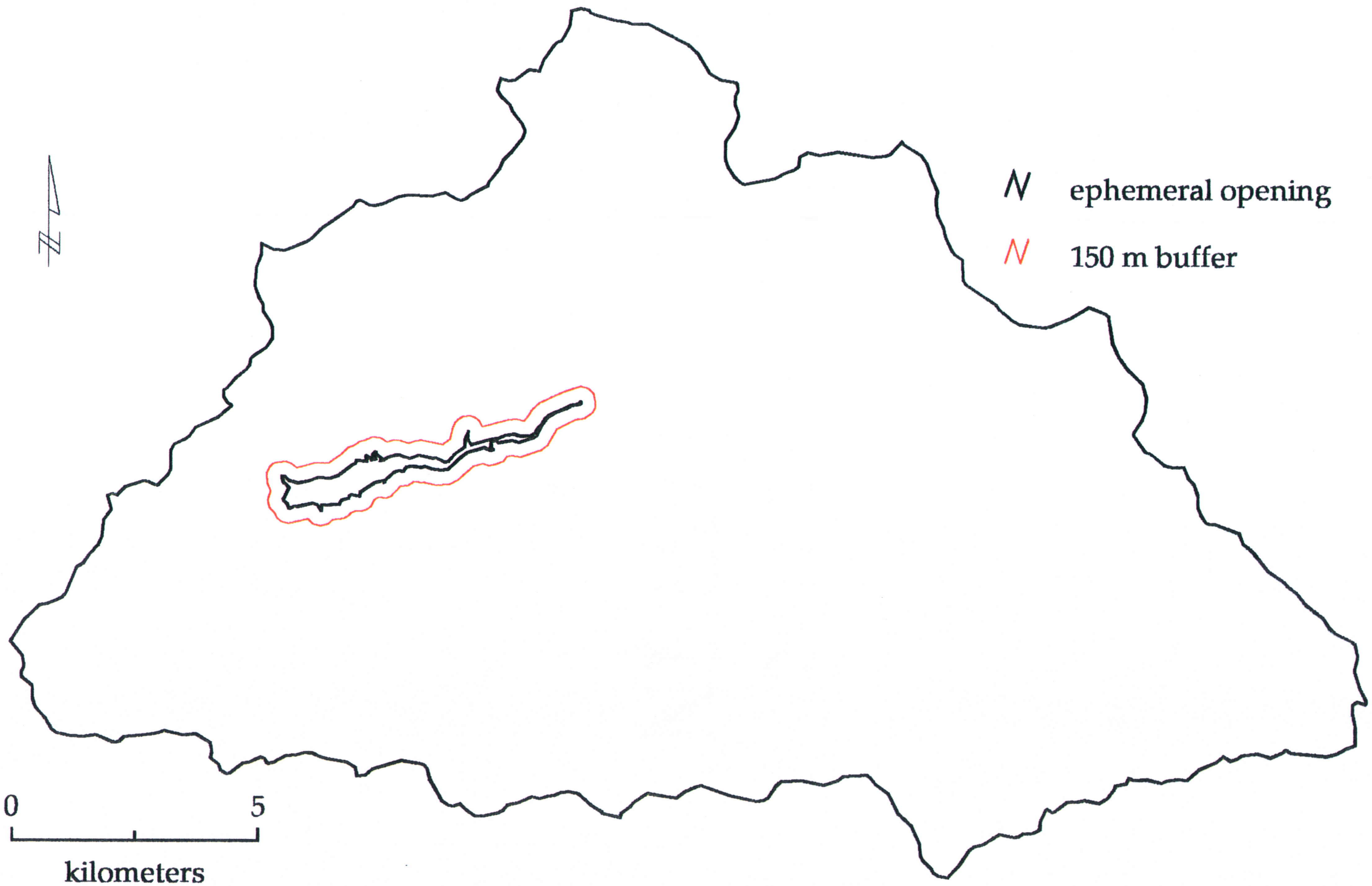


Figure 3.21 Ephemeral openings in the Bull Run watershed, 1973.

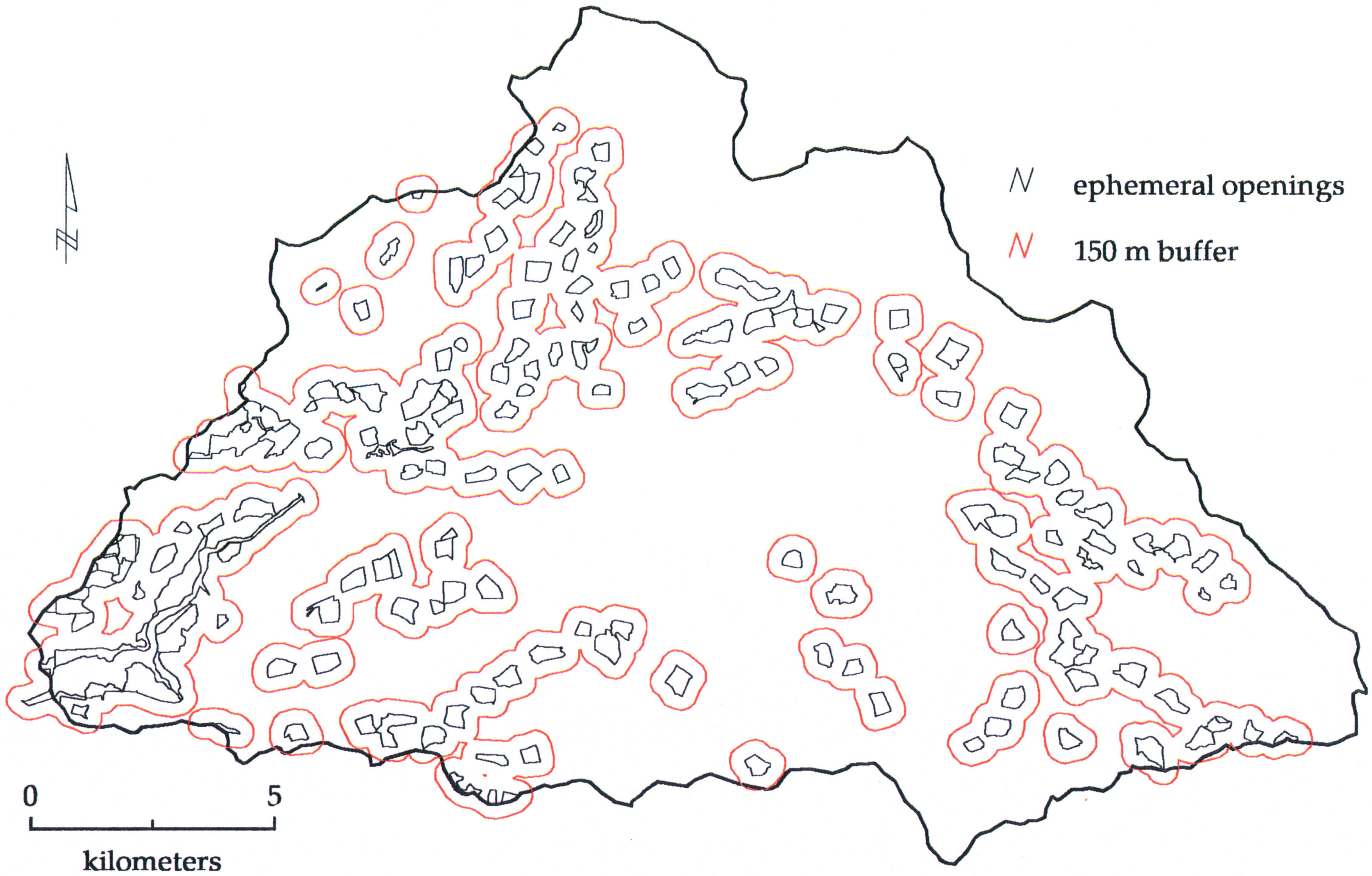
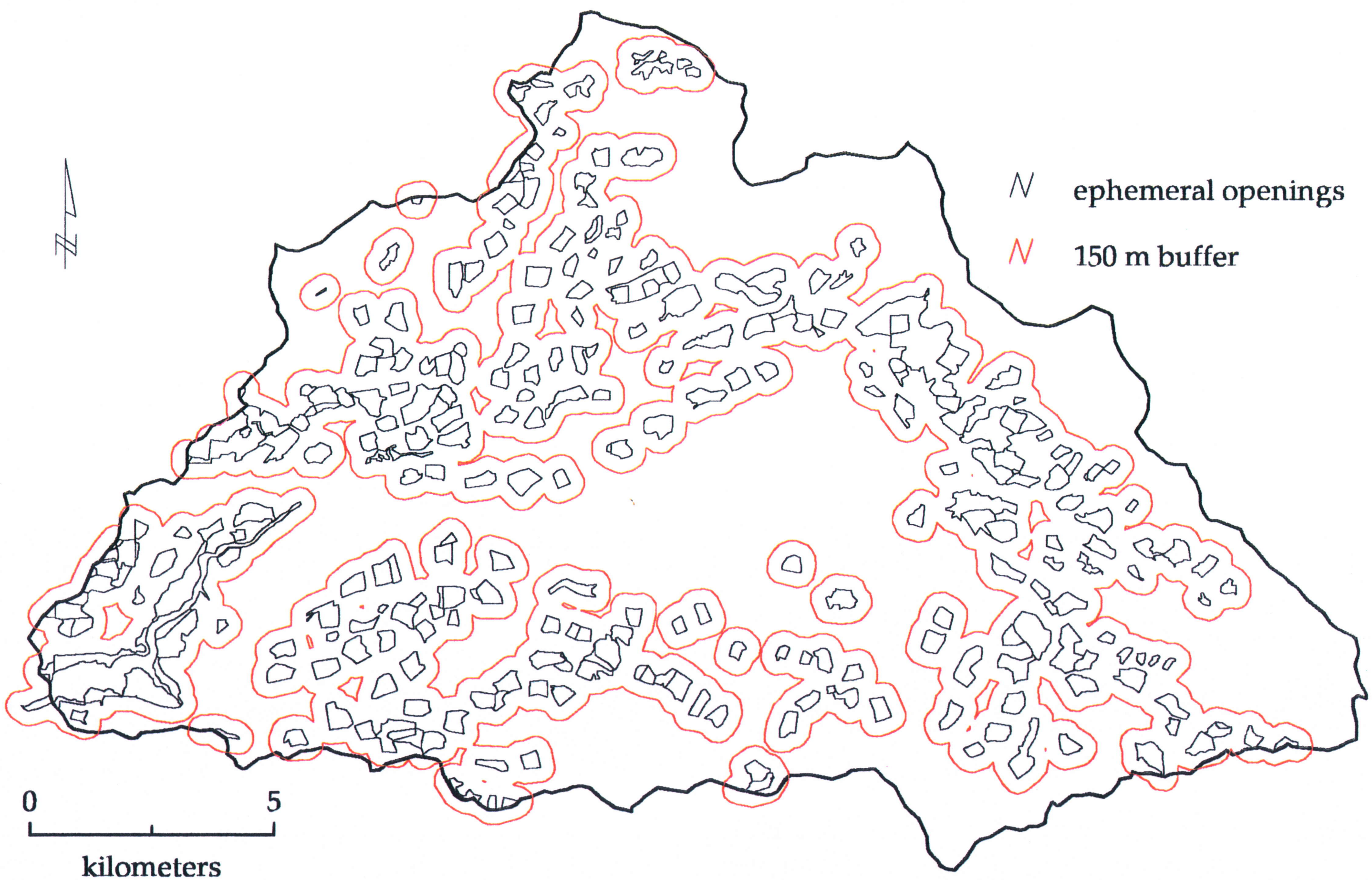


Figure 3.22 Ephemeral openings in the Bull Run watershed, 1983.



and 3) cross correlation, to calculate correlation coefficients. The correlation program was specified to run on only one grid at different offset distances, thus generating correlation coefficients relative to the one grid only, rather than a cross between two separate grids. The tabular results from all Arc/Info procedures were output in ASCII format for use with Excel (Version 4.0) to create tables and graphs. A brief description and the formulas for the spatial autocorrelation coefficients can be found in Fig. 3.23.

An additional test for spatial autocorrelation was made apart from the GIS. Vgram is a C program, written by B. Marks (1995b, unpublished), that calculated all-directional semivariances from a 2-dimensional image input of categorical data. Vgram was run on ASCII files of each grid-format data layer output with the GRIDASCII command in Arc/Info. The semivariance data that it produced were used to generate semivariograms at intervaled lag distances for each data layer; these provided information on the spatial autocorrelation and spatial structure of the data. Fig. 3.23 also contains a brief description of and the formula for calculating semivariance.

A second procedure external from Arc/Info provided information on windthrow patches from each storm. FRAGSTATS is a C program written by McGarigal and Marks (1995) that generates patch and landscape matrices such as patch size, nearest neighbor distances, and diversity indices. Acceptable forms of input include single variable files (svf) from Arc/Info. FRAGSTATS was run on the windthrow layers only to generate the distribution of patch sizes, from which the mean and median patch sizes from each storm were calculated.

3.2.6 Bivariate and multivariate spatial pattern analysis procedures

The first series of analyses performed with each windthrow layer described its spatial arrangement or location with respect to other data layers. This simple overlay procedure was done with the windthrow data layers and each of the other landscape variables used for analysis: aspect, elevation, slope, soil type, vegetation, and ephemeral and perennial openings. With the data layers in grid format, all of the layers could be overlaid simultaneously (with the COMBINE function). The output from this function allows for both bivariate and

Figure 3.23 Spatial autocorrelation coefficient formulas and descriptions. Formulas and descriptions are taken from Legendre and Fortin (1989) and Jones (1992, unpublished).

1. Moran's I and Geary's c

$$\text{Moran's I (d)} = [n \sum_i \sum_j w_{ij} (y_i - \bar{y})(y_j - \bar{y}) / W \sum_i (y_i - \bar{y})^2]$$

$$\text{Geary's c (d)} = [(n-1) \sum_i \sum_j w_{ij} (yi - \bar{y})^2] / [2W \sum_i (yi - \bar{y})^2]$$

d = a distance class
n = number of samples
w = no. of pairs of points in a distance class
$\Sigma (y_i - y)^2$ = measure of scatter in whole data set
$w_{ij} (y_i - y)(y_j - y)$ = measure of scatter in a distance class

Regular values for Moran's I range from -1 to 1; positive values equal positive autocorrelation; negative values equal negative autocorrelation; and zero equals no autocorrelation. Regular values for Geary's c range from 0 to 3, with positive autocorrelation increasing as values approach 0. The values can be used to construct correlograms, a graph that shows the correlations as a function of distance, showing the spatial structure of the data.

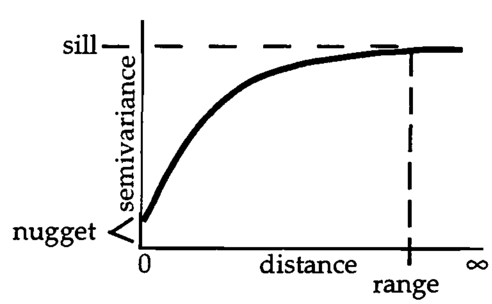
2. Semivariance for semivariograms

$$\text{semivariance (d)} = [1 / (2n_d)] \sum_{i=1} [y_{(i+d)} - y(i)^2]$$

d = a distance class
n_d = no. of pairs of points located at distance d from one another

Interpretation of autocorrelation is based on the construction of a semivariogram from semivariance values generated from different distance classes. The range depicts the distance below which the data are autocorrelated. The sill marks the point where semi- variance is no longer a function of distance, and the points are no longer correlated. If a semivariogram does not go through the origin, then there is some amount of variance even at distance zero: this is called the nugget effect.

semivariogram



multivariate results to be considered. It was repeated three times, once for each storm event in conjunction with the respective layers relevant for that storm.

A second set of spatial analyses considered linear features, i.e. the edges of ephemeral and perennial openings, that influenced windthrow. In this case, the edges (arcs) of openings were used in their original form, with no buffering performed. By using overlay procedures (e.g., IDENTITY in Arc/Info), attributes were added to the edges (arcs) of the openings to classify them by their location relative to landscape variables such as aspect, elevation, and windthrow-hazardous soils. Other data added separately to the arcs' attribute table (AAT) were the age of the edge (only if it were a clearcut), whether that length of edge was within 150 m of windthrow, and the orientation of the edge with respect to the opening (Fig. 3.24). These procedures were repeated six times: for each of the three storm events, both the ephemeral and perennial opening edges were considered.

To conduct a multivariate logistic regression with data from Arc/Info, two methods were followed. The first method used data generated by Arc/Info for use with a separate statistical package and the second procedure used the logistic regression command within GRID. Table 3.2 outlines all steps that were taken for performing a logistic regression both in SAS and Arc/Info.

To prepare the data for export from Arc/Info, all of the relevant independent variable data layers for each storm event were first COMBINED in GRID. The resulting output grid had the data for each of its associated underlying input grids in its value attribute table (VAT). Next the x,y location coordinates of each cell were attached to the data for that cell with the SAMPLE function in GRID. Without this step, there is no way within Arc/Info to calculate the distance from one cell to another or to relocate the data spatially. This step was repeated twice, once with the windthrow data layers only, and a second time with the layers of the independent variables. The output files from the SAMPLE function were in ASCII format.

To compensate for spatial autocorrelation, sample cells from the GIS data layers needed to be selected that were at least a minimum distance apart from one another. This technique, referred to hereafter as "distanced sampling," required the use of Distance, a C program that selects data points spaced at least a given distance apart (Marks 1995a, unpublished). The required input is an ASCII file with x,y location coordinates for each point. Distance was used first on ASCII files of windthrow locations from each storm to determine the

Figure 3.24 Example of edge orientation classification relative to an opening in the forest canopy.

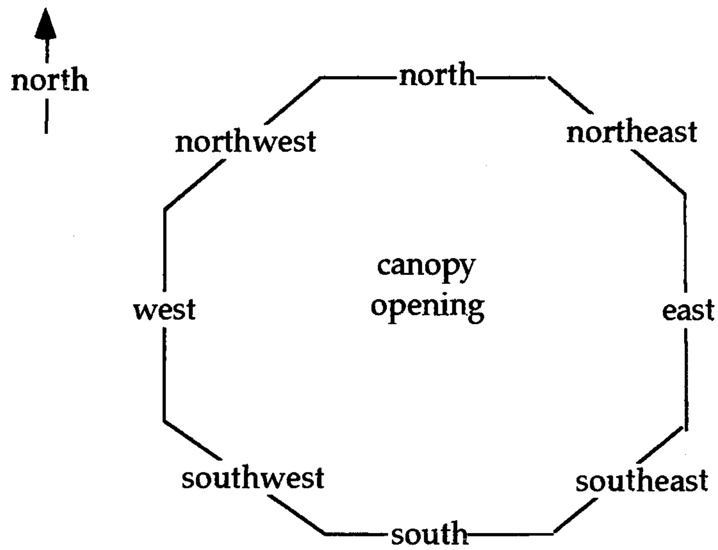


Table 3.2 Description of the steps taken for a logistic regression of spatial data involving a GIS and additional software and programs.

	Software or computer program	Function w/in software	Description of input	Action taken	Description of output or product	Number of lines in file or cells of data for output
1)	Arc/Info	various editing steps	coverages (point, polygon, grid) of data	various editing steps	grid coverages of all data layers at 75 m resolution	47100 cells / grid
2)	Arc/Info	GRID/sample	windthrow layers at 75 m resolution		ASCII file of all w'throw points w/ their associated x,y coords.	1931-775 lines 1973 - 915 lines 1983 - 2346 lines
3)	Arc/Info	GRIDASCII	all data layers as grid coverages at 75 m resolution		all data layers output as ASCII files	47100 lines / file
4)	Vgram		ASCII files from Step 3		ASCII files with variance data at intervaled lag distances	
5)	Excel		ASCII files with variance data for all coverages	plotted variance against intervaled distances	semivariograms that suggest how far apart to sample data (750 m)	
6)	Distance		ASCII files of all w'throw points w/ their associated x,y coordinates (one file/storm), output from Step 3	prompted program to select points at least 750 m apart from one another	ASCII files with w'throw points all at least 750 m apart from one another (one file/storm)	1931 - 43 lines 1973 - 48 lines 1983 - 115 lines

Table 3.2 continued

	Software or computer program	Function w/in software	Description of input	Action taken	Description of output or product	Number of lines in file or cells of data for output
7)	Arc/Info	Grid/Combine	all separate independent variable data layers		one grid coverage w/ all data attributed to each cell (one file/storm)	47100 cells
8)	Arc/Info	Grid/Sample	the grid coverages from Step 7		ASCII files with the cells' data and the x,y coordinates for each cell	47100 lines
9)	UNIX		the ASCII files output from Steps 6 and 8	files from Step 6 concatenated to top of respective files from Step 8	ASCII files with the w'throw cells (separated by > 750 m) listed at top and followed by a complete list of all cells & their locations in watershed	1931 - 47143 lines 1973 - 47148 lines 1983 - 47215 lines
10)	Distance		the ASCII files from Step 9	prompted program to select points at least 750 m apart from one another	ASCII files with w'throw lines at top and then non-windthrow points listed next, all > 750 m apart; any lines w/ missing data deleted	1931 - 363 lines (43 w'throw, 320 non) 1973 - 371 lines (48 w'throw, 323 non) 1983 - 355 lines (115 w'throw, 240 non)
11)	Excel	random number generator	the ASCII files from Step 10	non-windthrow lines of files sorted in ascending order on basis of random number; a batch selected to represent non-windthrow	one file per storm with matching number of w'throw and non-windthrow points	1931 - 86 lines per file 1973 - 96 lines per file 1983 - 230 lines per file

Table 3.2 continued

Software or computer program	Function w/in software	Description of input	Action taken	Description of output or product	Number of lines in file or cells of data for output
12) Excel		the ASCII files from Step 11	for each storm the non-windthrow points are analyzed for their representativeness of the watershed	Excel files, one per storm, with same number of w'throw and non-w'throw lines, and all independent variable data	1931 - 86 lines 1973 - 96 lines 1983 - 230 lines
13) SAS	PROC GENMOD	Excel files from Step 12	a logistic regression of windthrow with all of the variables and many combinations of variables tested for significance at the .05 level.	For the 1983 storm the regression worked well. For the 1931 and 1973 data sets there were not enough data points to have the model converge correctly.	
14) Reselect		ASCII files of all w'throw points w/ their associated x,y location coordinates for the 1931 and 1973 storms	prompted program to select points 350 m apart from one another	ASCII files with windthrow points all at least 350 m apart from one another	1931 - 87 lines 1973 - 103 lines

15) Steps 6 -12 were repeated for the regression of the data from the 1931 and 1973 storms. Then there were enough data points for the statistical analysis to work: a total of 174 for the 1931 storm and 206 for the 1973 storm.

maximum number of cells that could be selected from each storm's pattern that were at least a minimum distance apart from one another.

Each resulting output file of windthrow locations was concatenated on to an ASCII file that contained the independent variable data for that storm. When Distance was run on this concatenated file, the first points selected were the windthrow ones listed at the top, predetermined to be a minimum distance apart from one another. All cells chosen subsequently were non-windthrow cells, still at least the same distance apart from one another. This was done to ensure that the final data set for each storm could have all possible windthrow points selected, at that separation distance, and then the necessary data to select a matching number of non-windthrow points, also at the same separation distance from the chosen windthrow points. All of these procedures were repeated three times, once for each of the three storm events.

Excel was used with the ASCII data files that had been generated with Distance. Because windthrow covered no more than 5% of the watershed in any storm, each data set had many more non-windthrow than windthrow points. To create final data files for each storm event that had an equal number of windthrow and non-windthrow points, the random number generator in Excel was used to generate columns of random numbers, one of which was then attached to each data file. The data in ASCII files generated by Arc/Info begin with data from the upper, left hand corner of the image, eventually culminating with the lower, right hand corner data, and the Distance program selects points in the same sequence. Therefore, to reorganize the points to some degree, the data sets were sorted, by random number in ascending order, and a group of non-windthrow points were selected.

Finally SAS was used for logistic regressions with the three ASCII files containing the final data for each storm event. PROC GENMOD was used to model windthrow as the dependent variable. Independent variables were included in the model if they were significant at a minimum .05 alpha level. Interaction terms were considered among the significant independent variables. A final logistic model and odds ratios (Hosmer and Lemeshow 1989) were generated for each storm event.

The initial results from the 1931 and 1973 storms suggested that an insufficient number of sample points had been selected. Therefore the original data sets were resampled with a smaller minimum distance criterion and the analyses were redone. The second time both the 1931 and the 1973 regressions produced valid results.

Logistic regressions were also performed within Arc/Info. The logistic regression procedure in GRID is straightforward: the same ASCII files used with SAS were imported for use in Arc/Info and REGRESSION with the LOGISTIC option was run.

3.3 Results

3.3.1 Potential errors from data sources and manipulations

3.3.1.1 Associated with original data layers

There are several potential sources of errors associated with the windthrow layers created through aerial photo interpretation. Both the 1973 and the 1983 GIS windthrow data layers have a resolution of 0.56 ha and an estimated spatial displacement (mapping error) of 0.66 grid cells, or approximately 50 m. The scale of the 1973 and 1983 aerial photographs varied, and the distortion associated with the aerial photographs themselves created displacement errors.

There could be inaccuracies associated with the conversion from windthrow mapped as points to windthrow mapped as grid cells. However, each point was manually centered in the center of the 0.6 cm mylar grid when it was originally marked on to the mylar, and the Arc/Info support literature for the POINTGRID function states that the conversion centers the cell around the point.

One basic source of error in spatial data bases is the result of manually digitized data layers (Goodchild 1987; Goodchild *et al.* 1992b). The clearcut data layer was digitized by personnel at the Mt. Hood National Forest, from unknown source maps. Many of the clearcuts had undergone decades of regrowth and the edges may have been difficult to determine with precision. As a result, it occasionally appeared that windthrow occurred within an opening rather than adjacent to it. However, the use of buffers to denote an "area of edge influence," rather than using the exact line (edge of clearcut) itself, mitigates both the placement errors of windthrow points and the subjective digitizing errors associated with placement of the clearcut edge.

The data layers inherited from the Mt. Hood National Forest were converted from a MOSS GIS to Arc/Info, and this represents another possible source of error. Within MOSS the data were spatially separated within the areas of their respective U. S. G. S. quadrangles. Once these individual coverages were joined within Arc/Info, there were frequently cases of polygons not matching up with adjacent polygons. In particular, minor editing in Arc/Edit was necessary to "repair" the polygons from the clearcut data layer.

The original 1988 classified satellite image provided by the PNW Forestry Sciences Lab, from which the vegetation data layers were created, may have contained several errors. One possible source of error resides in the initial classification of the image. The accuracy of cover-type classification was estimated at 82% (Cohen *et al.* 1995). Moreover, the original satellite image captured vegetation conditions in August, 1988, five years after the 1983 windthrow storm, yet prior to extensive salvage logging. Most 1983 windthrown areas had been classified as open or semi-open areas, and the smaller patches of windthrow would have been difficult to detect and reclassify during the Erdas reclassification procedures. Therefore, they would still be showing as small patches of open or semi-open vegetation in the 1931, 1973 and 1983 windthrow layers.

3.3.1.2 Errors associated with editing procedures

The data layers created with the Mt. Hood DEM were modified by degrading their resolution from 30 m to 75 m to correspond with the windthrow layers. DEMs that were obtained from the U. S. Geological Survey were also modified and degraded with a change of resolution to 75 m. However, the data layer created from the U.S.G.S. DEMs was used for display purposes only, so errors from generalization did not affect analyses.

The vegetation layers were also altered from 25 m to 75 m resolution after the reclassification editing procedures. Additionally the use of a filtering process to smooth the vegetation layers may have both mitigated and created errors. The generalizing may have removed small patches of 1983 windthrow that had not been otherwise reclassified. However, both the smoothing procedure and the change of resolution result in a loss of heterogeneity within the forest landscape that the original image captured.

The reclassification procedure itself (GISEDIT in Erdas) has the potential to generate significant errors. Unfortunately, there is no way in Erdas to both display the polygons that are to be changed (with DISPOL) and do the editing (with GISEDIT) on the same scene at the same time. Therefore, two display windows are opened, each showing the same image. Over one image the polygons to be changed are overlaid, and in the other the editing is actually performed. However, one must rely on ocular estimation to coordinate the two images and select cells for reclassification.

This inability to display a coverage overlay and edit within the same window inevitably resulted in erroneous reclassification of individual cells. Moreover, by reclassifying all of the clearcuts and the areas under Reservoir #2 exclusively as old-growth conifer, the proportion of that cover type was likely overestimated.

The phenomenon of edge-related windthrow was of interest to this study, and the method of buffering the edges of openings proved helpful in estimating this windthrow. Yet there are inherent errors associated with buffering (Veregin 1994) and no one single buffer width is consistently adequate to describe edge-related windthrow. In this study the 150-m width was a slightly conservative one as it underestimated edge-related windthrow in the few contiguous windthrow patches that were greater than 150-m in length, but only by five percent or less (Sinton 1996a, unpublished).

A more significant source of error with the use of buffers is related to the interpretation of the results. Table 3.3 shows how the estimated percent of the basin affected by windthrow increases by increasing the buffer width. Due to the proximity of ephemeral and perennial openings in some areas of the watershed, the use of larger buffers resulted in significant "overlap." Consequently, windthrow would have been attributed to both the openings, even though only one or the other may have had a role in influencing tree fall.

Table 3.3 Amount of windthrow from 1931, 1973 and 1983 storms in the Bull Run watershed associated with varied buffer widths of ephemeral and perennial openings in the forest canopy. All ephemeral (clearcuts, reservoirs < 25 years old) and perennial (lakes, meadows, talus slopes, shrub fields, reservoirs > 25 years old) openings are buffered by increasingly large widths. This technique is used to measure the amount of windthrow that occurred adjacent to the opening. A 150-m buffer width was used for this study, selected after consideration of aerial photographs of windthrow patches at opening edges. Proportions of windthrow that can be ascribed to both ephemeral and perennial openings are listed, occurring in areas where ephemeral and perennial openings are in proximity to each other and the buffered areas overlap.

opening type and buffer width	Storm 1931(%)	1973 (%)	1983 (%)
ephemeral openings, 75 m	0	35	54
ephemeral openings, 150 m	0	56	77
ephemeral openings, 225 m	1	70	89
ephemeral openings, 300 m	1	80	94
perennial openings, 75 m	14	10	13
perennial openings, 150 m	35	34	31
perennial openings, 225 m	51	53	51
perennial openings, 300 m	67	70	66
both ephemeral and perennial, 75 m	0	1	5
both ephemeral and perennial, 150 m	0	12	21
both ephemeral and perennial, 225 m	0	33	44
both ephemeral and perennial, 300 m	0	55	60

3.3.2 Evaluation of spatial pattern interpretation procedures

3.3.2.1 Univariate analyses

The most direct way to graphically display the structure of each data layer and assess its patchiness, or spatial autocorrelation, was with Marks' Vgram program (Figs. 3.25-3.27). Alternately, graphs constructed with the correlation coefficients generated in GRID are essentially the inverse of a semivariogram and provided insight into the general size and clustering of data patches (Figs. 3.28-3.30). Based on interpretation of both sets of graphs, a minimum distance of 750 m between sampling points was selected.

The Moran's I and Geary's c coefficients suggest that many of the data are spatially autocorrelated, tending to be located in clusters (Table 3.4). Positive autocorrelation increases as Moran's I approaches one and Geary's c approaches zero (Upton and Fingleton 1985), so all of the variables, but particularly ephemeral and perennial openings, exhibited positive spatial autocorrelation.

Close examination of the semivariograms revealed that the vegetation layers and the elevation layer were not only autocorrelated, but that their patterns followed a slight gradient. Because of this gradient and the multiple errors associated with the creation of the vegetation layers, the vegetation data was not used in the multivariate analyses. Elevation was considered as an independent variable throughout the statistical analyses, but it failed to prove significant.

Simple information on "patches" of like-valued grid cells was difficult to obtain in GRID, but FRAGSTATS provided the desired data. Within a raster image, FRAGSTATS assumes cells of the same value, that are contiguous in an up, down, left, right, or diagonal direction, to be one "patch" and outputs information on each one of the patches it encounters. With these data, the distribution of patch sizes was derived, and mean and median patch sizes were calculated. In GRID, there was no way to gather information on groups of contiguous cells. Moreover, if the data were converted from points to polygons in Arc/Info, the shape of each polygon "patch" would no longer reflect the manner in which the points were mapped, i.e. the fact that each point had been marked in the center of a 0.6 cm grid cell.

Figure 3.25 Semivariograms of data used for analysis of 1931 windthrow in the Bull Run watershed, Oregon.

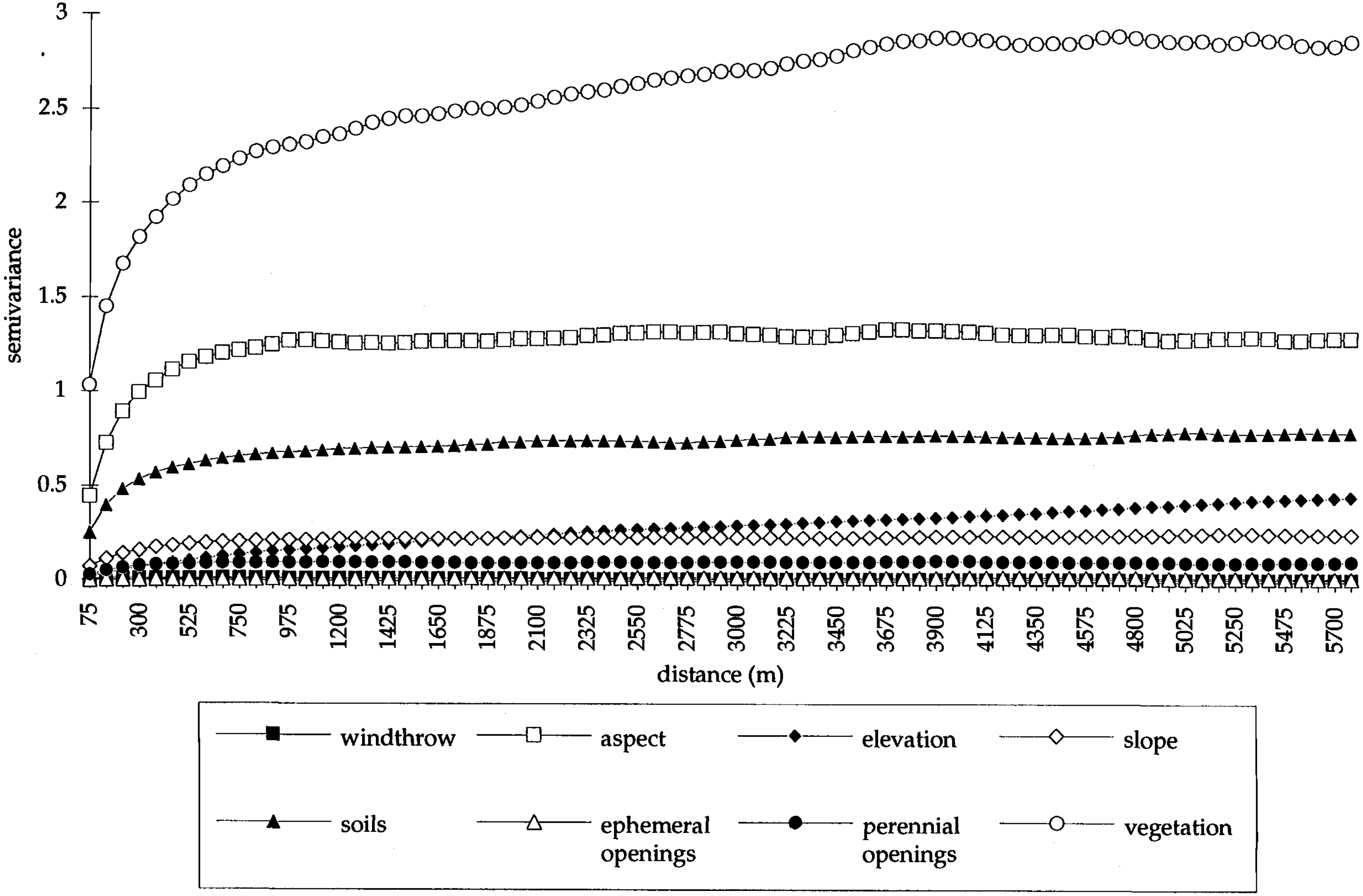


Figure 3.26 Semivariograms of data used for analysis of 1973 windthrow in the Bull Run watershed, Oregon.

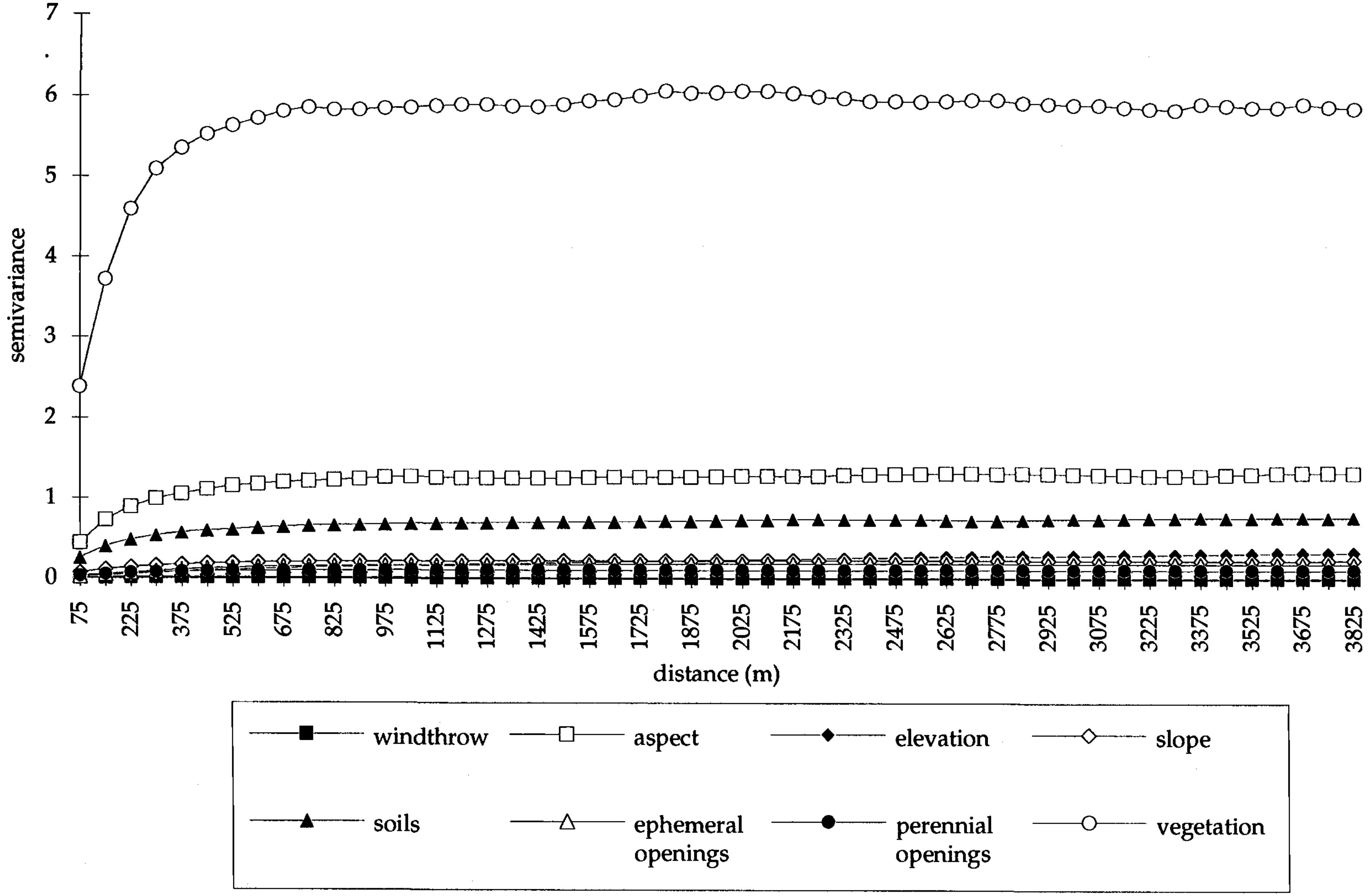


Figure 3.27 Semivariograms of data used for analysis of 1983 windthrow in the Bull Run watershed, Oregon.

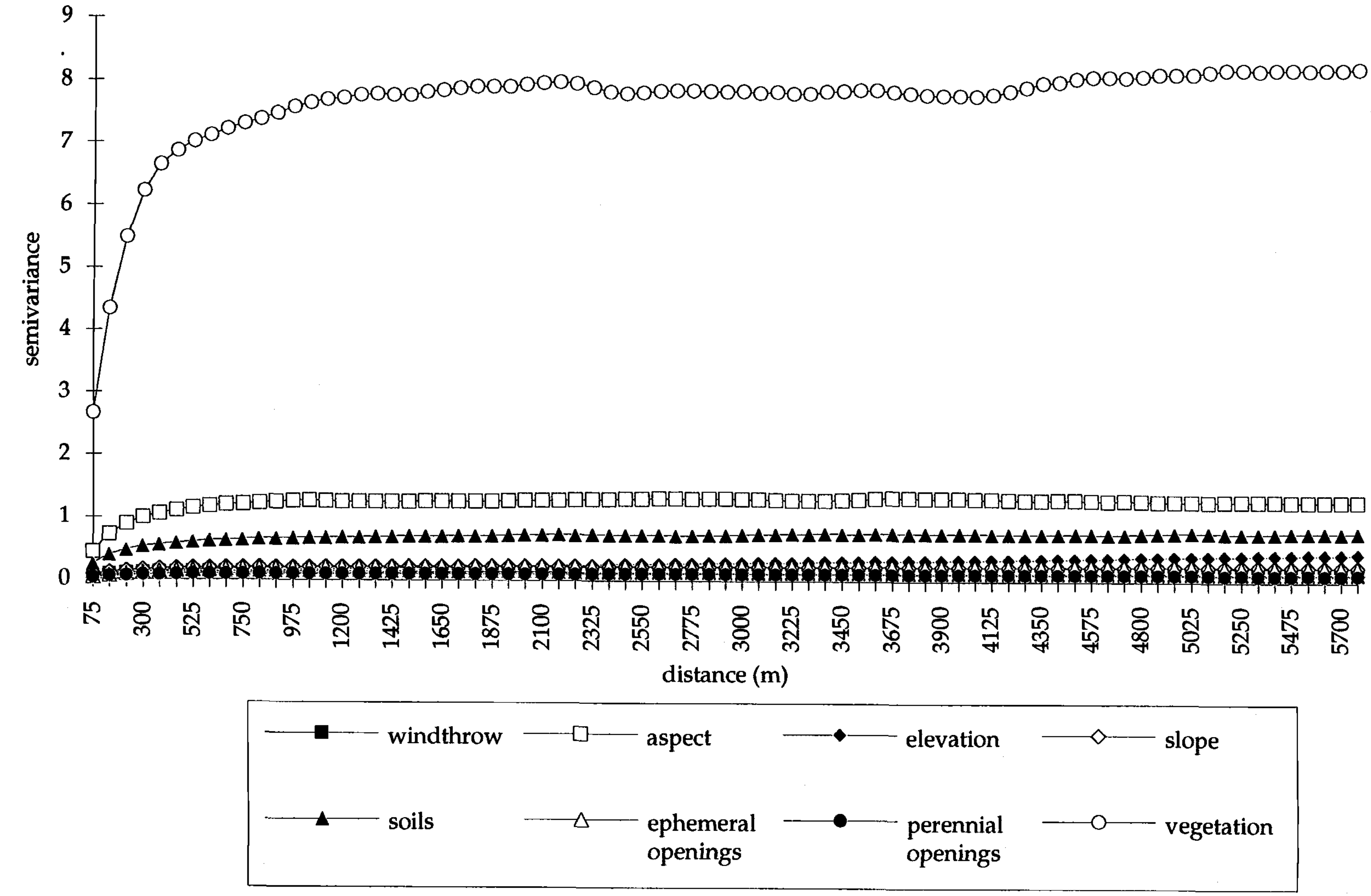


Figure 3.28 Correlation coefficients at varied offset distances of data used for analysis of 1931 windthrow in the Bull Run watershed, Oregon.

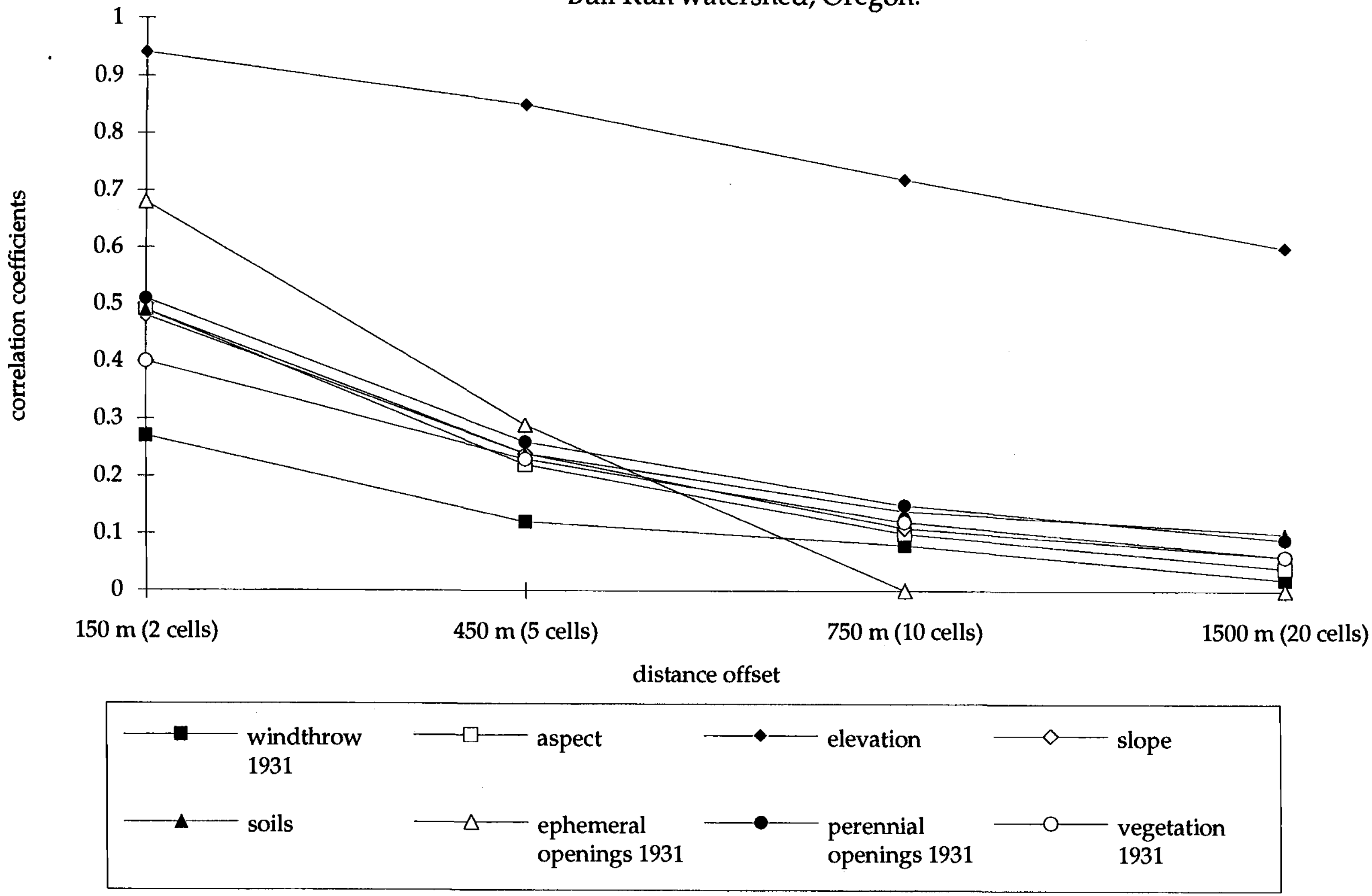


Figure 3.29 Correlation coefficients at varied offset distances of data used for the analysis of 1973 windthrow in the Bull Run watershed, Oregon.

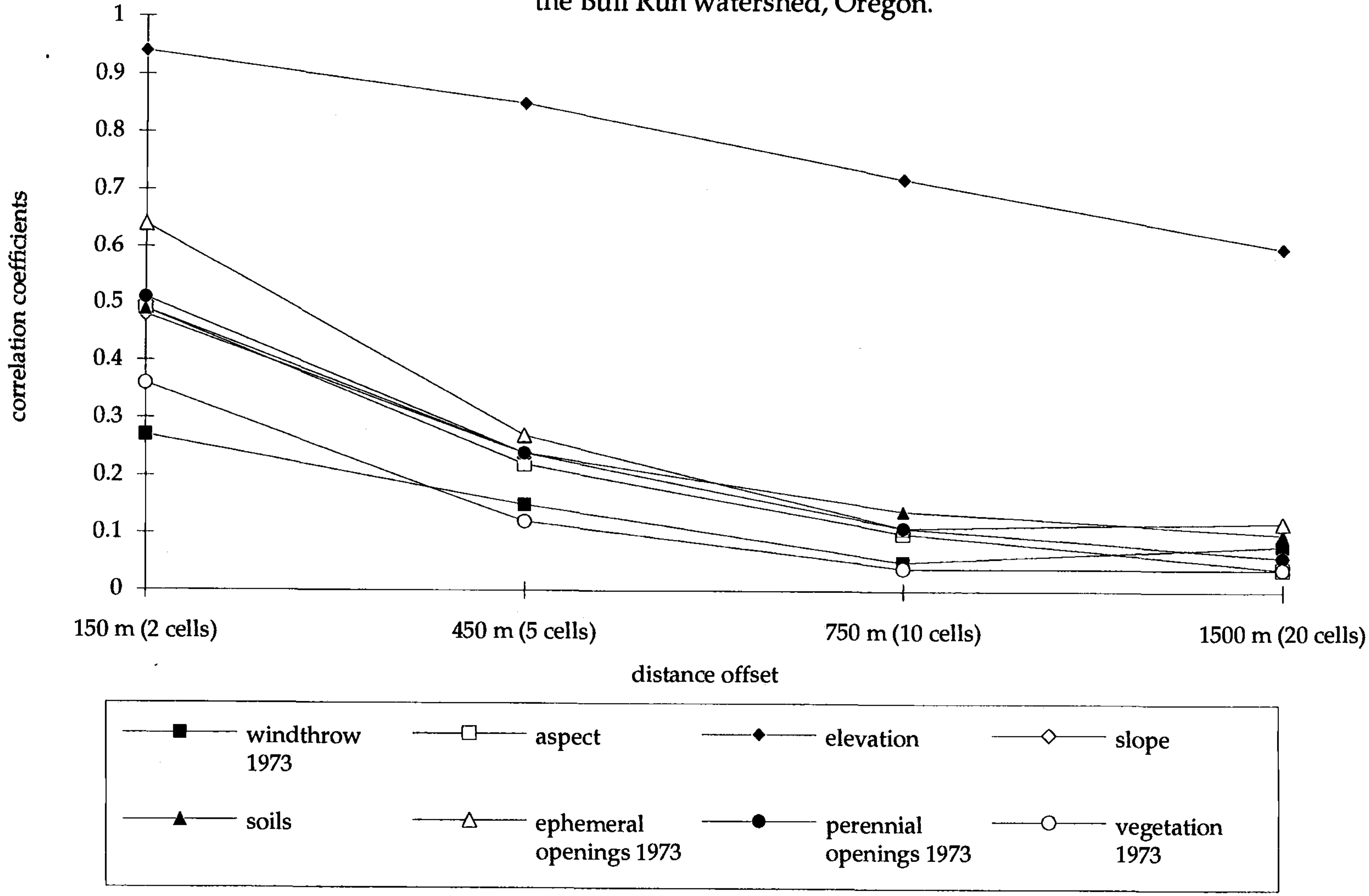


Figure 3.30 Correlation coefficients at varied offset distances of data used for the analysis of 1983 windthrow in the Bull Run watershed, Oregon.

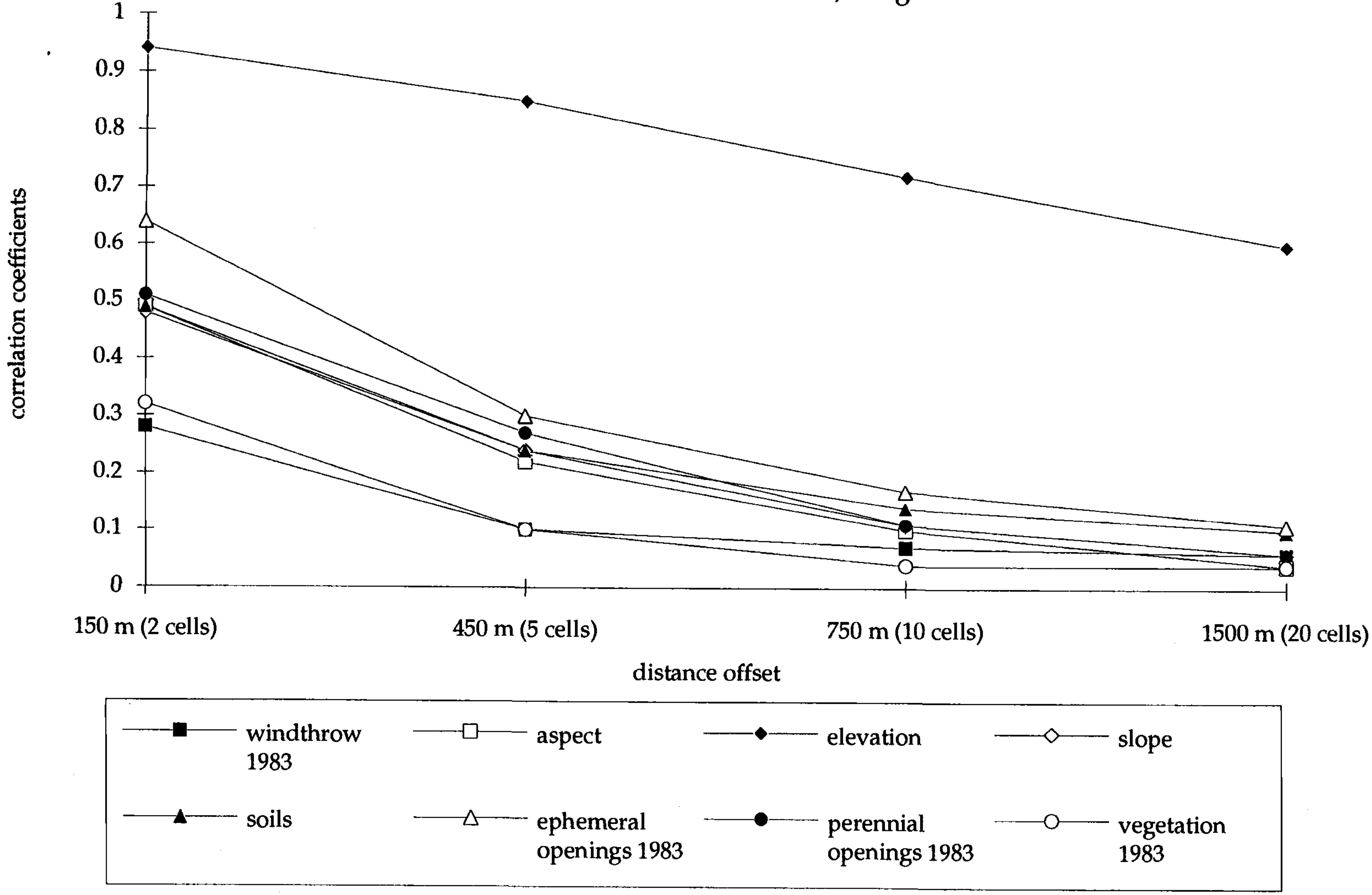


Table 3.4 Moran's I and Geary's c coefficients for the GIS data layers in the Bull Run watershed spatial analysis. The data layers used for the spatial data analysis of 1931, 1973 and 1983 windthrow in the Bull Run watershed were tested for spatial autocorrelation by calculating Moran's I and Geary's c coefficients in Arc/Info's GRID. The resulting coefficients are shown. The information on coefficient interpretation is from the Arc/Info Version 7.1 support literature.

Data Layer	GRID's Moran's I	GRID's Geary's c
windthrow (1931)	0.590	0.404
windthrow (1973)	0.567	0.430
windthrow (1983)	0.624	0.376
aspect	0.687	0.255
elevation	0.975	0.011
slope	0.755	0.235
soils	0.714	0.276
ephemeral openings (1931)	0.908	0.092
ephemeral openings (1973)	0.872	0.123
ephemeral openings (1983)	0.866	0.128
perennial openings (1931)	0.796	0.198
perennial openings (1973)	0.798	0.197
perennial openings (1983)	0.798	0.197
vegetation (1931)	0.642	0.352
vegetation (1973)	0.688	0.307
vegetation (1983)	0.685	0.311

Interpretation	Moran's I	Geary's c
similar, regionalized, smooth, clustered	$I > 0$	$0 < c < 1$
independent, uncorrelated, random	$I = 0$	$c = 1$
dissimilar, contrasting checkerboard	$I < 0$	$c > 1$

3.3.2.2 Multivariate logistic regression

The results from the logistic regression in SAS suggested that different landscape variables influence each of the three windthrow patterns (Table 3.5). In the 1931 storm, aspect and soils were the significant variables. The 1973 windthrow pattern was most strongly influenced by aspect and the interactions between soils and ephemeral openings, and in 1983 soils and ephemeral openings were the two significant variables. All the variables were compared to a Chi-square distribution and deemed significant at greater than a .05 alpha level.

The logistic regression in Arc/Info's GRID produced coefficients for each variable, a residual mean square error, and a Chi-square value for the model as a whole (Table 3.6). No information was provided for guidance with the results, such as which of the variables were significant and how many degrees of freedom were used to generate a Chi square value.

3.4 Discussion

3.4.1 What were limitations or constraints to the study as it was conducted?

The indirect method of locating pre-1970s windthrow limited the ability to locate the smallest windthrow, resulting in an underestimation of small patch sizes. However, it is debatable whether this fault warrants the field work that would be necessary to more thoroughly sample the watershed. An additional set of spatial arrangement analyses were repeated after excluding all 1973 and 1983 patches < 2 ha, and the resulting comparisons to expected values or the 1931 pattern did not change significantly (Sinton 1996a, unpublished).

Windthrow could not be mapped consistently by severity class in the three storms. No severity classification of 1973 windthrow was possible based on the 1973 photographs alone, and the identification and mapping methodology used with 1931 and 1983 windthrow varied to such a degree that one single method of severity classification was not possible. As a result, the logistic regression could only consider windthrow as a binary response variable.

Table 3.5 Results from the SAS logistic regression of 1931, 1973 and 1983 windthrow in the Bull Run watershed. Windthrow patterns from three storm events were tested against five independent variables (aspect, slope, soils, ephemeral and perennial openings) in a logistic regression in SAS. The main effects and all combinations of interactions were tested for all variables. Variables were included in the final model if they were significant at the .05 alpha level. The odds ratios were calculated for the significant variables (Hosmer and Lemeshow 1989). The odds ratios were based on a reference class from each variable, designated by an odds ratio of 1.0; the other odds ratios are with respect to that class.

1931 Final Model:

variables:	n	DF	ChiSquare	Pr > Chi
aspect	174	3	14.8414	0.002
soils	174	3	25.194	0.0001

1931 Odds Ratios:

	aspect NE	SE	SW	NW
estimate	1.041	0.447	-0.67	0.0
stnd. error	0.457	0.512	0.466	
odds ratio	2.82	1.56	0.51	1.0

	windthrow hazard of soils			
	none	slight	moderate	severe
estimate	-2.154	0.0	-1.74	0.509
stnd. error	0.698		0.568	0.486
odds ratio	0.116	1.0	0.175	1.664

1973 Final Model:

variables:	n	DF	ChiSquare	Pr > Chi
aspect	189	3	8.4027	.0384
soils * ephemeral openings	189	2	10.1752	.0062

1973 Odds Ratios:

	aspect NE	SE	SW	NW
estimate	1.069	-0.186	.561	0.0
stnd. error	0.475	0.525	0.43	
odds ratio	2.91	0.83	1.75	1.0

ephemeral openings	windthrow hazard of soils		
yes	slight	moderate	severe
estimate	0.0	-0.344	2.314
stnd. error		2.626	1.519
odds ratio	1.0	.71	10.12

ephemeral openings	windthrow hazard of soils		
no	slight	moderate	severe
estimate	0.0	-1.286	-0.371
stnd..error		.945	.854
odds ratio	1.0	.276	.69

Table 3.5 continued

1983 Final Model:

variables:	n	DF	ChiSquare	Pr > Chi
ephemeral openings	230	1	10.312	0.0013
soils	230	3	17.456	0.0006

1983 Odds Ratios:

	ephemeral openings	
	yes	no
estimate	.964	0.0
stnd. error	.306	
odds ratio	2.62	1.0

	windthrow hazard of soils			
	none	slight	moderate	severe
estimate	-0.765	0.0	-0.365	1.153
stnd. error	0.569		0.402	0.37
odds ratio	0.465	1.0	0.694	3.168

Table 3.6 Results from the Arc/Info logistic regression of 1931, 1973 and 1983 windthrow in the Bull Run watershed. Windthrow patterns from three storm events were first tested against five independent variables (aspect, slope, soils, and ephemeral and perennial openings) in a logistic regression in Arc/Info (Version 7.0.1). A second model was run that incorporated only the variables determined to be significant in a logistic regression with SAS software. No information was provided by ARC/INFO on how to test for interaction among the variables.

1931 model #1				1931 model #2			
variables:	coefficient	rms error	Chi 2	variables:	coefficient	rms error	Chi 2
constant	-0.35	0.48	40.02	constant	0.06	0.49	40.92
aspect	-0.36			aspect	-0.36		
slope	-0.26			soils	0.39		
soils	0.29						
eph. openings	-0.18						
per. openings	-0.27						
1973 model #1				**1973 model #2**			
variables:	coefficient	rms error	Chi 2	variables:	coefficient	rms error	Chi 2
constant	-0.76	0.472	45.97	constant	-0.28	0.49	45.58
aspect	-0.24			aspect	-0.19		
slope	-0.88			soils	0.28		
soils	0.51			eph. openings	0.44		
eph. openings	0.51						
per. openings	-0.04						
1983 model #1				**1983 model #2**			
variables:	coefficient	rms error	Chi 2	variables:	coefficient	rms error	Chi 2
constant	-1.04	0.472	51.14	constant	-1.99	0.48	52.19
aspect	-0.22			soils	0.51		
slope	-0.27			eph. openings	1.03		
soils	0.52						
eph. openings	1.05						
per. openings	-0.11						

No one single software program provided all the necessary functions, and additional computer programs needed to be written and utilized to complete the analysis. It was necessary to move data back and forth multiple times between different software packages and computer programs (Fig. 3.31). These moves were labor intensive and may have been the source of errors (e.g., moving data from Moss to Arc/Info).

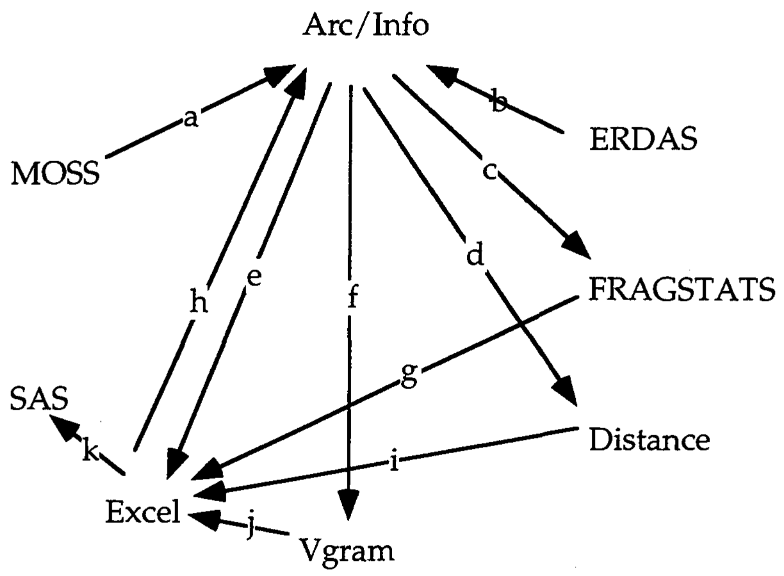
The labor- and time-consuming procedures associated with the regression centered around the preparation of the data. Performing a logistic regression in GRID would have been the quickest way to produce results. However, the data were spatially autocorrelated. Without the use of the Distance program, it would have been extremely time-consuming and difficult to create, within Arc/Info, the windthrow layer for the regression in which half the points were windthrow, half not, and all points at least a minimum distance apart from one another.

3.4.2 Could the conclusions have been reached without multivariate statistics?

The general results of this study could have been reached without the use of a logistic regression and the use of a separate statistical package. The basic trends in the data were apparent in the comparisons made in the GIS with windthrow overlaid on different data layers, e.g. that windthrow occurred more on some aspects than others. The connection between 1983 windthrow and canopy openings such as clearcuts and roads was evident from the 1984 aerial photos, and had been made by the Forest Service soon after the storm (U.S.D.A. Forest Service 1987). With data directly from Arc/Info, these associations could have been tested for significance with a Chi Square test, but this would have only provided for testing each of the variables individually, and interactions among variables could not have been considered. Because the degrees of freedom would have differed depending on which variables were being tested, the results could not be compared across variables. The need for as thorough a quantification of the results as possible required the use of separate software packages and computer programs.

Admittedly, it remains uncertain whether the errors associated with preparation of the data for the analyses (see above) and the issues surrounding autocorrelation justified the use of parametric statistics. Goodchild *et al.* (1992b)

Figure 3.31 Data conversions and software links used for a spatial data analysis with a GIS.



[a] Import of MOSS files through MOSSARC command; cleaning/editing coverages necessary.

[b] Import of ERDAS (Version 7.5) files to Arc/Info with ImageGrid command.

[c] Export an svf file of an Arc/Info (Version 7.0.1) GRID coverage for use with Fragstats.

[d] Use SAMPLE to export an ASCII file from Arc/Info that has x and y coordinates attached to each cell location; Distance takes ASCII files as input.

[e] Export ASCII files (e.g., through UNLOAD in TABLES) from Arc/Info to be read by Excel (Version 4.0).

[f] Export ASCII files (e.g., through GRIDASCII in GRID) from Arc/Info for use by Vgram.

[g] FRAGSTATS output are ASCII files that can be analyzed and charted in Excel.

[h] Use GENERATE a POINT coverage with an Excel ASCII file of x and y coordinates; then POINTGRID can be used for making a grid coverage. This path is also followed to input data into Arc/Info for a logistic regression.

[i] Distance outputs ASCII files that can be read in Excel.

[j] Vgram outputs ASCII files that can be read in Excel.

[k] Excep can output ASCII files for use with SAS (Release 6.10).

warn that errors in GIS maps of categorical data can be profound, and the use of a GIS to "sample" data can be problematic (Fotheringham and Rogerson 1993). Nevertheless, in each of the three windthrow patterns tested, multiple variables and/or variable interactions were significant, results that could not have been estimated without a multivariate statistical analysis.

3.4.3 How does this study compare to other windthrow studies?

The earliest published studies of windthrow described its location at a specific place or following a particular storm event (Baker 1915; Behre 1921; Brooks 1939; Ruth and Yoder 1953; Gratkowski 1956). Once the need to quantify the phenomenon was recognized, multivariate statistics that described the relationship between windthrow and other variables were increasingly used (Steinblums *et al.* 1984; Lohmander 1987; Foster 1988a; Foster 1988b; Boose *et al.* 1994; Esseen 1994). However, I could find no examples of logistic regression specifically in the published windthrow literature.

The effect of recent forest edges on the probability of windthrow is intuitively clear, yet apart from studies of windthrow in stream-side buffer strips (Steinblums *et al.* 1984; Andrus 1992), few studies have closely examined edges specifically (Tang 1995). Furthermore, information on edge characteristics, such as how recently they had been created, is often not readily available.

This Bull Run study identified several edge factors (i.e., edge location and edge age) that were correlated with windthrow and affected the probability of windthrow occurring at a particular location, yet true causal factors cannot be singled out. Particularly in areas of overlapping buffer zones it was desirable to know for certain which, if any, of the openings may have contributed to the windthrow. In some situations, a logical conclusion could be drawn if the windthrow were located downwind of one opening and upwind from another. However, there was no way in the GIS to systematically locate windthrow points relative to an upwind edge. Moreover, while the general wind patterns are known from storm data, topographical variations in the landscape created local variability of wind directions, making the upwind/downwind distinction more difficult tô determine.

3.4.4 How does this study compare with other logistic regression work?

Logistic regression has been used most frequently in the social and medical sciences, where a binary or categorical response variables are common (Hosmer and Lemeshow 1989; Long *et al.* 1993; Glass *et al.* 1995). Its usefulness with ecological data is only now being more widely recognized (Trexler and Travis 1993). Statistical methods must be followed to account for spatial autocorrelation when testing for significance (Legendre 1993), or distanced sampling must be employed. However, distanced sampling would not be possible with typical ecological studies involving plots < 1 m or even 10 m in size, unless the patterns in question were also scaled down in proportion.

The use of a binary response variable does not provide for the continuous degree of response that is characteristic of most ecological data. Even in this windthrow study, the severity of windthrow in a sampled cell was not considered as part of the response: either the cell was windthrown or not. Lowell (1994) identified this as a primary concern when using categorical spatial data for probabilistic GIS modeling. This elucidates the popularity of logistic regression with medical studies rather than ecological ones: the patient is either pregnant or not, with no chance of a middle area. On the other hand, attempts to characterize different windthrow patterns by severity on a common scale were unsuccessful due to variations in the identification and mapping procedures.

The method of distanced sampling as an attempt to remove spatial autocorrelation among data is not widely used primarily because it may involve eliminating a majority of the data (Legendre 1993). In this study, only about 5% of the windthrow points for each storm, sampled at a 750 m spacing, were initially used for analysis. This number of sampled points proved insufficient for the logistic regression of the 1931 and 1973 storm data, and approximately 11% of the total number of mapped points from each storm, at 350 m spacing, were eventually used. In those cases the attempt to thoroughly account for spatial autocorrelation by distanced sampling was forfeited in order to obtain sufficient sample points for the regression, although the original 750 m spacing may have been a conservative figure, based on interpretation of the semivariograms from some data layers.

Other statistical techniques are available to test for significance in the presence of autocorrelation, for example by modifying the parameter standard error estimates or the degrees of freedom, or with permutational tests (Legendre 1993). However, because this study involved a data set that spanned a landscape, the use of distanced sampling proved adequate to compensate for spatial autocorrelation.

3.4.5 How does this study relate to other spatial data analysis (SDA) and GIS research?

The coupling of spatial data analysis with GIS has long been identified as a worthwhile and desirable goal (Goodchild 1987; Goodchild *et al.* 1992b; Bailey 1994; Haining 1994). However, Bailey (1994) identified that the potential is greater than the progress to date for the use of multivariate statistical methods with GIS. The current availability of techniques to perform spatial analyses within a GIS remains poor, and researchers with inadequate background training in parametric and spatial statistics are limited in their ability to interpret and use the results (Goodchild 1992).

Two examples of limitations with GIS-based, spatial analyses were encountered in this windthrow study. The support literature available with Arc/Info 7.0.1. does not describe the way in which a distance interval is used in calculating Moran's I and Geary's c coefficients, and the output is simply a single coefficient for the coverage as a whole. When distance intervals are known, the resulting coefficients can be used to construct correlograms that provide insight into the spatial structure of the data, or describe how the autocorrelation varies with distance (Upton and Fingleton 1985; Legendre and Fortin 1989).

The logistic regression function in Arc/Info 7.0.1. is another example of a data analysis technique that lacks a thorough explanation in the support literature. Moreover, possible spatial autocorrelation of the data is not mentioned in the section of the manual dealing with regression. If the results from this function had been used indiscriminately, no adjustment for spatial autocorrelation would have been made and the resulting output would have been statistically flawed.

In this study, as well as others, it was necessary to use statistical programs external to a GIS in order to complete the spatial analysis (Gonzalez 1995; Powers 1995; Nesje 1996). I relied heavily on the "loose coupling via ascii files" method of transferring data from one program to another (Goodchild *et al.* 1992b; Bailey 1994). While the processes were time consuming, this method allowed for the various analyses of the data with a "package which is best suited to that task" (Goodchild *et al.* 1992b, p. 419). Until better links exist between spatial data analysis and GIS, this remains a logical procedure for producing the most accurate results possible.

3.5 Conclusions

The GIS data layers created for the Bull Run watershed enabled a suite of univariate, bivariate and multivariate analyses to be performed. In a landscape-level study such as this, any other method of compiling and organizing the spatial data base would have been impractical. When the need for certain analyses exceeded the capabilities of the GIS, additional software, statistical packages, or separate computer programs were utilized. This allowed for a thorough assessment of spatial autocorrelation of the data, without which the multivariate statistical analyses would have been invalid.

The use of GIS in conjunction with spatial statistics is an increasingly common and popular means of performing spatial data analysis (Goodchild *et al.* 1992b), yet one that should be used with caveats (Fotheringham and Rogerson 1993). By definition, landscape-level studies present inherent challenges with regards to data collection and field work. The use of spatial and parametric statistics to interpret data from a GIS is a logical and practical method to address landscape ecological questions.

Chapter 4

An analysis of wind and other climate data for the Bull Run watershed and vicinity

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in preparation for journal submission

4.1 Introduction

Many factors contribute to the occurrence of windthrow in the Bull Run watershed. Wind itself may be the most important variable, yet it is also the most dynamic and unpredictable, and least understood. Data do not exist to interpret the canopy-level, wind conditions during storm events in the Bull Run. However, because of its status as the municipal water supply for Portland, Oregon, data have been collected on precipitation, temperature, and wind conditions.

Two storms in 1973 and 1983 generated considerable amounts of windthrow in the Bull Run, in addition to storms from the 1890s to 1931 (Sinton 1996a, unpublished). The 1973 and 1983 storms were both east wind events with high wind speeds, yet similar storms that occurred before and after failed to produce significant windthrow. This suggests that factors beyond wind and climatic conditions influence the probability of windthrow. Evaluation of other factors contributing to windthrow are reviewed in Sinton (1996a, unpublished).

The objective of this chapter is to characterize the types and frequencies of wind storm events that have and have not led to windthrow in the Bull Run watershed. Wind and other climatic data collected from multiple sites within and around the Bull Run will be used to describe the climatic regime. Wind data from the Portland Airport, the location closest to the watershed with a long record of available data, will be used to describe the wind regime for the general area. Temperature and precipitation data from the Bull Run will be combined with Portland wind data to create a predictive model for the types of storms that generate windthrow in the Bull Run. Return intervals of these events will be calculated, and the distribution of predicted windthrow storm events compared to the frequency of known events.

4.2 Methods

4.2.1 Data collection

4.2.1.1 Wind data within the Bull Run watershed

Since the mid-1970s, wind speeds have been monitored at two sites in the Bull Run watershed: on the dam at Reservoir #1 (DAM) and at a site near Log Creek (LC). However, neither of the data sets is complete or wholly accurate.

The DAM site is situated mid-way across the top of the dam on Reservoir #1, in the central western part of the Bull Run watershed (Fig. 4.1). The anemometer itself is attached to a weather station pole, one to two meters above the ground, and was designed to measure surface wind effects on evapotranspiration. The City of Portland Water Bureau manages the weather station and provided the wind data in either digital format or in hard copy, paper format.

Two time periods of data were available from the DAM site. The first set covered the period October, 1978, through June, 1985. The year 1984 was excluded entirely. These data were provided in hard copy format, and were manually entered into spreadsheet software (Excel, Versions 3.0 and 4.0). Only 78% of the days during the period had data recorded, and the fall season data were slightly more complete than other seasons (Table 4.1). The recording device measured revolutions per day, and no transformation factors were available to convert the value to an average wind speed per day.

The second set of data from the DAM site, available in digital format, covered the period January, 1993, through May, 1995. Approximately 85% of the days during the period had data recorded; more winter and spring days were represented than days in other seasons (Table 4.1). The measuring device provided wind speeds in miles per hour for each hour of the day. These data were converted to a daily average speed, and the highest recorded hourly wind each day was designated the daily maximum wind speed. Only this later data set, covering January, 1993, through May, 1995, was used from the DAM site

Figure 4.1 Weather data sites in and around the Bull Run watershed.

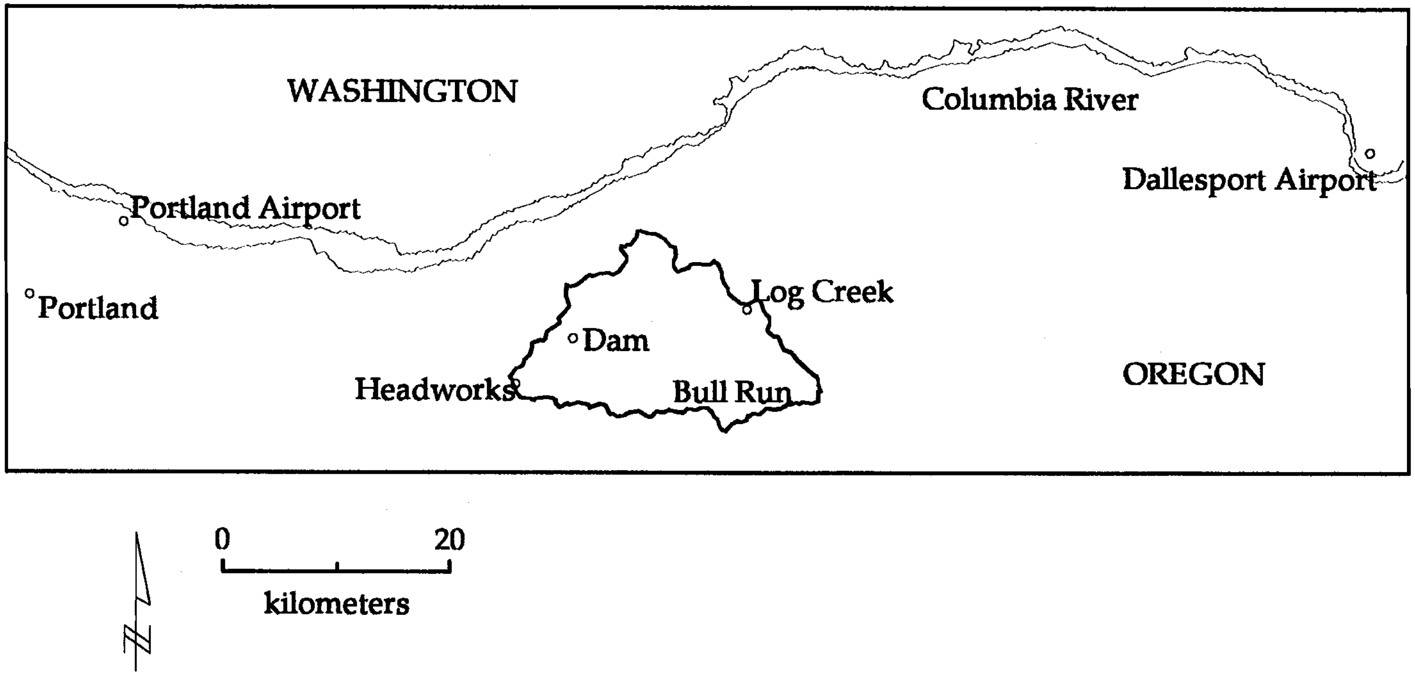


Table 4.1 Availability and type of wind data collected from four sites in and near the Bull Run watershed, Oregon.

	Data site DAM[1]	DAM[2]	LC[3]	PDX[4]	PDX[5]	DPA[6]
% of days during period of record with data available	78	85	63	> 99	> 99	>99
% of record by season with data available:						
winter (Dec. - Feb.)	22	30	17	25	25	25
spring (Mar. - May)	25	32	19	25	25	25
summer (June - Aug.)	25	19	35	25	25	25
fall (Sept. - Nov.)	28	18	29	25	25	25
type of wind data:						
average speed / day[7]		x		x	x	x
maximum speed / day[8]		x		x		x
maximum speed / day[9]					x	
one wind speed / day			x			
rotations of device / day	x					

1 Data in hard copy format from a site on the dam across Reservoir #1 in the Bull Run watershed, Oregon; data available from 1978 through 1985.

2 Data in digital format from the same site on the dam; available from 1993 to 1994.

3 Data in digital format from a site near Log Creek in the Bull Run watershed, Oregon; data available from 1975 through 1994.

4 Data in digital format from the Portland Airport, Oregon; data available from 1948 through 1984.

5 Data in hard copy format from the Portland Airport, Oregon; data available from 1985 through 1994.

6 Data in digital format from the Dallesport Airport, Washington.

7 Average of wind speeds from 24 hourly observations/day.

8 Highest wind speed from 24 hourly observations/day.

9 Highest wind speed from 8 hourly observations/day.

because of the difficulties encountered converting the revolutions per day measurements from the earlier period.

Additional wind data from within the Bull Run watershed were available from a site near Log Creek (LC), located in the northeastern portion of the watershed (Fig. 4.1). The site is a Remote Access Weather Station (RAWS), managed by the U. S. Forest Service, and is higher in elevation than the DAM data site. T. Parker of the Columbia Gorge Ranger District provided the LC data on computer floppy disks.

The LC data contained daily wind information from the period June, 1975, to November, 1995, but the data set was not complete. RAWS sites are managed by the Forest Service with regard to forest fires, so during the rainy season, data are not always collected and maintenance of weather stations is less frequent (T. Parker, Columbia Gorge Ranger Station, pers. comm.). Overall, only 63% of the days during the period had data available, and fewer days in winter months had data available (Table 4.1). Until the mid-1980s, the data were manually collected once a day at 2:00 p.m., the time of day when weather conditions best reflect fire danger. The collection procedure was later automated, but the available LC wind data still represented a single wind speed per day, in miles per hour, and the direction of that wind, so the value was neither a true daily average speed nor a maximum speed.

4.2.1.2 Wind data from outside the Bull Run watershed

Data from the Portland International Airport (PDX) were obtained both in digital and hard copy format from G. Taylor of Oregon Climate Services in Corvallis. The digital data, originally from the National Climatic Data Center in Asheville, North Carolina, were transferred to the U. S. Forest Service's PNW Forestry Sciences Laboratory (FSL) computer system via file transfer protocol (FTP). The airport is located along the Columbia River east of Portland (Fig. 4.1), only slightly above mean sea level elevation and topographically exposed to all directions. The anemometer at the airport is typical of the standard National Weather Service instruments. Weather conditions are monitored once each hour for five to ten minutes, and the wind speed is recorded.

The PDX digital data cover the longest period of record available for this study, from January, 1948, through December, 1984. Over 99% of the days during this period had data available (Table 4.1). The original data set included hourly observations on wind speed, in knots, and wind direction; D. Henshaw at the FSL then calculated a daily average wind speed in miles per hour and designated the highest hourly speed per day, based on 24 observations, as the maximum daily speed.

Wind data from January, 1985, through December, 1994, were obtained in hard copy format as the "Monthly Summary of Local Climatological Data" for the Portland Airport, published by the National Oceanic and Atmospheric Administration (NOAA) and provided by G. Taylor. These wind data were manually entered into spreadsheet software (Excel, Versions 3.0 and 4.0). The data set included an average wind speed per day in miles per hour. The daily data also included wind speeds throughout the day at 3-hour intervals; the highest speed listed per day, based on eight observations, was selected as the maximum daily wind.

Another site external to the Bull Run watershed from which wind data were obtained was the Dallesport Airport (DPA), along the Columbia River in Washington (Fig. 4.1). G. Taylor provided a magnetic tape of data that was read by the University Computing Services at Oregon State University, and then transferred, via FTP, to the FSL computer system. Nothing is known about the recording device at DPA, such as site factors that would affect the local wind speeds, although the airport itself is located in close proximity to the Columbia River. The data covered the period January, 1948, through December, 1964, and over 99% of these days were included in the data set (Table 4.1). Average and maximum daily winds, in miles per hour, were provided. Because the wind directions for the period 1959-64 were excluded from the data set, only the years 1948 through 1958 were used for analysis.

4.3.1.3 Other climatic data

Daily temperature and precipitation data from within the Bull Run watershed are recorded at the Headworks for the reservoirs, located one-quarter of a mile downstream from the dam at Reservoir #2 (Fig. 4.1). These data were available in digital format from January, 1931, through December, 1994, via FTP from G. Taylor, and were maintained on the computer system at FSL. From the daily precipitation figures, a 14-day cumulative amount of precipitation, i.e. the sum of the precipitation in the 14 days preceding the day of interest, was calculated as an indicator of soil moisture.

4.2.2 Data analysis

To characterize the weather in the Bull Run watershed, histograms were generated of daily minimum and maximum temperatures for the years 1931 through 1994 with the data from Reservoir #1. Daily precipitation data were used for the same period to chart the daily and seasonal amounts of precipitation.

To establish relationships between wind speeds at different sites, the availability of wind data from each site was compared to determine the years when data sets coincided. Simple linear regressions were performed in Systat (Version 5.1.2) to establish a mathematical relationship between the wind speeds at different sites. Regressions were also estimated with the data classified by season and wind direction.

The PDX wind data for the 47-yr. period between 1948 and 1994 were used to characterize the wind regime at the airport site. Histograms of the daily average and maximum wind speeds were created, and the frequency distribution of wind directions was graphed. These data were also divided by season to ascertain if the wind regime fluctuated during the year, and histograms of daily average, maximum, and wind directions by season were generated.

Wind data from PDX and temperature and precipitation data from the Bull Run were consolidated for the years 1948 - 1994 to characterize storm events that generate windthrow in the Bull Run. Soil moisture has been identified as a contributing factor to windthrow (Gratkowski 1956; Quine and White 1993; Coutts 1986). Additionally, sub-freezing temperatures were associated with the 1973 and 1983 windthrow events in the Bull Run (Sinton 1996a, unpublished), and this can affect the modulus of elasticity and bending strength of wood (Comben 1964; U.S.D.A. Forest Service 1972; Gerhards 1982), although it is uncertain whether the effects could be manifested on stands of trees over the course of a single storm event.

The basis for a predictive model for windthrow-generating storms was the ranking of wind and climate data in conjunction with mean return intervals for extreme events. All 1948-1994 data for maximum daily temperature, daily precipitation and 14-day cumulative precipitation amounts, as well as maximum and average daily wind speeds, were ranked, and days that fell within the top 1% of precipitation amounts and wind speeds, and bottom 1% of maximum temperatures, were selected. The 1%-level was chosen both because it represented extreme events and the known windthrow events of 1973 and 1983 were included within the group.

The calculation of the frequency or mean return interval of windthrow-generating storms in the Bull Run first involved using the wind data from PDX. Individual mean return intervals for both the daily maximum and average wind speeds in the top 1% category were formulated, and as a second step, a return interval was determined for days in which *both* maximum and average wind speeds were in the top 1%. Return intervals were also generated for storm "events," i.e., when all criteria were met on consecutive days, the days were pooled into one single event.

All days and events identified by their 1% wind rankings were organized by direction to establish the most likely directions of origin for fast winds. Over the past 100 years, significant windthrow has been created only by winds coming from the east, northeast, or north at the Bull Run (Sinton 1996a, unpublished). Therefore, the third step involved excluding days in which winds were from any direction other than the east, northeast or north, and return intervals were calculated for the remaining days and events.

A fourth step in calculating a mean return interval for windthrow-generating storms involved selecting, from the data set that met all wind criteria, the days that fell within the bottom 1% of the maximum temperature rankings.

4.3 Results

4.3.1 Climate in the Bull Run watershed

The temperature and precipitation regimes in the Bull Run watershed are typical of the Pacific Northwest: summers are warm and dry, and winters are cool and wet. The mean minimum temperature during the years 1931 to 1994 was 42°F, and the mean maximum temperature was 61°F (Fig. 4.2 and Fig. 4.3). One-percent of the days had a maximum temperature less than 32° F, and the minimum temperature was less than 20° F on 1% of the days measured. Over 60% of days during the 64-year period had zero precipitation (Fig. 4.4) and nearly forty percent of all precipitation occurs during the winter months of December through February (Fig. 4.5). Seventy-one percent of all precipitation falls during the period between November and April. The average annual amount of precipitation measured at the Headworks station was 84 inches (2134 mm), a value that may under-represent precipitation at higher elevations in the watershed. Cumulative precipitation during any two-week period was less than 2 inches of rain over two-thirds of the time (Fig. 4.6).

4.3.2 Wind data from multiple sites

Portland Airport wind data were available for the 47-yr. period between 1948 and 1994; no other site had as long an available record (Fig. 4.7). Four different sets of linear regressions were conducted among the available data sets, depending on the dates of available data from each site.

4.3.2.1 Dallesport Airport (DPA) and Portland Airport (PDX)

On any given day, wind speeds between Dallesport and Portland were not similar. The closest relationship existed during winter months (Fig. 4.8). Except at very low wind speeds, PDX wind speeds were faster than DPA winds. When

Figure 4.2 Daily minimum temperatures in the Bull Run watershed, Oregon, from 1931 - 1994

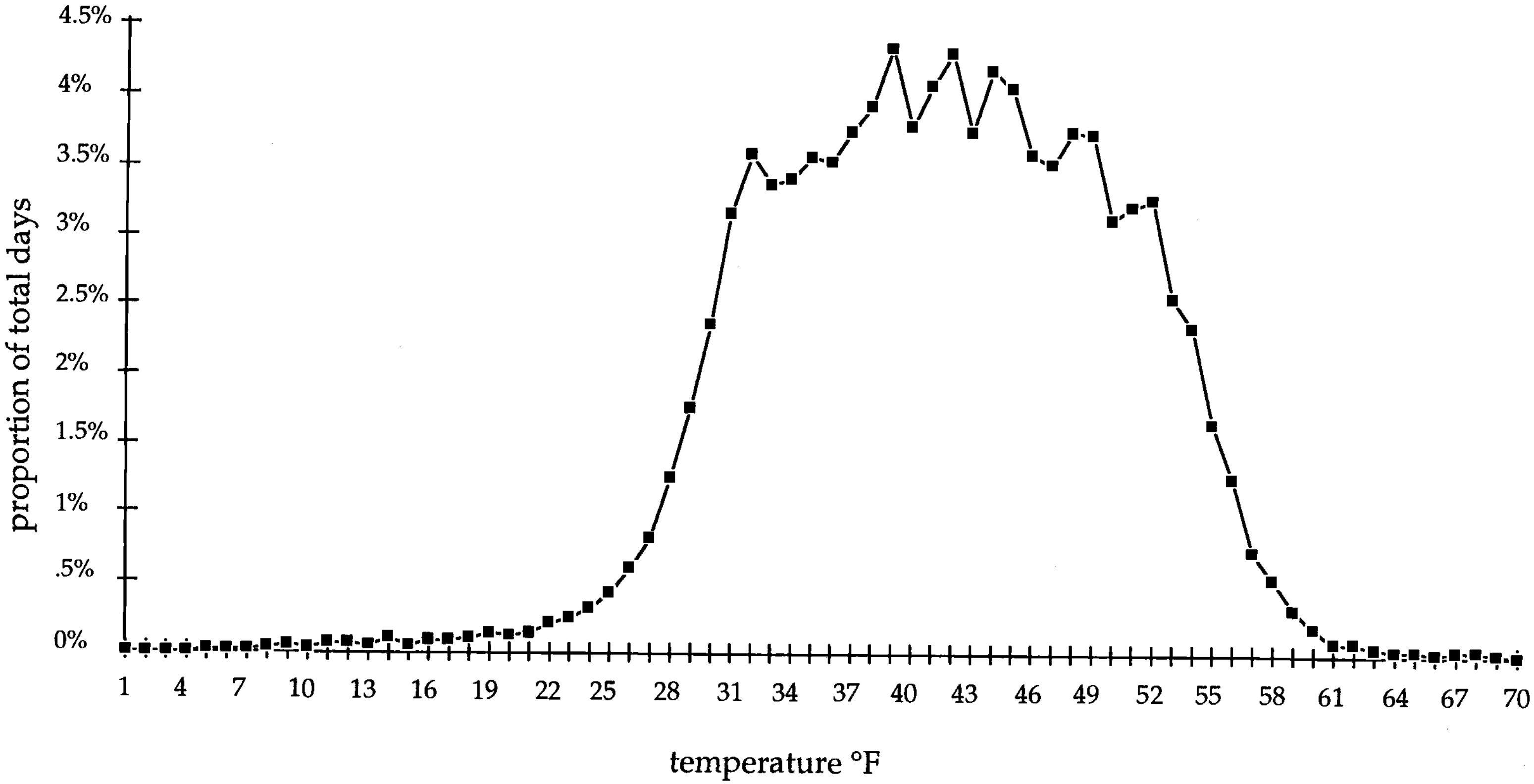


Figure 4.3 Daily maximum temperatures in the Bull Run watershed, Oregon, from 1931-1994

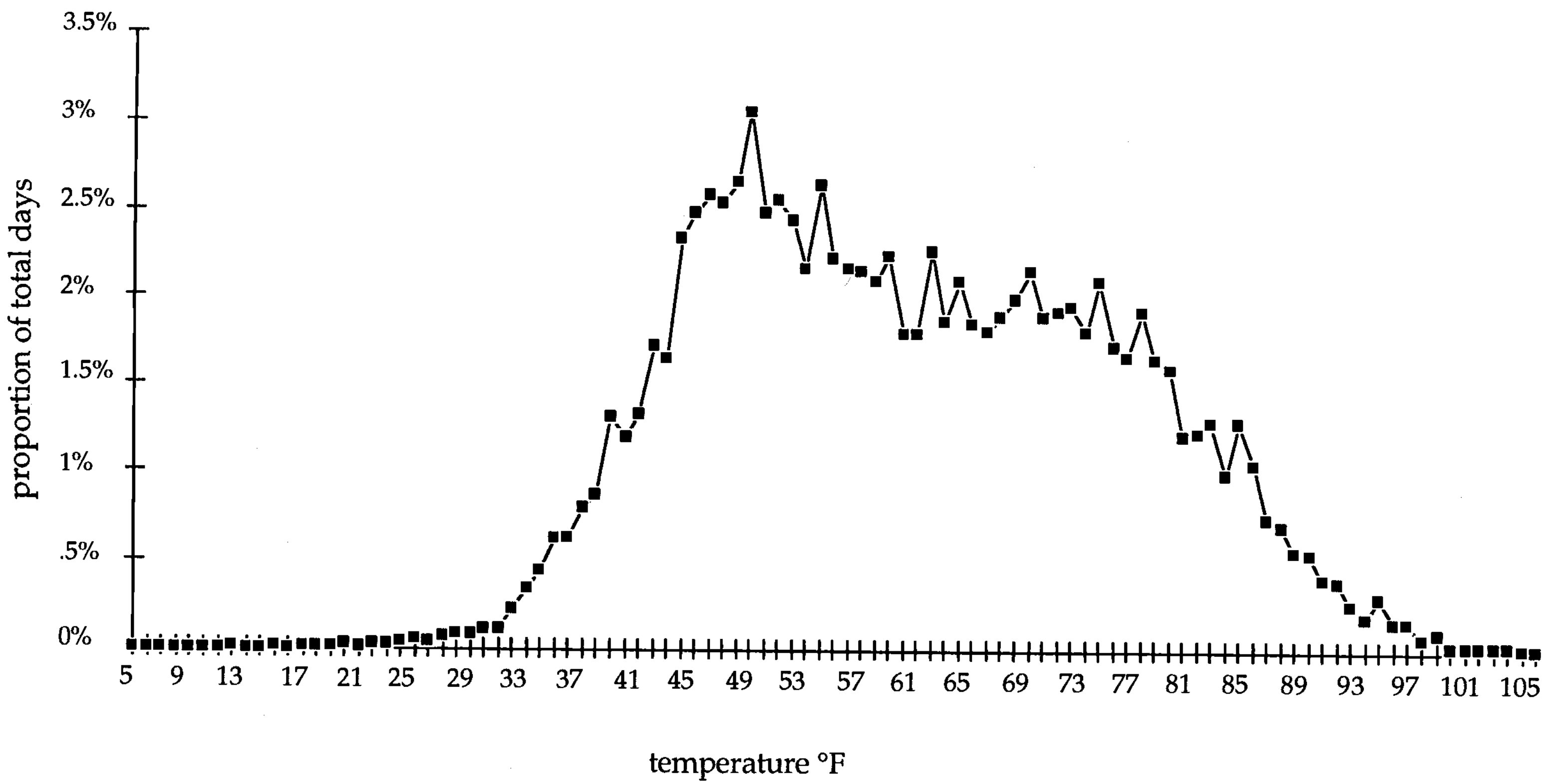


Figure 4.4 Daily precipitation in the Bull Run watershed, 1931-1994.

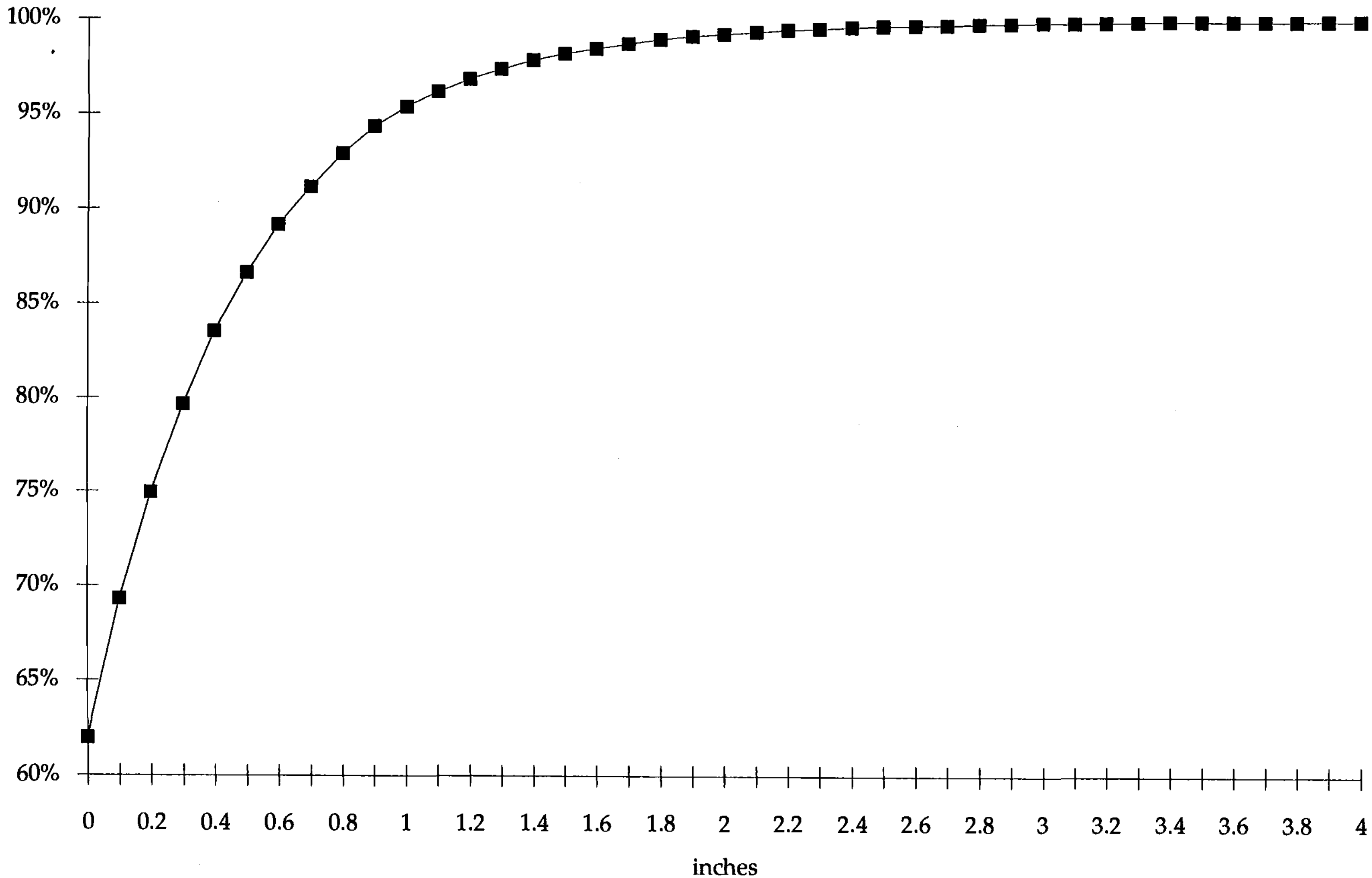


Figure 4.5 Precipitation in the Bull Run watershed, Oregon, by season, 1931-1994. Winter equals December to February; spring is March through May; summer months are June through August; and fall equals September to November.

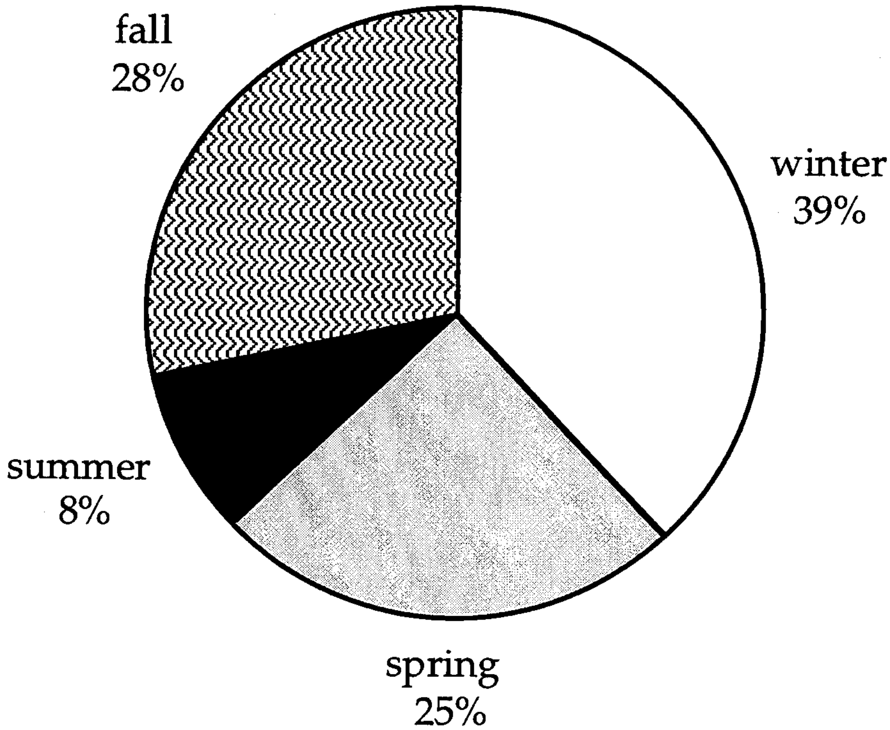


Figure 4.6 Cumulative precipitation over two week periods in the Bull Run watershed, 1931-1994.

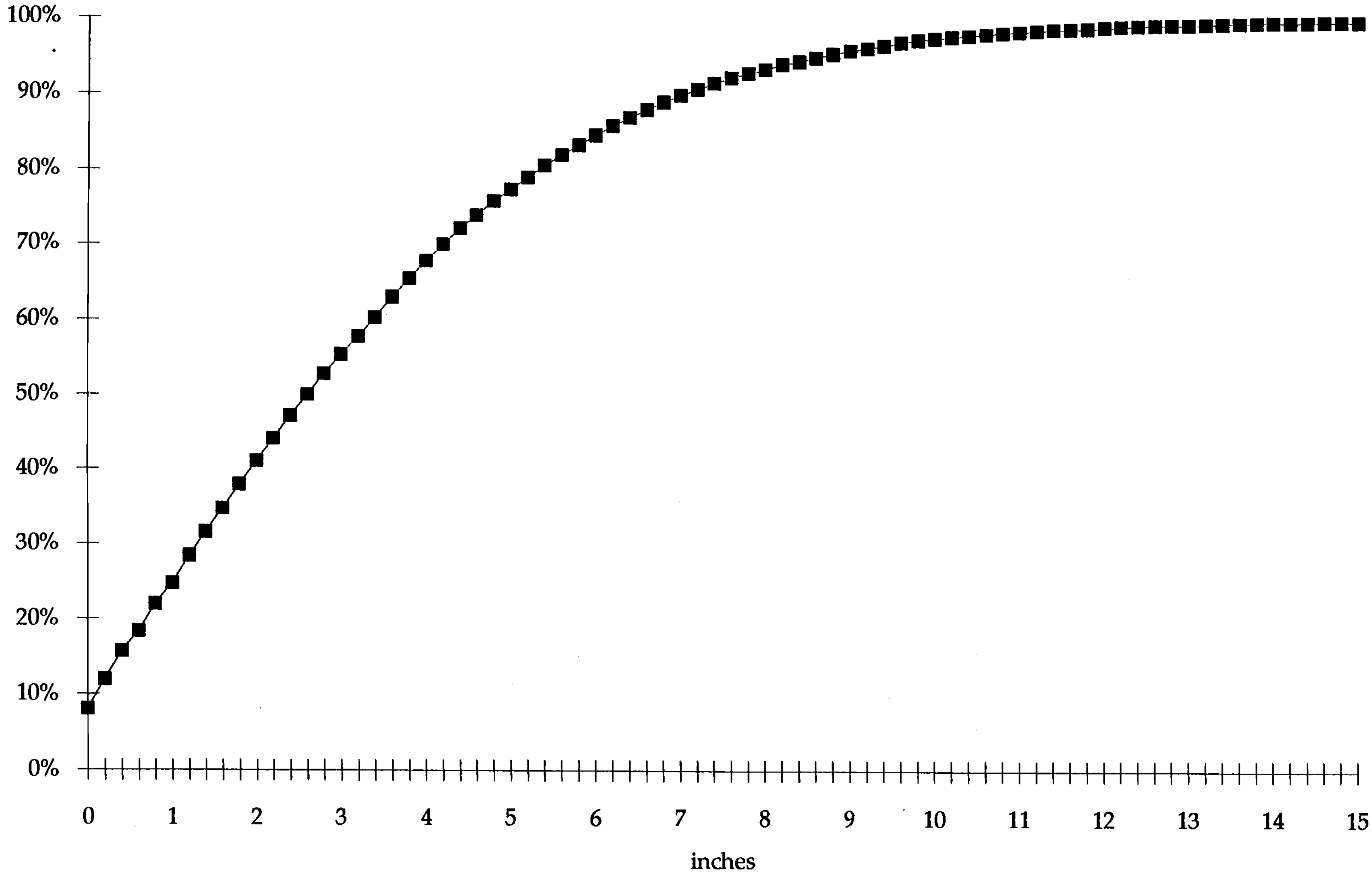


Figure 4.7 The period of record available for wind data in the vicinity of the Bull Run watershed, Oregon. Linear regressions were performed between wind data from different sites when the data overlapped in time. The four different sets of regressions were between the data sets designated with arrows.

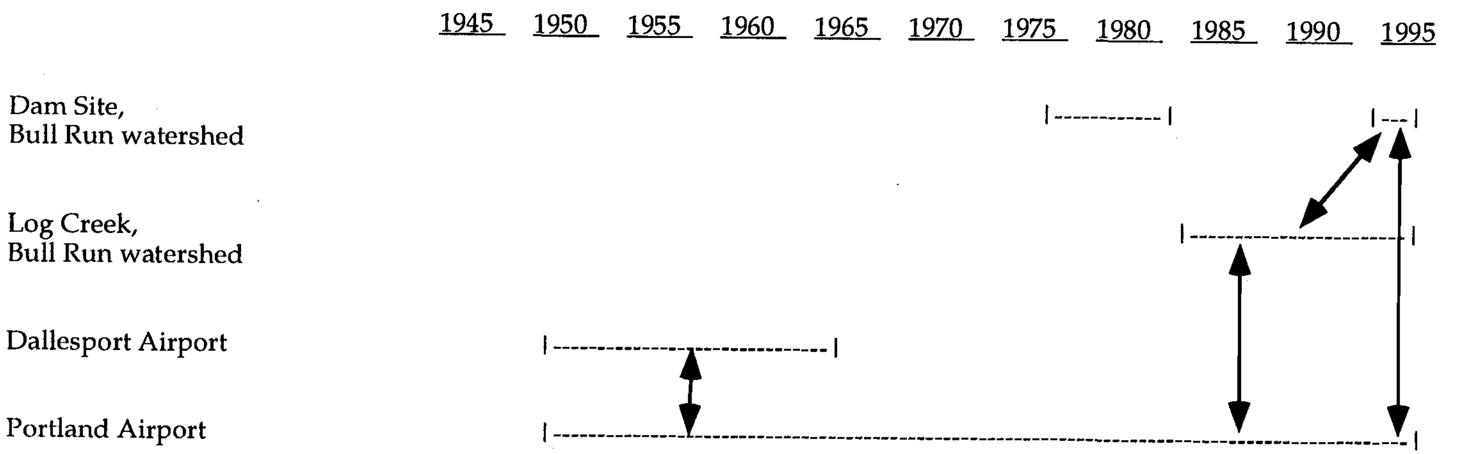
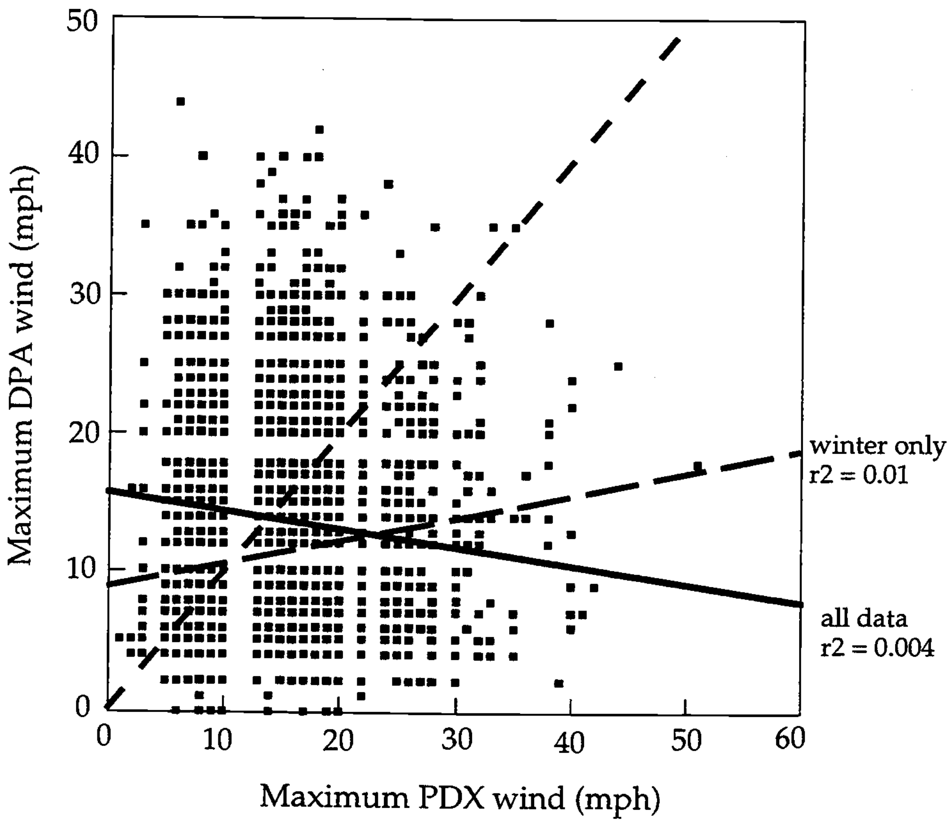


Figure 4.8 Linear regressions of wind speeds from Dallesport Airport, Washington, and Portland Airport, Oregon, 1948-1958. Small-dashed line indicates equal values at both stations.



winds were from the east, either in Dallesport or Portland, the wind speeds at the two sites were slightly similar at low speeds, but when wind speeds were greater, PDX winds were faster than DPA winds (Table 4.2). No statistical relationship existed between wind speeds at DPA and PDX when winds were from the southwest.

The Dallesport Airport and the Portland Airport were the two sites furthest apart from one another, and they are located on different sides of the topographical division created by the Cascade Mountains. This affects not only wind speeds, but also wind directions. In the summer months, winds at both sites are most frequently from the northwest (Fig. 4.9). During the winter, however, most of the winds at the Portland Airport are blowing from the southeast and east, while winds at Dallesport Airport are equally divided between the northeast/east and southwest/west directions.

4.3.2.2 Dam site in the Bull Run (DAM) and Portland Airport (PDX)

Average and maximum daily wind speeds were higher at PDX than at DAM (Fig. 4.10). During the winter months, wind speeds were more similar than at other times. On days when winds were from the east at PDX, wind speeds between the two sites were closely matched (Table 4.3). This relationship was not as strong on days with east winds at the Dam site, or on any day with southwesterly winds at either site (Fig. 4.10).

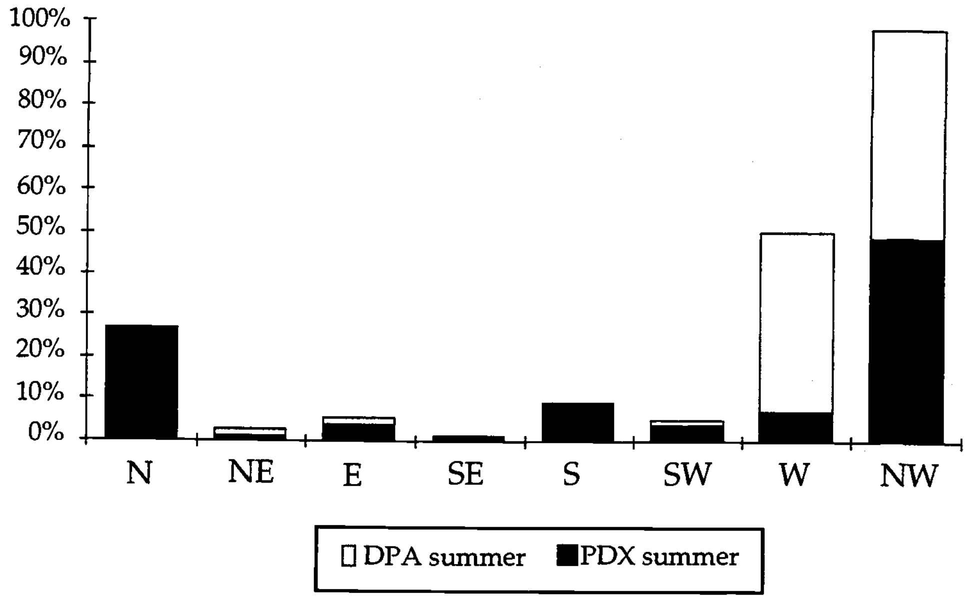
4.3.2.3 Log Creek site in the Bull Run (LC) and Portland Airport (PDX)

Wind speeds at LC were matched slightly more closely with average than maximum wind speeds at PDX (Fig. 4.11). This is consistent with the method with which the LC wind data were collected: one measurement per day versus calculations of daily wind speeds based on hourly observations. Winter wind speeds were slightly more consistent between the two sites than winds during other seasons. The wind direction did not greatly affect the relationship between

Table 4.2 Results of linear regressions of wind speeds from different directions at the Dallesport Airport, Washington, and the Portland International Airport, Oregon. Linear regressions were performed with data from days with winds from the east/northeast and south/southwest directions at the Dallesport and Portland airports.

dependent variable	independent variable	n		coefficient	stnd. error	p-value	adj. squared multiple r
DPA wind speeds when wind is from E @ DPA	PDX wind speeds when wind is from E @ DPA	861	constant	7.223	0.425	0.000	0.03
			ind. variable	0.128	0.024	0.000	
DPA wind speeds when wind is from E @ PDX	PDX wind speeds when wind is from E @ PDX	804	constant	12.605	0.62	0.000	0.011
			ind. variable	-0.122	0.038	0.002	
DPA wind speeds when wind is from SW @ DPA	PDX wind speeds when wind is from SW @ DPA	3018	constant	16.789	0.364	0.000	0.000
			ind. variable	0.001	0.024	0.965	
DPA wind speeds when wind is from SW @ PDX	PDX wind speeds when wind is from SW @ PDX	2873	constant	16.915	0.368	0.000	0.000
			ind. variable	-0.027	0.023	0.244	

Figure 4.9 Summer and winter winds by direction at the Portland Airport, Oregon, and the Dallesport Airport, Washington. Summer months are June through August, and winter months are December through February.



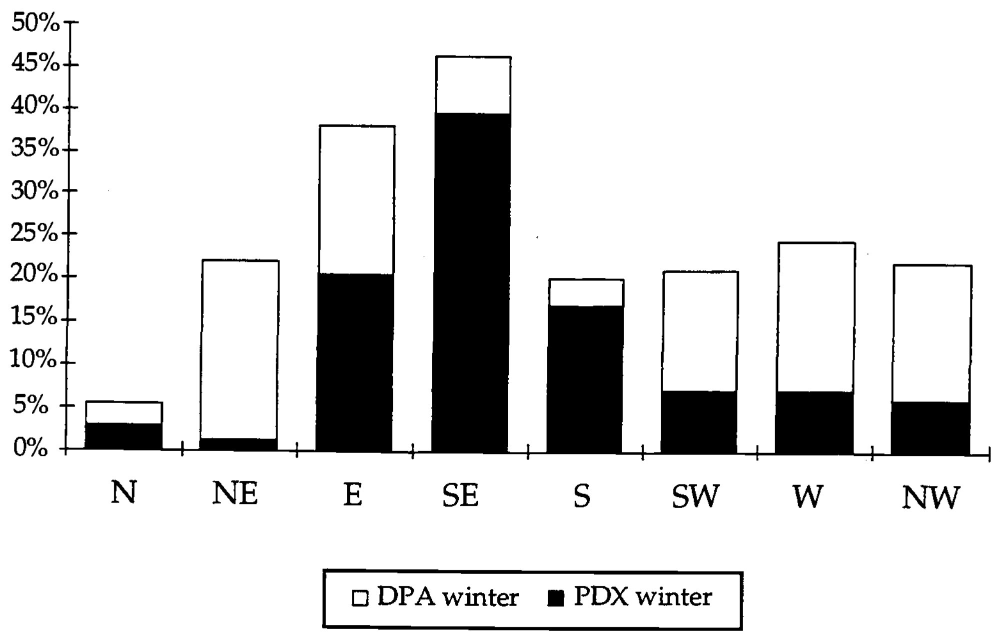
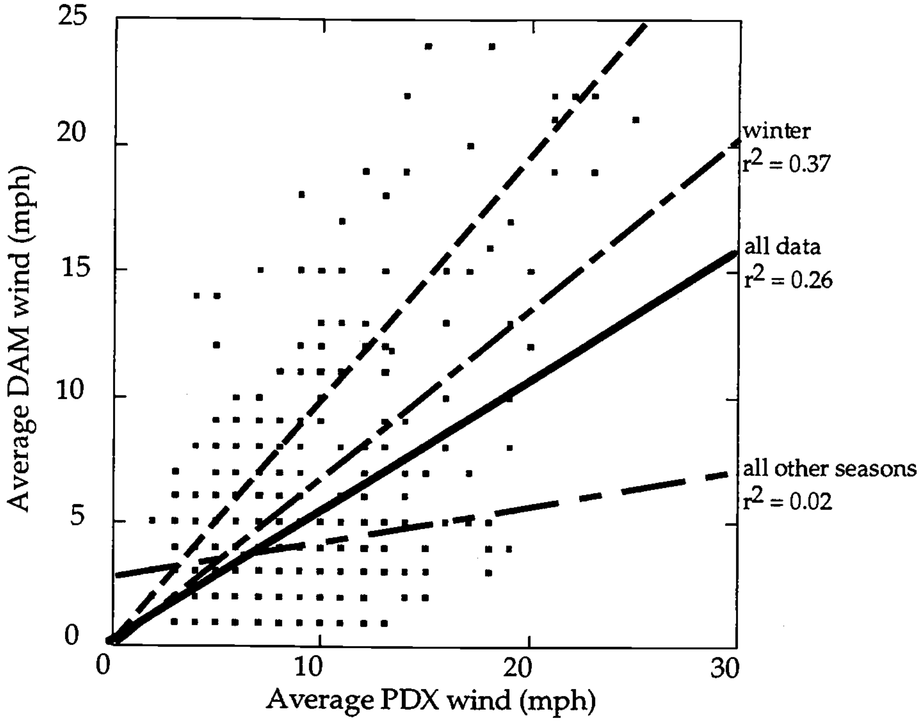


Table 4.3 Results of linear regressions of wind speeds from different directions at the Dam site, Bull Run watershed, and the Portland International Airport, Oregon. Linear regressions were performed with data from days with winds from the east/northeast and south/southwest directions at the Dam site and the Portland Airport.

dependent variable	independent variable	n		coefficient	stnd. error	p-value	adj. squared multiple r
DAM wind speeds when wind is from E @ DAM	PDX wind speeds when wind is from E @ DAM	40	constant	9.652	2.152	0.000	0.342
			ind. variable	0.539	0.177	0.000	
DAM wind speeds when wind is from E @ PDX	PDX wind speeds when wind is from E @ PDX	144	constant	-0.607	0.952	0.525	0.649
			ind. variable	0.975	0.06	0.000	
DAM wind speeds when wind is from SW @ DAM	PDX wind speeds when wind is from SW @ DAM	522	constant	4.295	0.563	0.000	0.161
			ind. variable	0.398	0.04	0.000	
DAM wind speeds when wind is from SW @ PDX	PDX wind speeds when wind is from SW @ PDX	333	constant	8.304	0.493	0.000	0.000
			ind. variable	0.013	0.035	0.72	

Figure 4.10 Linear regressions of wind speeds from the DAM site in the Bull Run Watershed and the Portland Airport, Oregon, 1993-1994. Small-dashed line indicates equal values at both stations.



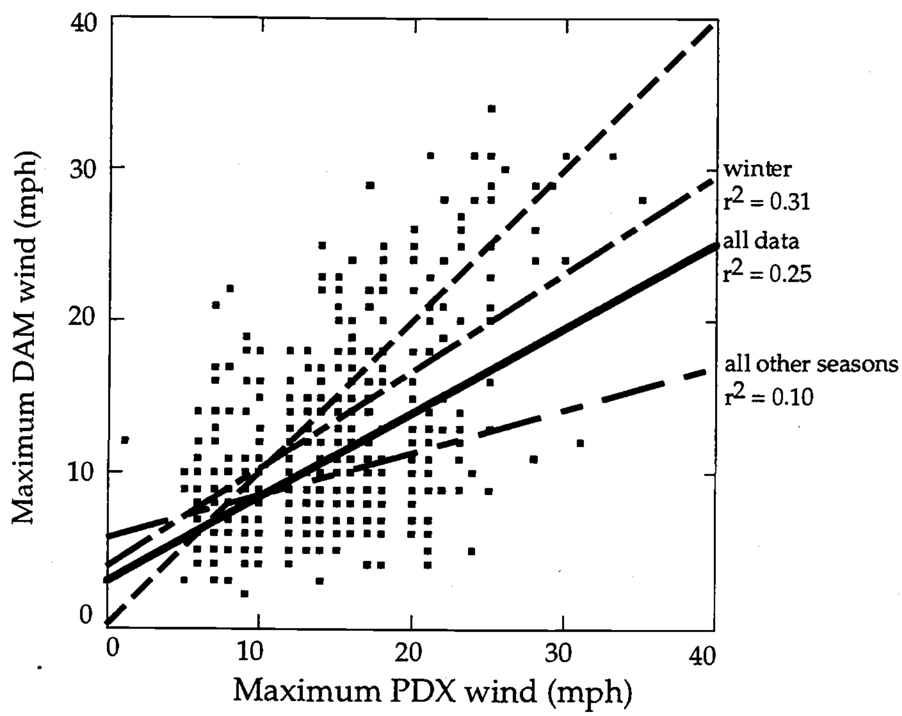
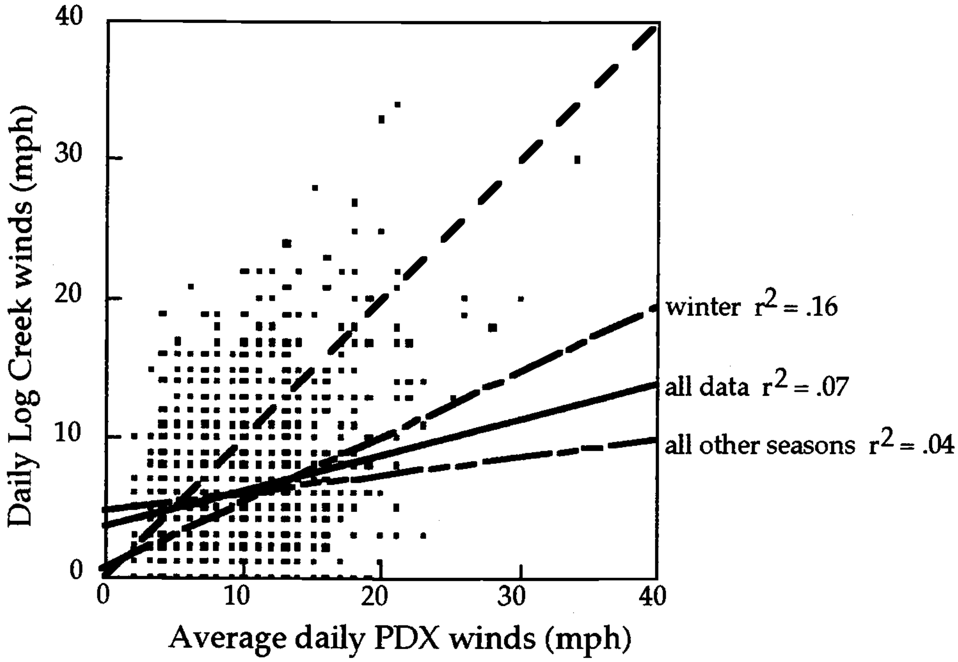
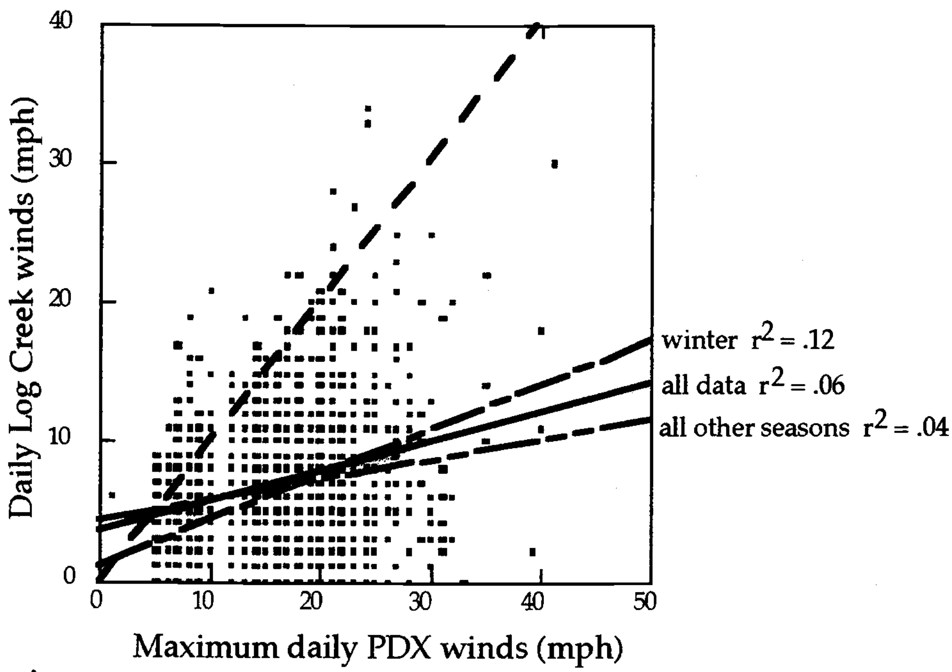


Figure 4.11 Linear regressions of wind speeds from the Log Creek site, Bull Run watershed, and the Portland Airport, Oregon, 1981-1994. Evenly-dashed line indicates equal values at both stations.





wind speeds at LC and PDX, though it was closer with easterly winds than winds from the southwest (Table 4.4).

4.3.2.4 Dam site (DAM) and Log Creek site (LC)

The correlation between wind speeds at LC and the Dam site was stronger with daily average winds than daily maximum speeds (Fig. 4.12), and winter winds were more similar than winds during other seasons. Overall, wind speeds at the Dam site tended to be higher than at LC. There was a closer relationship between wind speeds on days with easterly winds, whether they were recorded at LC or DAM, than on any day with winds from a southwesterly direction (Table 4.5).

4.3.3 Wind regime at the Portland Airport

The distributions of average and maximum daily wind speeds at the Portland Airport were dominated by low wind speeds. Over the years 1948 - 1994, the mean average wind speed was 8 m.p.h. (3.5 m/sec), and the median was 7 m.p.h. (3.1 m/sec) (Fig. 4.13). The highest daily average wind speeds occur in winter (Fig. 4.14).

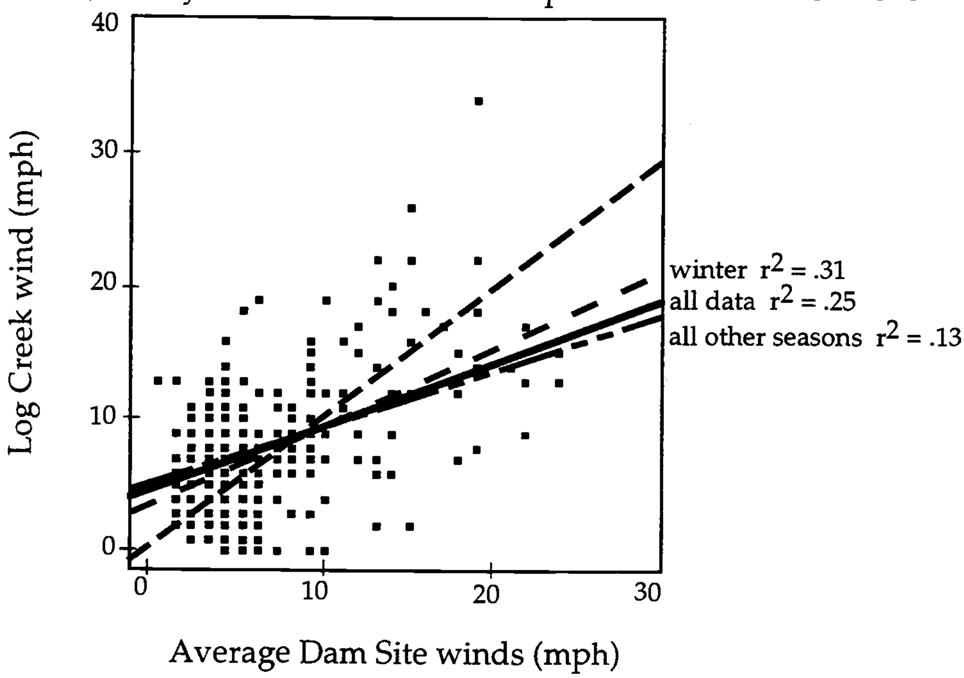
The mean maximum daily wind speed over the same time period was 14 m.p.h. (6.2 m/sec) and the median was 13 m.p.h. (5.7 m/sec). The range of recorded maximum daily wind speeds at the Portland Airport extended from 1 m.p.h. (.4 m/sec) to 63 m.p.h. (28 m/sec) (Fig. 4.15). This maximum value was associated with the Columbus Day Storm (October 12, 1962), a severe wind storm in western Oregon.

Daily maximum winds tend to be higher during the storm season (October through May) than during the summer (Fig. 4.16), but there are no strong annual trends in maximum daily wind speeds averaged over the 47-yr. period (Fig. 4.17). The slight decrease in extreme values since the mid-1980s is a reflection of the method in which the data were collected for the period 1985-1994 (see Methods section above).

Table 4.4 Results of linear regressions of wind speeds from different directions at the Log Creek site, Bull Run watershed, and the Portland International Airport, Oregon. Linear regressions were performed with data from days with winds from the east/northeast and south/southwest directions at the Log Creek site and the Portland Airport.

dependent variable	independent variable	n		coefficient	stnd. error	p-value	adj. squared multiple r
LC wind speeds when wind is from E @ LC	PDX wind speeds when wind is from E @ LC	731	constant	2.716	0.46	0.000	0.128
			ind. variable	0.48	0.046	0.000	
LC wind speeds when wind is from E @ PDX	PDX wind speeds when wind is from E @ PDX	935	constant	2.316	0.333	0.000	0.188
			ind. variable	0.528	0.036	0.000	
LC wind speeds when wind is from SW @ LC	PDX wind speeds when wind is from SW @ LC	2696	constant	4.111	0.183	0.000	0.029
			ind. variable	0.206	0.023	0.000	
LC wind speeds when wind is from SW @ PDX	PDX wind speeds when wind is from SW @ PDX	2338	constant	4.295	0.201	0.000	0.024
			ind. variable	0.188	0.024	0.000	

Figure 4.12 Linear regressions of wind speeds from the Dam site and Log Creek, Bull Run watershed, Oregon, 1993-1994. Small, evenly-dashed line indicates equal values at both stations.



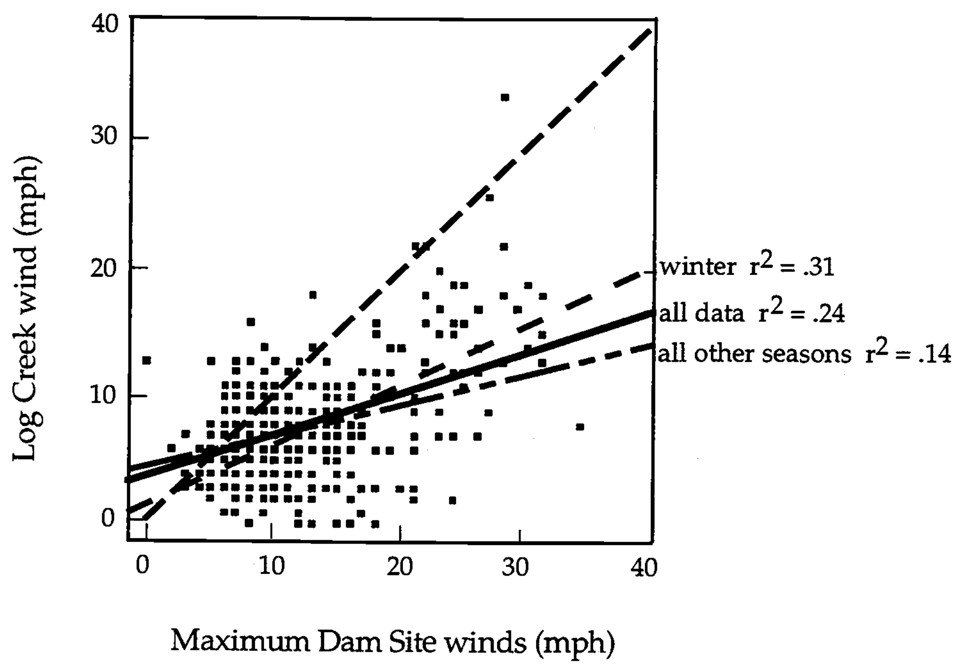


Table 4.5 Results of linear regressions of wind speeds from different directions at the Log Creek and Dam sites, Bull Run watershed, Oregon. Linear regressions were performed with data from days with winds from the east/northeast and south/southwest directions at the Log Creek and Dam sites.

dependent variable	independent variable	n		coefficient	stnd. error	p-value	adj. squared multiple r
LC wind speeds when wind is from E @ LC	DAM wind speeds when wind is from E @ LC	119	constant	2.819	0.798	0.001	0.423
			ind. variable	0.737	0.079	0.000	
LC wind speeds when wind is from E @ DAM	DAM wind speeds when wind is from E @ DAM	32	constant	2.933	2.088	0.17	0.315
			ind. variable	0.651	0.167	0.000	
LC wind speeds when wind is from SW @ LC	DAM wind speeds when wind is from SW @ LC	378	constant	5.84	0.249	0.000	0.022
			ind. variable	0.18	0.059	0.002	
LC wind speeds when wind is from SW @ DAM	DAM wind speeds when wind is from SW @ DAM	460	constant	4.729	0.24	0.000	0.22
			ind. variable	0.526	0.046	0.000	

Figure 4.13 Average daily winds at the Portland Airport, 1948 - 1994.

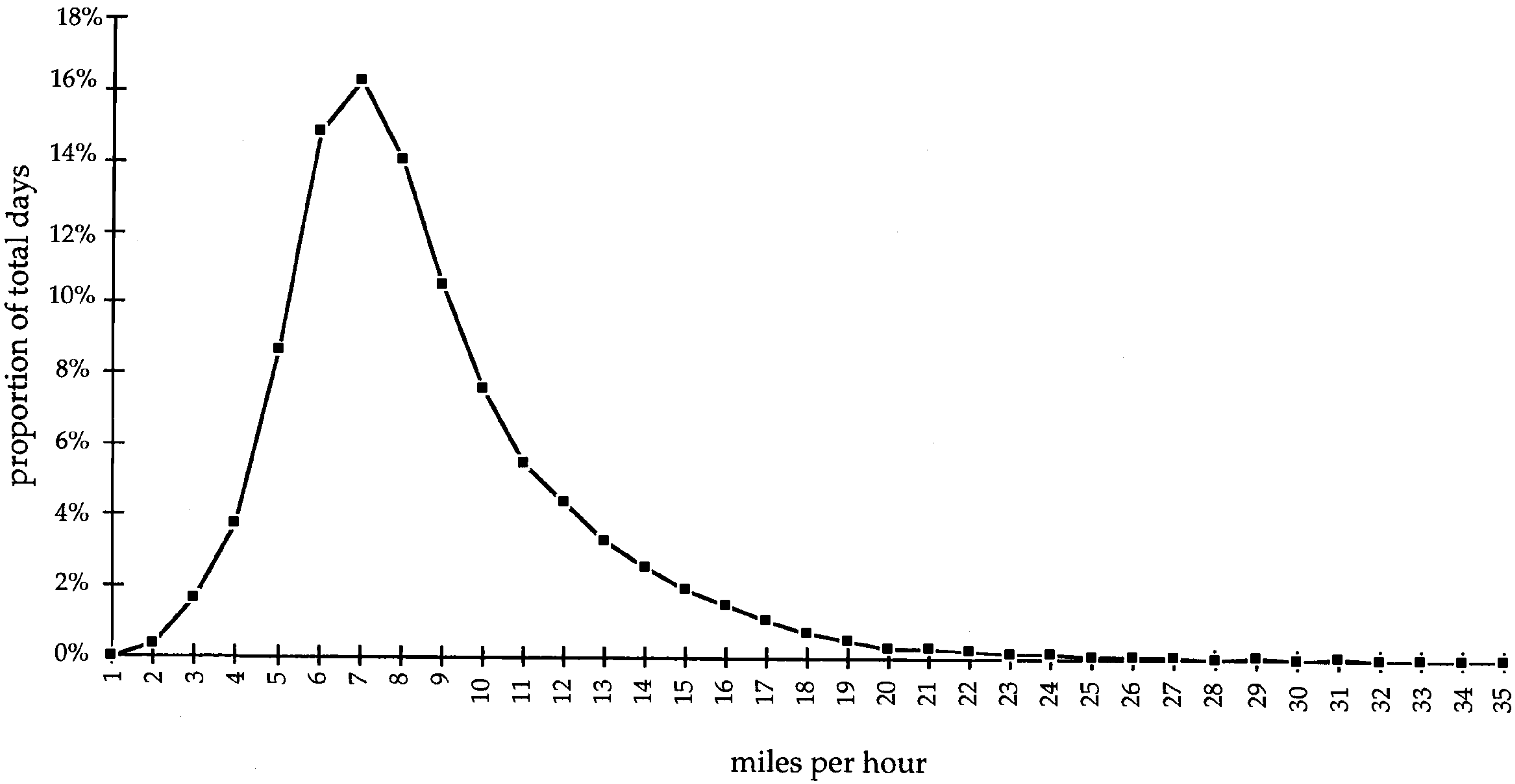


Figure 4.14 Average daily wind speeds by season at the Portland Airport, 1948-1994.
Winter months include December - February; spring are March - May; summer months are June - August; and fall are September through November.

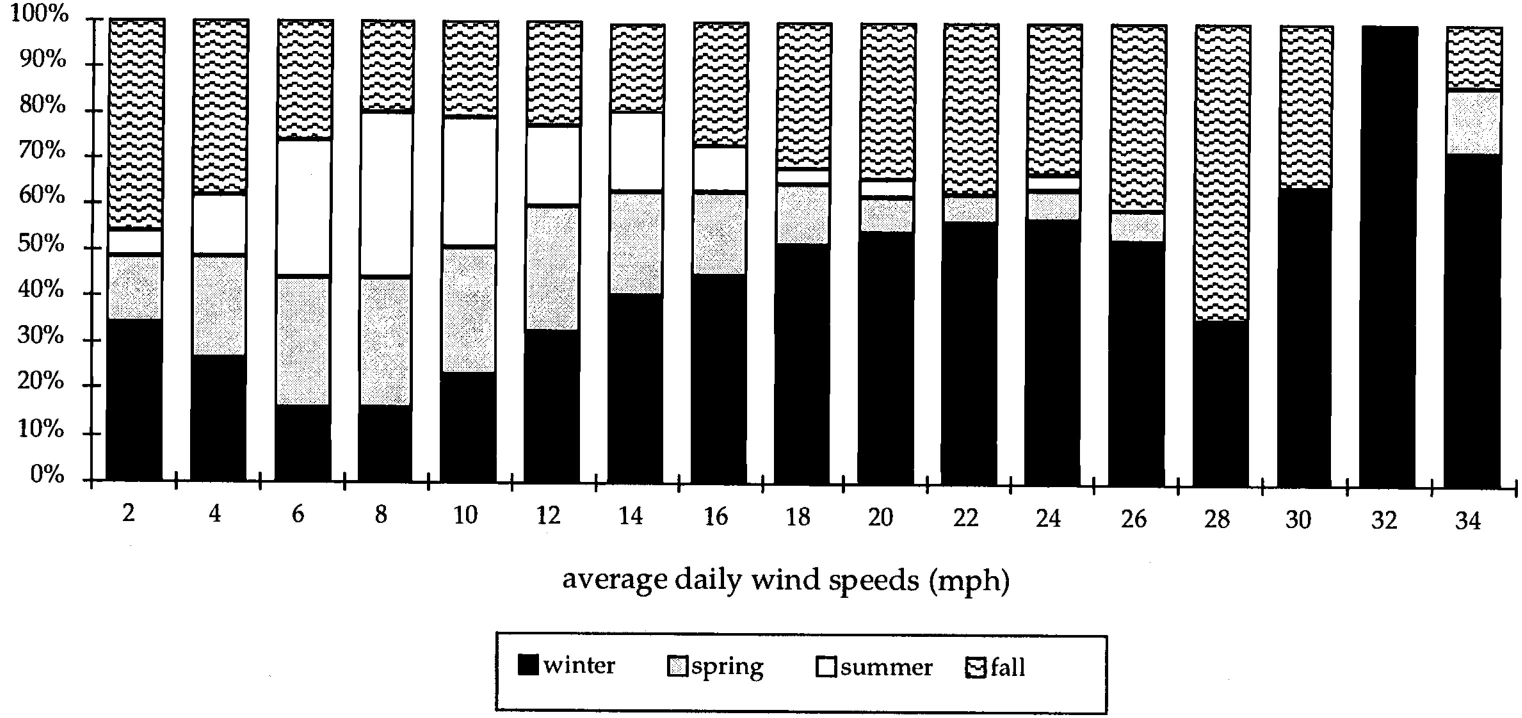


Figure 4.15 Maximum daily winds at the Portland Airport, 1948-1994.

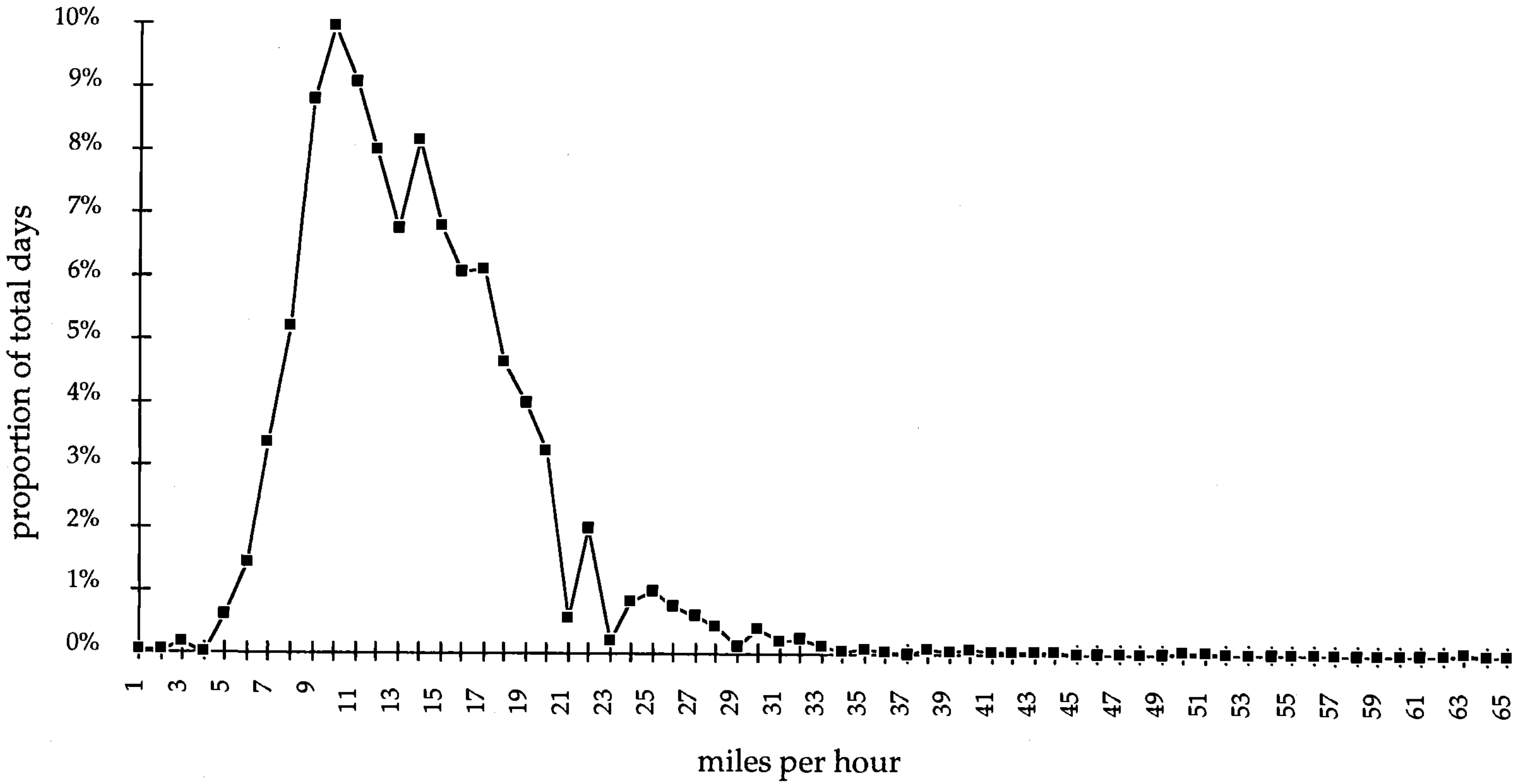


Figure 4.16 Maximum daily winds by season at the Portland Airport, 1984 - 1994. Winter months are December through February, spring months are March through May, summer are June through August and fall months are September through November.

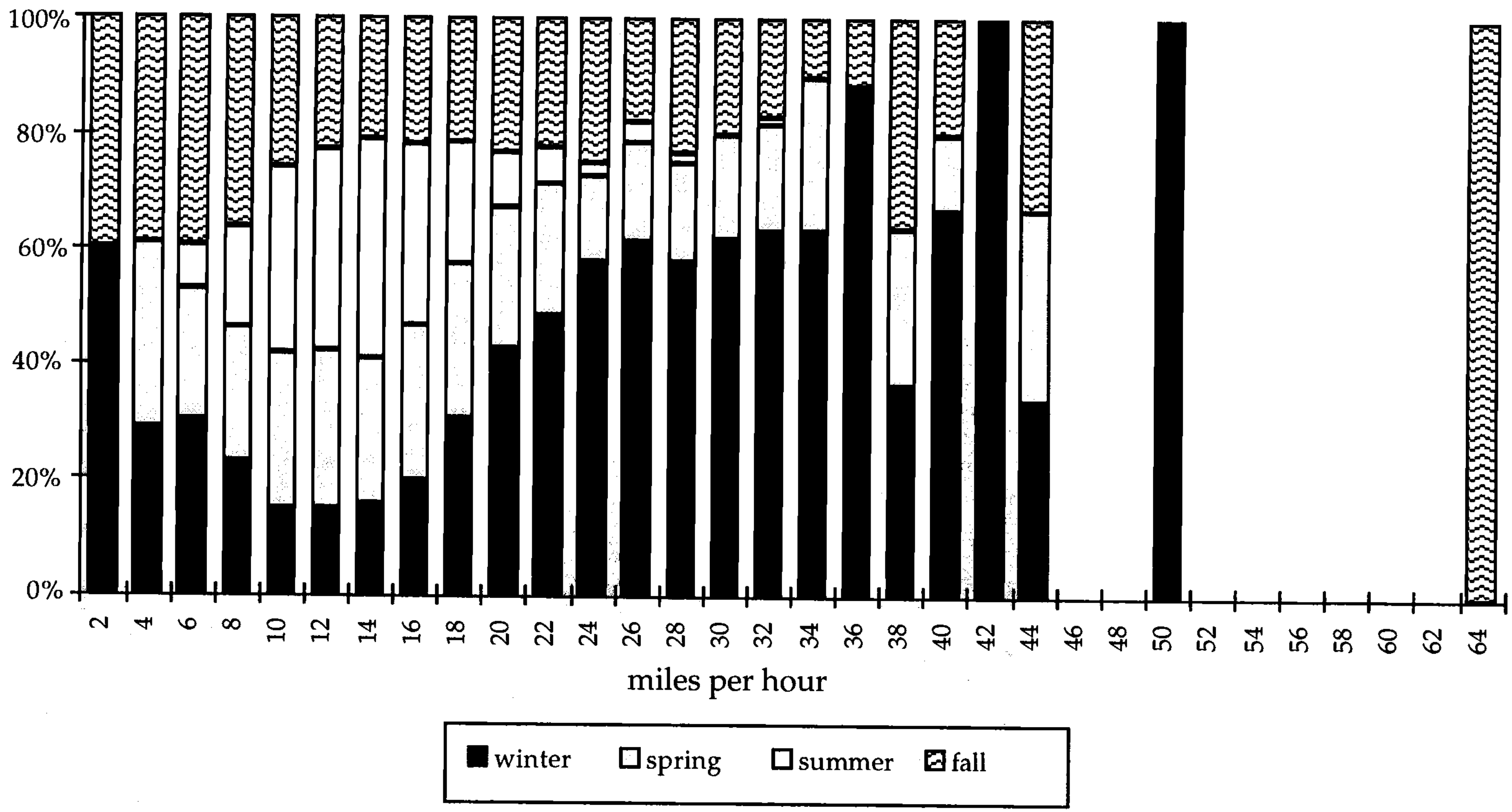
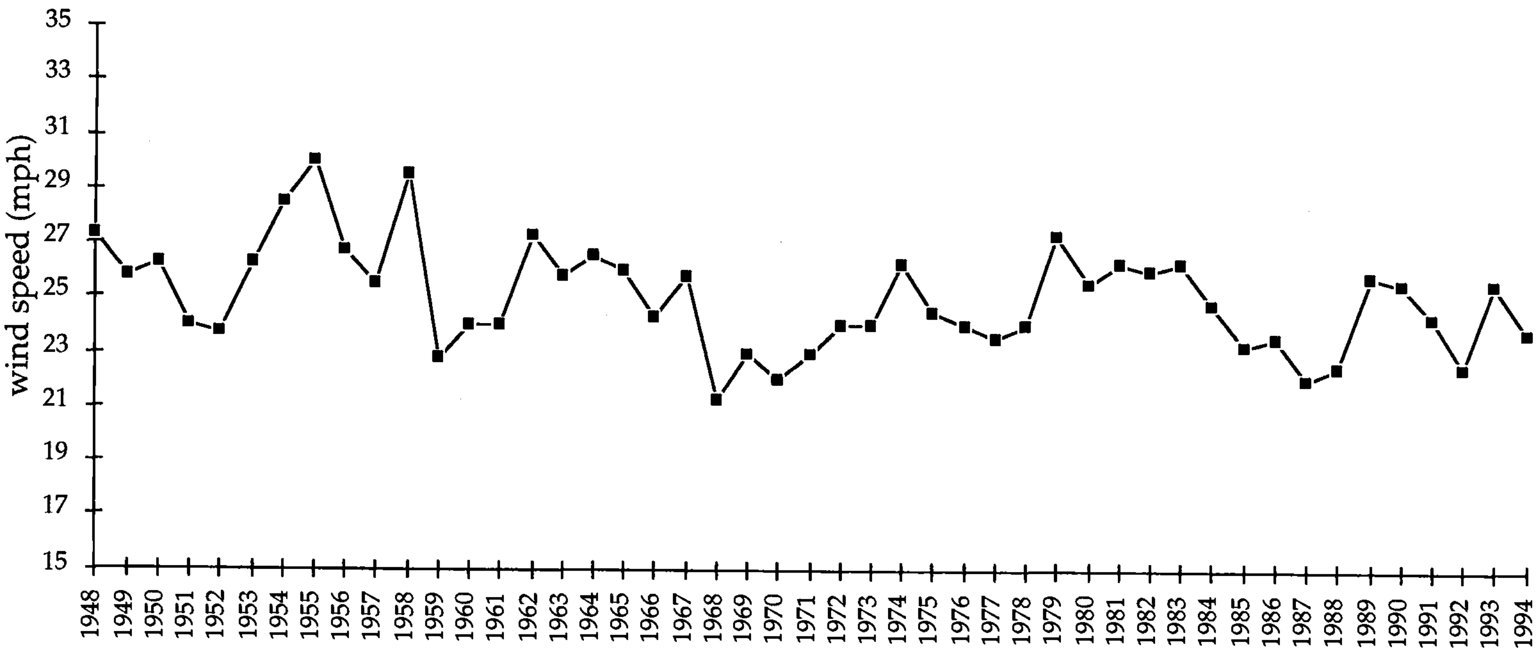


Figure 4.17 Trends in the average annual maximum wind speeds at the Portland Airport, 1948 - 1994. The wind speed for each year was obtained by taking the average of the five highest speeds in each season of every year, and then averaging the seasonal values for each year.



Over the whole period between 1948 and 1994, most of the winds came from the northwest and west at the Portland Airport (Fig. 4.18). Only 17% of the winds came from the north, northeast, and east, the directions most associated with windthrow in the Bull Run. Seasonally, winds from the north and northwest are more common in the summer months, and in the winter, most winds are easterly or southeasterly (Fig. 4.19).

There has been a shift over time in the directions of the daily maximum winds (Fig. 4.20). Between 1948 and 1958, few days had maximum winds from the east. Since that time, the most common direction of maximum wind speeds appears to fluctuates between an east/northeast direction and a south/southwest direction in one-to-three year cycles, though it is not certain whether this cyclical pattern is authentic or a reflection of the methods in which maximum wind speed data were collected.

4.3.4 Windthrow-generating storms in the Bull Run watershed

The top 1% of daily wind speeds over the 1948-1994 period included days with maximum daily wind speeds of greater than or equal to 30 miles per hour (13 m/sec), and average daily wind speed of greater than or equal to 20 miles per hour (9 m/sec). There were 230 and 165 days that met the maximum and average wind criteria, respectively (Table 4.6). Only 89 days met both average and maximum wind speed criteria, and 49 (55%) of those days were associated with winds from the east. When only the maximum wind criterion was met, winds were most commonly from the south, but when both the maximum and average wind criteria were met, easterly winds dominated (Fig. 4.21).

The bottom 1% of maximum daily temperatures over the time period 1948-1994 consisted of daily temperatures less than 32° F (0°C). Only fifteen of the days that met all three wind criteria also met the temperature criterion (Table 4.6), and of those days, at least five are associated with windthrow in the Bull Run watershed.

Many of the days that meet wind and temperature criteria are consecutive, producing higher mean than median return intervals. Both the 1973 and the 1983 storms that caused windthrow in the Bull Run watershed were two or three days' duration. The return intervals of events are greater than individual days; only

Figure 4.18 Direction of winds at the Portland Airport, 1948-1994.

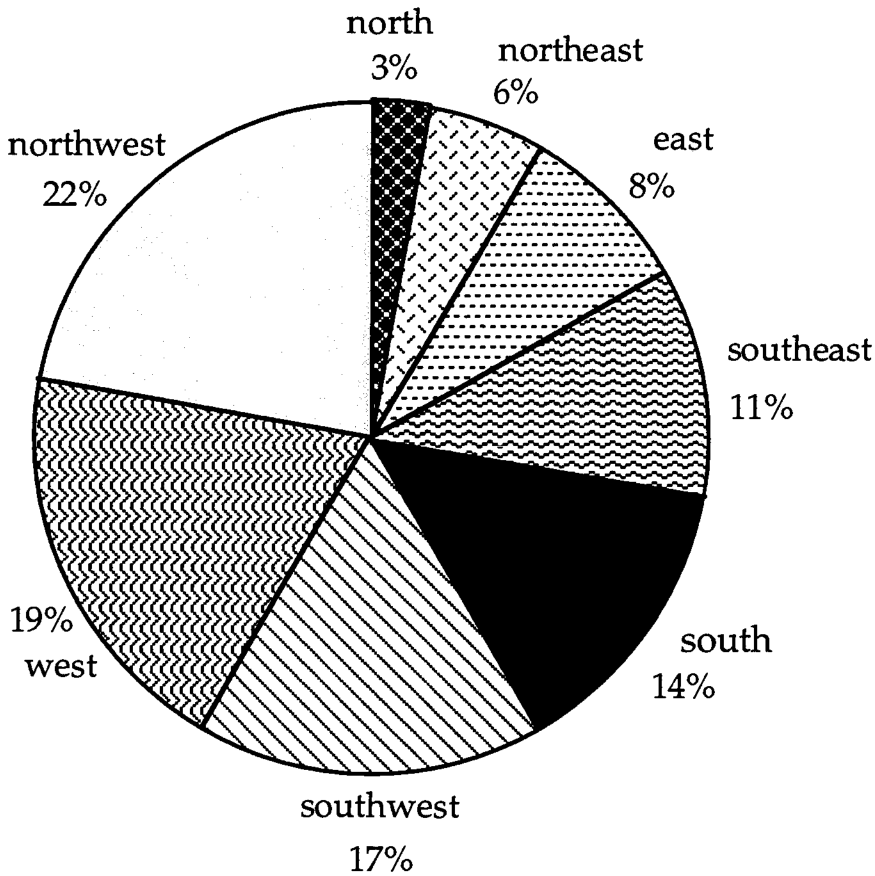


Figure 4.19 Directions of wind at the Portland Airport by season, 1948-1994.
Winter months are December throuth February, spring months are March through May, summer are June through August, and fall months are September through November.

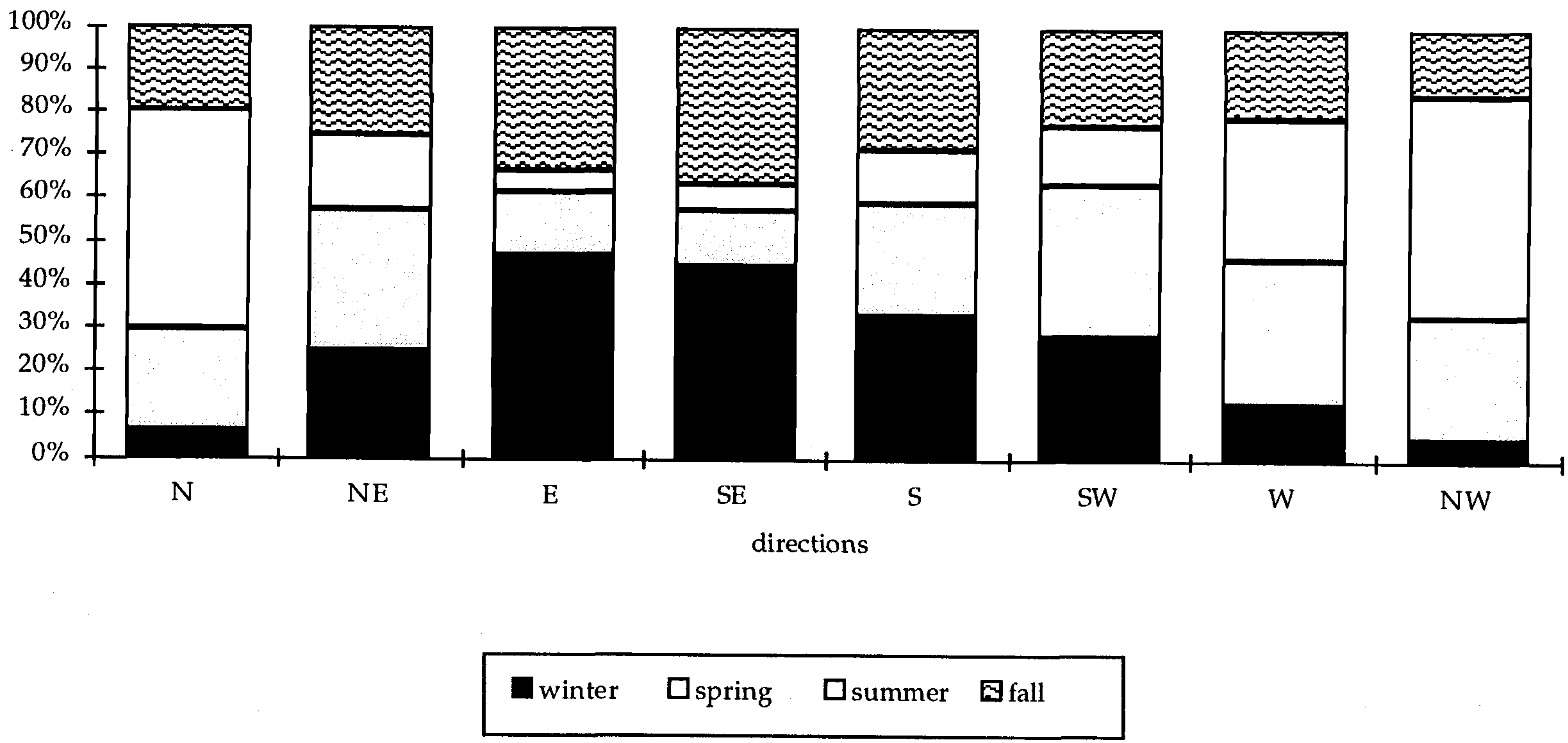


Figure 4.20 Trends in maximum wind speed directions at the Portland Airport, 1948-1994.

Table 4.6 Steps for calculating the mean return intervals of windthrow-generating storms in the Bull Run watershed, Oregon.

1. List days during 47-yr. period (1948-94) when the maximum daily wind was => 30 miles per hour (13 m/sec) or the average daily wind was => 20 miles per hour (9 m/sec) at the Portland International Airport (PDX). These values represent the top 1% of maximum and average wind speeds when all days were ranked. Two or more days in a row that meet the criteria are considered "events." To calculate return intervals (r.i.), count the number of days between single days or events that meet each criterion. Calculate the mean and median values from the two lists of intervals.

	total no. of days	total no. of events	r.i. of days		r.i. of events	
			mean	median	mean	median
max. winds	230	170	75	15	100	32
OR						
avg. winds	165	121	105	25	145	50

2. List days when both the maximum daily wind and the average daily wind were equal or greater than their 1% level. Create mean and median return intervals as described above.

	total no. of days	total no. of events	r.i. of days		r.i. of events	
			mean	median	mean	median
max. winds AND avg. winds	89	71	195	49	245	120

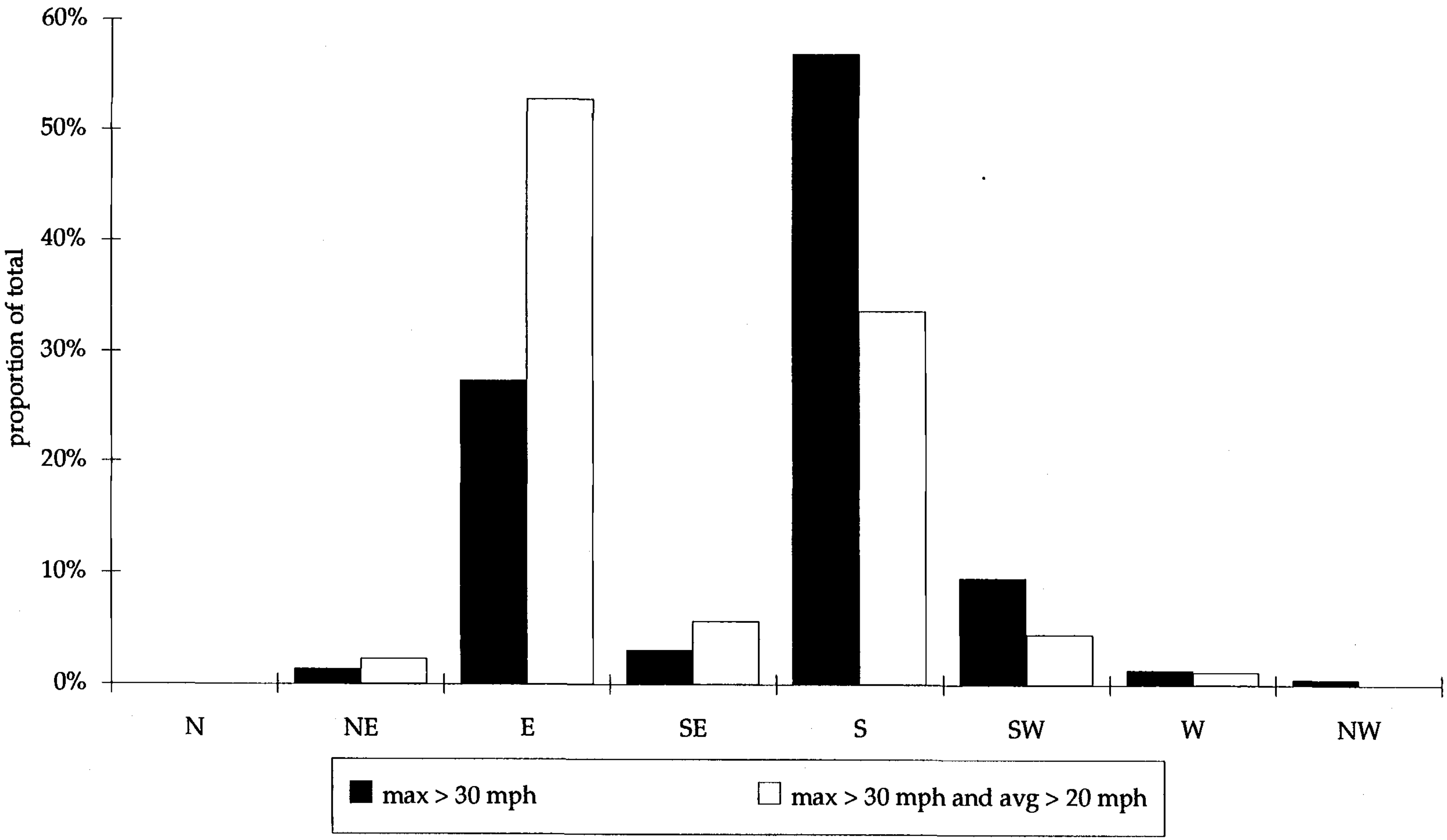
3. List days when both the maximum and average daily winds are equal or greater then their 1% level, and these winds are from the east or northeast. Create mean and median return intervals as described above.

	total no. of days	total no. of events	r.i. of days		r.i. of events	
			mean	median	mean	median
max. winds, avg. winds, AND E/NE	49	36	350	171	467	328

4. List days when all wind criteria are met and maximum daily temperatures at the Bull Run are less than 32°F (0°C), the bottom 1%-level for maximum temperatures. Create mean and median return intervals as described above.

	total no. of days	total no. of events	r.i. of days		r.i. of events	
			mean	median	mean	median
all wind criteria AND max. temps. less than 32°F	15	10	814	393	1097	707

Figure 4.21 Proportions of fast winds by direction at the Portland Airport, 1948 - 1994.



ten distinct one- or more day events, meeting all wind and temperature criteria, occurred between 1948 and 1994 (Tables 4.6, 4.7).

A comparison of days ranked by precipitation to the days ranked by wind and temperature criteria showed surprising results, since windthrow has often been associated with excessive soil moisture. The 1%-level criterion for the precipitation data equaled an amount per day of 2 inches (51 mm) and a cumulative amount greater than or equal to 11 inches (279 mm) of precipitation in the 14 days preceding each day. None of the days that met the wind and temperature criteria also met the precipitation criterion. Therefore, precipitation data were not used in the final model that calculated the return interval of windthrow-generating storms in the Bull Run.

4.4 Discussion

4.4.1 Lack of wind speed similarity at different sites

There are several possible explanations for the poor fit of the linear regression models. The method and frequency of data collection varied among sites, as well as the type of data gathered. The analyses showed that an average wind speed was not necessarily comparable to a wind speed sampled once a day, and none of the observation sites had the equipment to continuously monitor wind for the true peak or maximum daily gust.

The local topography surrounding each of the four sites of wind data collection is distinct. The Dallesport and Portland airport sites are the two most similar sites based on elevation and exposure, yet they demonstrated the weakest relationship of wind speeds. One explanation for this is the east/west division along the Columbia River Gorge, coinciding roughly with the perpendicular north/south Cascade Mountain range (Lawrence 1939). Portland falls on the west side and Dallesport is on the east, a geographical fact that influences wind speed and direction, precipitation and temperature. During the Columbus Day storm (October 12, 1962), the most extreme wind event of this century in western Oregon, the highest hourly wind speed recorded at the Portland Airport was 63 m.p.h. (28 m/sec); at the Dallesport Airport, it was only 9 m.p.h. (4 m/sec).

Table 4.7 Days that meet established wind criteria for windthrow-generating storms in the Bull Run watershed, Oregon. All days between 1948 and 1994 that had a maximum daily wind speed >= 30 m.p.h., an average daily wind speed of >= 20 m.p.h., and had winds from the east or northeast at the Portland Airport were selected as days when windthrow could have happened in the nearby Bull Run watershed.

date	average daily wind (m.p.h.)	maximum daily wind (m.p.h.)	direction of max. wind	temperature on day (°F)	avg. temp. of previous three days (°F)	precip. (inches)	cum. precip. during 14 days before (inches)
1) 12/24/48	23	32	east	32	35	0.0	7.08
2) 12/26/52	20	30	east	40	39	0.0	3.12
3) 12/14/55	23	30	east	36	46	0.0	7.74
4) 1/20/60	27	32	east	34	33	0.14	5.47
5) 3/3/60	21	32	east	32	38	0.29	1.38
6) 12/8/60	22	30	east	44	45	0.0	5.83
7) 1/26/61	22	30	northeast	49	47	0.0	1.43
8) 1/19/62	24	32	east	27	35	0.0	3.48
9) 1/29/63	23	31	northeast	28	38	0.0	1.01
10) 12/16/64	20	33	east	34	41	0.03	4.88
11) 12/17/64	26	31	east	16	34	0.0	4.49
12) 12/19/64	20	30	east	33	28	0.38	4.85
13) 12/22/66	23	31	east	49	48	0.0	4.66
14) 11/22/70	27	32	east	36	42	0.02	7.59
15) 1/26/72	27	31	east	31	38	0.2	9.59
16) 12/5/72	23	40	east	27	37	0.22	4.98
17) 12/6/72	22	32	east	28	31	0.0	4.96
18) 1/8/73	28	31	east	26	30	0.0	3.87
19) 1/9/73	31	35	east	31	29	0.0	3.87
20) 1/27/73	25	30	east	44	43	0.0	4.23
21) 2/7/73	26	31	east	44	49	0.0	1.47
22) 12/18/73	22	30	east	52	50	0.15	8.38
23) 1/2/74	20	32	east	32	39	0.0	8.75
24) 11/20/77	21	30	east	32	36	0.0	3.72
25) 12/20/77	27	32	east	42	44	0.0	11.5
26) 1/1/78	25	30	east	33	40	0.0	2.05
27) 1/2/78	24	30	east	35	38	0.17	2.01
28) 1/4/79	29	32	east	33	29	0.02	1.05
29) 1/5/79	27	32	east	31	31	0.0	0.9
30) 11/28/79	30	36	east	41	42	0.0	5.21
31) 2/10/81	21	32	east	40	48	0.0	1.27
32) 11/22/82	22	30	east	43	46	0.0	4.09
33) 11/23/82	25	31	east	42	44	0.0	4.09
34) 12/10/82	23	30	east	47	43	0.0	6.6
35) 1/29/83	20	31	east	52	54	0.0	3.02
36) 12/23/83	24	35	east	19	23	0.0	3.34
37) 12/24/83	34	39	east	18	19	0.09	3.16
38) 12/25/83	24	33	east	31	22	0.21	2.0
39) 12/1/85	28	40	east	22	26	0.02	2.13
40) 2/2/89	30	32	east	28	41	0.1	3.49
41) 2/3/89	34	41	east	12	31	0.0	3.49
42) 4/9/89	20	30	east	67	68	0.0	3.99
43) 1/11/90	23	35	east	46	53	0.18	8.02
44) 12/4/92	26	31	east	39	43	0.0	7.3
45) 1/7/93	23	33	east	33	36	0.0	3.53
46) 1/9/93	20	30	east	35	34	0.0	2.82
47) 11/25/93	25	30	east	35	38	0.0	2.31
48) 12/30/94	21	35	east	45	44	0.0	5.24
49) 12/31/94	25	30	east	41	41	0.0	4.27

4.4.2 Southwest vs. east storm events

In spite of the prevailing southwesterly winter storm pattern in the Pacific Northwest, virtually all the windthrow found in the Bull Run watershed has been generated by east-wind events (Sinton 1996a, unpublished). The basin itself is topographically open and flat to the southwest, and several high, steep-sided ridgelines are oriented into the basin on the northern and northeastern perimeters (Fig. 4.22). With repeated exposure to winds from a particular direction, trees respond physiologically with the growth of reaction wood on the leeward side (Telewski 1995), and the strengthening of their root systems in the windward direction (Stokes *et al.* 1995), making them less vulnerable to mechanical failure (windthrow). Because of the frequent and prevailing winds from the southwest and open topography towards the southwest, trees in the Bull Run may be better able to withstand strong southwesterly winds.

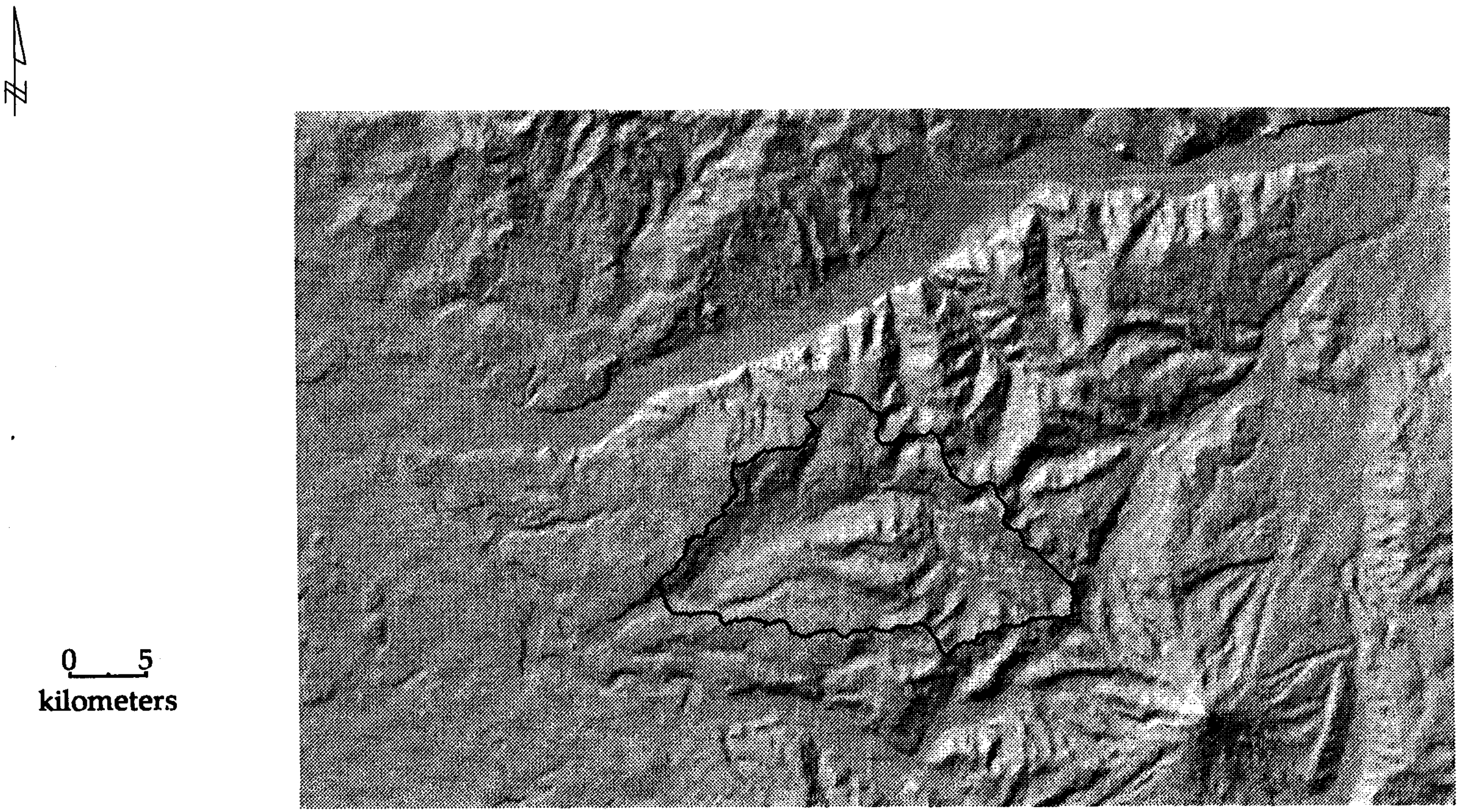
In contrast, the valleys in the northeast of the basin could act as channels or funnels for winds during east wind events. Moreover, east wind storms are associated with colder temperatures and lower humidity, conditions that may further affect a tree's ability to withstand extreme winds (Cameron 1931a, 1931b). Lawrence (1939) found that throughout the western half of the Columbia River Gorge, tree morphology indicated trees were more frequently affected by easterly winds.

4.4.3 Effects of moisture and temperature on windthrow

The Mt. Hood National Forest's Bull Run/Sandy Area Soil Survey identified locales with shallow soils and perched water tables as representing a "severe" windthrow hazard (U.S.D.A. Forest Service 1964). However, much of the windthrow from storms over the last 100 years in the Bull Run occurred in areas designated as having a "slight" hazard, rather than the "severe" areas (Sinton 1996a, unpublished). In fact, certain areas of the Bull Run where perched water tables are a perennial characteristic did not experience windthrow until clearcutting opened the canopy forest (Sinton 1996a, unpublished).

It is typical of western Cascade forests to receive the majority of annual precipitation during the winter months. Therefore, it was surprising to find that

Figure 4.22 Regional topography surrounding the Bull Run watershed.



none of the storms identified as having windthrow-generating potential in the Bull Run were characterized by extreme precipitation. This result was based solely on precipitation data collected at the Headworks site, and as mentioned earlier, precipitation in the upper reaches of the basin might have been greater. Furthermore, by mid-winter, soils in the western Cascades are frequently saturated, regardless of the amount of rainfall during one particular storm event.

Sub-freezing temperatures could influence windthrow potential in a variety of ways. Wood becomes stiffer as temperatures decrease, and this could cause a tree to function as a lever, decreasing its natural sway and causing it to uproot. However, if soils themselves were frozen, the rooting system would be firmly anchored, and snapping of boles rather than uprooting would occur.

In either case, more than one single day of sub-freezing temperatures would be necessary to affect soils. Of the fifteen days predicted to have windthrow-generating potential, eight had experienced an average maximum temperature of below 32° F for the three preceding days (Table 4.8), including the 1973 and 1983 Bull Run windthrow events. The Environmental Impact Statement prepared by the Forest Service for the salvage of 1983 windthrow stated that the soils were in an "unfrozen and saturated" condition (U.S.D.A. Forest Service 1987). Conclusions about soils conditions, including temperature and moisture content, could not be reached retrospectively with the Bull Run climate data alone.

An interaction between precipitation and sub-freezing temperatures could create ice-loading in a tree canopy. This phenomenon would decrease the canopy's ability to streamline itself in high winds, increasing the drag force of the wind and leading to a higher windthrow potential. It has been suggested that ice-loading in tree canopies may have been a factor contributing to the 1983 Bull Run windthrow (N. Diaz and I. Steinblums, Mt. Hood National Forest, pers. comm.), and the conditions existed to create rime ice. Rime ice forms when fog or other moisture-laden air is blown against a cold surface. While little precipitation was measured during either the 1973 or 1983 storm event itself, fog is a common characteristic of the Bull Run watershed (Harr 1982), and it is possible that rime ice could have formed when fog was blown against tree canopies.

Table 4.8 Predicted vs. observed windthrow in the Bull Run watershed based on wind and temperature criteria. Days that met established wind and temperature criteria for windthrow-generating events are listed as predicted-windthrow dates, and days from this list when windthrow was known to have occurred are marked. One day (11/19/75) is listed when windthrow is known to have occurred, yet neither wind nor temperature criteria were met. The numbering system divides events rather than individual days.

date	average daily wind (mph)	maximum daily wind (mph)	direction of max. wind	max. temp. (°F)	avg. max. temp. of previous 3 days (°F)	windthrow predicted	windthrow observed
1) 1/19/62	24	32	east	27	35	y	n
2) 1/29/63	23	31	northeast	28	38	y	n
3) 12/17/64	26	31	east	16	34	y	n
4) 1/26/72	27	31	east	31	38	y	n
5) 12/5/72	23	40	east	27	37	y	?
12/6/72	22	32	east	28	31	y	?
6) 1/8/73	28	31	east	26	30	y	y
1/9/73	31	35	east	31	29	y	y
7) 11/19/75	20	28	east	43	43	n	y
8) 1/5/79	27	32	east	31	31	y	n
9) 12/23/83	24	35	east	19	23	y	y
12/24/83	34	39	east	18	19	y	y
12/25/83	24	33	east	31	22	y	y
10) 12/1/85	28	40	east	22	26	y	n
11) 2/2/89	30	32	east	28	41	y	n
2/3/89	34	41	east	12	31	y	n

4.4.4 Prediction of windthrow in the Bull Run based on available weather data

The selection of criteria used to predict windthrow events was based on the wind and temperature characteristics of days in which windthrow was known to have occurred. Given those criteria, windthrow-generating storm events are unusual, occurring with a mean return interval of approximately three years (Table 4.6). However, the distribution of these predicted or observed events has not been uniform over the 47-yr. period considered, and windthrow in the Bull Run is known to have occurred on only two of the predicted events (Fig. 4.23). An additional windthrow event, albeit a minor one, occurred on November 19, 1975, a day when neither of the established criteria for maximum wind speeds nor temperature was met (Table 4.8).

Anecdotal evidence exists for the occurrence of other easterly and southwesterly wind events that led to minor windthrow in the Bull Run (U.S.D.A. Forest Service 1987). Yet records concerning timber salvage operations are poorly maintained, and aerial photographs are not available to document windthrow from any storms during the 47-yr. period between 1948 and 1994 other than the 1973, 1975 and 1983 ones.

One characteristic of the 1973 and 1983 events that stands out is their duration. Among all days that meet the established windthrow criteria, only four are events lasting two or more consecutive days (Table 4.8). It is interesting to note that the January, 1973, event occurred only one month after an event in December, 1972, that also met the windthrow criteria and was of 2-days' duration. It is possible, though impossible to prove, that some of the windthrow attributed to the 1973 event actually occurred in 1972. Moreover, the storm in December, 1972, could also have created structural damage to tree roots or boles that exacerbated windthrow one month later.

The data used for describing the maximum daily wind speeds at the Portland Airport may inadequately describe the true fastest wind speeds of that day. Additional wind parameters, such as the fastest mile of wind (the highest recorded speed for which a mile of wind passes the weather station) or the fastest one- or two-minute wind (the highest wind speed sustained for one or two minutes) may be better descriptors of the types of wind that actually lead to windthrow. On any given day, the fastest mile of wind tends to be a higher wind speed than the maximum daily speed as measured. However, these particular

Figure 4.23 Periodicity of climatic events leading to potential windthrow-generating storms in the Bull Run watershed, Oregon, 1948-1994.

data (fastest mile, fastest minute) were not available consistently throughout the period of record and could not be used for analyses.

S. Ferguson, an atmospheric scientist working with the U. S. Forest Service in Seattle, Washington, has created a model that predicts days of high windthrow potential based on wind dynamics in the upper-atmosphere. The model, based on data at 6.6 km by 9.3 km resolution, was designed to interpret windthrow potential across the entire Columbia River basin rather than an area as small as the Bull Run. Nevertheless, peaks in windthrow potential were identified in the mid-1970s, 1983 and 1989 with her model, dates that coincide with the types of storms predicted with our criteria-based model to have had windthrow-generating potential.

Climatic conditions alone cannot predetermine or predict the occurrence of a natural disturbance such as windthrow. An active timber harvesting program in the Bull Run was initiated by the Forest Service in 1958, and by the end of 1972, 10% of the forested part of the basin had been cut (Sinton 1996a, unpublished). Windthrow is commonly found at the edges of openings such as clearcuts, and the windthrow in 1973 and 1983 displayed a strong spatial correlation with ephemeral and perennial openings in the forest canopy (U.S.D.A. Forest Service 1987; Sinton 1996a, unpublished). Yet a severe east-wind storm of two days duration occurred in 1989, when approximately half of the 1983 windthrow had been recently salvaged, and no measurable windthrow was detected. Furthermore, a storm in January, 1996, also met the wind criteria and again, no significant windthrow was recorded.

4.5 Conclusions

Characterization of the wind regime within the Bull Run watershed is not a simple or straight-forward task. Local topographic conditions and a variety of data collection techniques contributed to the variability between wind speeds and directions among the data sites.

Nevertheless, by establishing a set of criteria for what constitutes a windthrow-generating storm, a mean return interval for such an event was calculated to be approximately once every three years. The distribution of these storm events was not uniform through time, suggesting longer term cycles of wind speeds and directions. Using these criteria, windthrow in the Bull Run was accurately predicted in 50% of the cases when storms were of at least two days' duration.

Yet the other half of the time, windthrow was not observed, suggesting the model was inadequate for predicting windthrow occurrence in the Bull Run. A variety of topographic, edaphic and vegetative factors also contribute to a tree's or stand's windthrow susceptibility. Moreover, reliable wind data were not available from within the windthrown portions of the Bull Run, and data collected elsewhere, such as the Portland Airport, did not necessarily represent conditions in the basin.

Recent windthrow in the Bull Run represents an interaction between two dynamic patterns, the spatial pattern of forest fragmentation and the temporal pattern of infrequent, severe east wind events. Since the early 1970s, the coincidence of these patterns has contributed to significant windthrow, resulting from two east-wind storm events. Yet since 1983, windthrow has not occurred on days when storm criteria were met, in spite of the numerous ephemeral opening edges. Portions of the Bull Run landscape that were most vulnerable to windthrow may have already been affected during the last hundred years (Sinton 1996a, unpublished), ensuring that future windthrow patterns will again vary.

Chapter 5

Estimating windthrow risk in the Bull Run watershed, Oregon

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in preparation for journal submission

5.1 Introduction

Hazard and risk assessment are a multi-billion dollar industry in the world today, and the largest portion involves health risk assessment, based primarily on studies of risks to humans from drugs, toxic waste and other chemicals (White 1988; Haness and Warwick 1991; Pascoe and DalSoglio 1995). Studies of the risks that natural disturbances present to human life and property are also numerous. These include geophysical events such as landslides (Aulitzky 1994; Fell 1994; Kienholz and Mani 1994; Hearn 1995); floods (Waylen and Woo 1982); volcanoes (Perry and Greene 1982); earthquakes (Hewitt 1984); comet or asteroid impacts (Chapman and Morrison 1994); and extreme wind events (Lynott and Cramer 1966; Walker *et al.* 1991). Additionally, certain biological disturbances pose a threat to vegetation, such as insect or decay infestations (Cornelius 1955; Reynolds and Holsten 1994; van der Kamp 1995).

Apart from its association with tornadoes and hurricanes, windthrow impacts trees more directly than if affects humans. From an ecological standpoint, windthrow is a mechanism that uproots trees, resulting in injury or death to a tree (Coutts and Grace 1995). A tree's fall creates an opening in the forest canopy, allowing light to penetrate through to the forest floor and providing an opportunity for another plant to take the place in the gap. Thus windthrow can be one part in a natural cycle of forest growth and death.

The risk of windthrow is a forest management concern. Windthrow represents a risk of potential loss of timber and other values, such as wildlife habitat. In places such as England and New Zealand, winds are so constant and the trees so vulnerable that foresters manage and plan for inevitable annual windthrow (Coutts and Grace 1995; Somerville 1995; Studholme 1995). In the Bull Run watershed, where regular timber harvesting is now prohibited, windthrow represents a perceived danger to water quality and increases the risk of wildfires and insect infestations (U.S.D.A Forest Service 1987).

Risk assessment can be quantified by the formula (Kapustka and Williams 1991; U. S. Environmental Protection Agency 1992):

$$\text{RISK} = \text{HAZARD} * \text{EXPOSURE}$$

Hazard represents the innate variables or factors that contribute to a risk (U. S. Environmental Protection Agency 1992; Hearn 1995). For example, in a health risk assessment, the hazard might be the toxic waste itself, but the risk from this waste is not realized until there is exposure to it. In the case of windthrow, certain factors, such as perched water tables or an area of root rot, create a location of inherent hazard for windthrow, but the risk is not realized until the trees are exposed to a strong wind.

Some research into windthrow risk has focused on the topographical exposure of the trees to wind (Bellingham 1991), while other researchers have concentrated on the more innate biological factors that could predispose certain trees to blow down (Petty and Swain 1985; Foster 1988; Mattheck and Berge 1990). In order to generate a comprehensive windthrow hazard map it is necessary to consider both hazard and exposure, using geologic, topographic and biological variables, that together contribute to the overall risk of windthrow in a certain place at a certain time.

The exposure component of windthrow risk assessment incorporates more than just direct wind exposure. Exposure based on topography or landforms may remain constant given a certain wind direction. However, vegetation characteristics, such as the height of trees or the presence of openings in a forest canopy, can change over a relatively short period of time. Both of these factors in particular have been identified as significant in windthrow studies (Ruth and Yoder 1953; Gratkowski 1956; Petty and Swain 1985; Franklin and Forman 1987; Miller *et al.* 1987; Galinski 1989; Quine and Wright 1993).

An additional factor to be considered with regard to exposure is the probability of the occurrence of winds of a certain magnitude. Storms causing the most recent windthrow in the Bull Run watershed have had at least two days duration in the winter months, with east winds and sub-freezing temperatures (Sinton 1996c, unpublished). A mean return interval for these types of windthrow-generating storms can be incorporated into a description of the temporal hazard of windthrow.

In this chapter, the issues surrounding windthrow risk assessment are addressed. Methods used for quantifying and determining windthrow hazard and exposure will be reviewed. Two approaches to mapping windthrow risk will be tested: one involves the adaptation of an exposure model created at the Harvard Forest (Boose *et al.* 1994), and the second incorporates the results from a logistic regression analysis of windthrow variables (Sinton 1996a, unpublished).

The resulting maps will be tested with the locations of windthrow from previous storms. Windthrow risk in the Bull Run is then evaluated and mapped for present forest conditions, as well as for two future time steps, the years 2010 and 2075. Finally, a discussion of how success can be measured and how the risk assessment can be used by forest managers will be presented.

5.2 Background

5.2.1 Techniques used to assess hazard

Various methods have been employed for calculating the risk of a natural disturbance. Many involve a relative ranking of variables that are believed to "cause" or initiate the disturbance (Gratkowski 1956; Alexander 1964; Aulitzky 1994; Fell 1994; Hearn 1995). Others incorporate mathematical models of probability (Chapman and Morrison 1994) or statistical analyses (Lohmander and Helles 1987; Carrara *et al.* 1991). Where comprehensive windthrow risk classifications have been established, the ranked or selected criteria are used in an additive equation to establish relative hazard classes that can be mapped (Quine and White 1993; Quine and Wright 1993).

5.2.2 The use of GIS in hazard assessment

The spatial component of hazard analysis has benefited in recent years from the use of geographic information systems (GIS). The ability of GIS to overlay multiple "layers" of data is being utilized for ecological risk assessment (Clifford *et al.* 1995), for water quality testing (Mattson and Godfrey 1994; Merchant 1994; Wylie *et al.* 1994) and for mapping geological hazards (Carrara *et al.* 1991). Both the Irish Forestry Board and the British Forestry Authority are using GIS for their windthrow hazard assessments and mapping (Lowe and Keane 1993; Quine and Wright 1993).

Boose *et al.* (1994) used GIS to map windthrow and establish "protected" and "exposed" zones within an area, based on assumptions about the deflection of wind over a landform. Their model (EXPOS) was designed for use with hurricane winds and worked best when a large area was considered (~100 km^2) (E. Boose, Harvard Forest, pers. comm.). An earlier GIS-based predictive model by Foster and Boose (1992) used vegetation type and height, and site exposure to identify degrees of windthrow susceptibility.

5.2.3 Assessing a windthrow hazard

Western Great Britain is one of the few, if not the only, place in the world where windthrow is a serious enough concern for detailed information to have been compiled on wind zones and subsequently developed into a spatially explicit hazard classification. Elsewhere, wind data, especially in mountainous terrain, are gathered sporadically, if at all, and information regarding historic windthrow is more anecdotal than definitive. Exceptions to this are in the hurricane belt of the Caribbean and the eastern United States, where storms are relatively frequent and predictable.

Studies that discuss windthrow hazard are primarily descriptions of windthrow patterns from one or more previous storm events, and are most frequently based on topographic and vegetation criteria (Table 5.1). Three of the most extensive risk classifications are highlighted below and in Table 5.2.

5.2.3.1 British Windthrow Hazard Classification

The British model was first developed by the British Forestry Commission in the 1970s (Booth 1977). It was based on four site factors: the wind zone, elevation, topographical exposure, and soil characteristics. Recently the British hazard classification underwent revision with the addition of an aspect component to the model (Quine and White 1993).

Wind zones are based on tatter flag data on wind frequency and severity collected throughout Great Britain, and these data form the basis for a map of the

Table 5.1 Risk factors associated with windthrow in selected studies.

	topography			soils			canopy openings			decay	tree factors				old windthrow	
	funneling, channeling	lee slope	ridges, upper slopes	moisture	drainage	depth	edges	edge age	edge location	root rot	species	height	bole taper	stand density	pit/mound topo.	old boles on ground
Alexander (1964)					x	x	x		x	x	x					
Boose et al. (1994)			x								x	x				
British Windthrow Hazard Classification (Miller 1985; Quine and White 1993)	x	x	x	x	x	x						x		x		
Canadian Risk Classification (Stathers et al. 1994)	x	x	x		x	x	x		x	x		x	x		x	x
Foster & Boose (1992)		x	x		x						x	x				
Galinski (1989)												x	x			
Gratkowski (1956)	x	x	x	x	x	x	x	x	x	x	x					
Irish Risk Class. (Lowe & Keane 1993)	x	x	x		x	x						x			x	x
MacKenzie (1976)		x	x	x	x									x		
Petty & Swain (1985)												x	x			
Ruth & Yoder (1953)	x	x	x		x	x	x	x	x		x			x	x	x

Table 5.2 Steps for development of the British, Irish, and Canadian windthrow risk classifications.

system	variables included	how variables used to create classification	how classification used by forest managers
British[1]	wind zone elevation topographical exposure soil characteristics	scores for wind/exposure variables added to score for soil; sum is divided into six classes.	Classes 1-6 ranked from "very stable" to "very unstable." Hazard classes define the "critical height" at which trees should be harvested, depending on whether stands are thinned or not.
Irish[2]	windthrow present exposure harvesting ground preparation techniques soil method of timber extraction	scores for all variables are combined; sum is divided into six classes.	Classes 1-6 ranked from "very stable" to "very unstable." Used for critical height assessment.
Canadian[3]	wind force factors (exposure to wind, stand density, tree height, etc.) resistance to overturning factors (rooting, presence of rots, soil depth and drainage, etc.) other indicators (evidence of old windthrow)	factors are combined in a primarily qualitative fashion into three classes (lower, moderate and high) of windthrow hazard.	Forest managers assess windthrow risk on a site-by-site basis.

1 Miller 1985; Quine and White 1993; Quine and Wright 1993.

2 Lowe and Keane 1993.

3 Stathers *et al.* 1994.

relative "windiness" of a site. The elevation factor is deterministically based on the notion that wind speed increases with elevation (Miller 1985). The topographical exposure variable (topex) is calculated from the summed skyline angles of eight compass direction points. The score for soil conditions is based on drainage characteristics and apparent rooting depth of the trees on that particular soil type. Two ways are used to calculate the aspect score, a simple and a detailed method, but both are based on the prevailing winds in Great Britain coming from the southwest or west. The simple method is based strictly on the slope aspect of the site in question, and the detailed method takes into account both the slope aspect and any funneling effect of local topography (Quine and Wright 1993).

To calculate the windthrow hazard class, the scores of the individual factors are summed, and the results are divided into six equal interval groups, each corresponding to a hazard class. Lower class numbers correspond to areas where there is a low risk for windthrow, while Class 5 and 6 areas are frequently subjected to damaging winds. Forest managers in Great Britain adhere closely to the calculated hazard classes to determine the critical time for timber harvesting.

5.2.3.2 Irish Windthrow Hazard Classification

The system being developed by the Irish Forestry Board (Coiltte Teoranta) in 1993 was based heavily on the British and Northern Irish systems (Lowe and Keane 1993). Eight variables were assessed and assigned scores that were then summed and grouped into windthrow risk classes. The Irish system emphasizes both species and silvicultural practices influencing windthrow (Lowe and Keane 1993). The Irish classification system was still being developed in late 1993 and no recent updates have been obtained by this author.

5.2.3.3 Canadian Windthrow Hazard Classification

In 1994, the British Columbia Forest Service prepared a Windthrow Handbook for use by forest managers (Stathers *et al.* 1994). The guide was not designed to function strictly as a hazard classification, but rather as an introduction to the intricacies of windthrow for an otherwise uninformed forester, and no maps of windthrow risk have been generated. Knowing that extensive wind data are not available for forests in British Columbia, the authors derived a hazard evaluation checklist for use in the field that incorporates wind force factors, variables associated with resistance of the tree to toppling, and other indicators, such as evidence of historic windthrow at the site.

5.3 Methods

5.3.1 Spatial hazard of windthrow

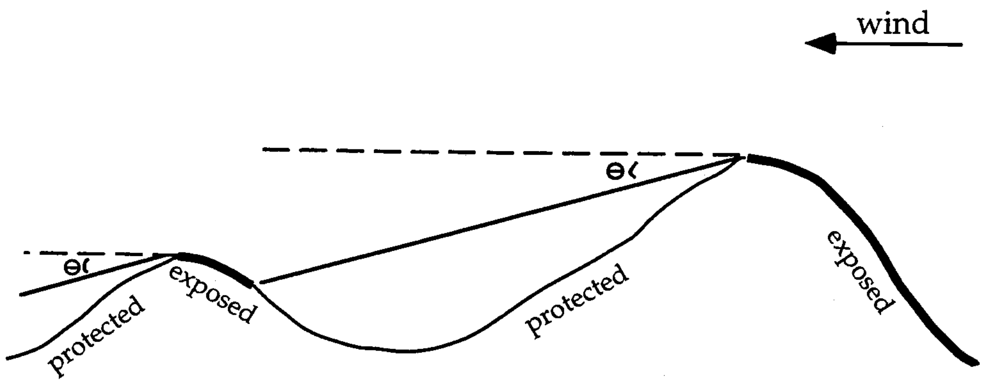
5.3.1.1 Adaptation of the EXPOS model

The EXPOS model, developed by Boose *et al.* (1994), was modified for use with Arc/Info (Version 7.0.1). The model was based on the principle that wind passing over a landform is deflected down only a certain amount (Fig. 5.1).

Several steps were taken to generate an Arc/Info coverage of ridgelines and prominent landforms in the Bull Run. First the FLOWACCUMULATION function was used to identity areas of the landscape that are higher than neighboring areas. This function works with a DEM grid, assuming that flow of a fluid moves from a cell of higher elevation to an adjacent cell of lower elevation. The resulting grid was converted to a line coverage that was "draped" over a 3-dimensional image of the Bull Run watershed. On-screen editing was performed to ensure that the both the perimeter of the watershed and each prominent ridgeline within the watershed had been identified and included in the final ridgeline coverage.

The next step involved assessing the extent of vertical deflection of wind. The ridgeline coverage was used with the VISIBILITY command in Arc/Info. This command allows the operator to designate how far down, in a vertical direction from the horizon line, could be "seen" from a given location or, for the windthrow study, how far down the wind might extend. To compare

Figure 5.1 Protected and exposed zones as defined by the modified EXPOS model of Boose *et al.* (1994). A landscape can be divided into protected and exposed zones depending on exposure to a wind deflected downward a certain degree (Θ) as the wind passes over a landform. Figure is from Boose *et al.* (1994).



windthrow in protected vs. exposed areas, the view was limited to winds from the north and northeast for the 1931 storm, and shifted to northeast and east winds for the 1973 and 1983 storm events; this reflected the best information known about the local winds during each of the storm events (Sinton 1996a, unpublished). Multiple iterations were performed for each storm event, varying the degree of deflection from 7° to 20° degrees down from the horizon.

The output from VISIBILITY was used to create maps showing the division of the watershed into areas that were "exposed" to and "protected" from north, northeast, and east winds, depending on the degree of deflection. To assess the validity of these maps, the location of windthrow from known storm events in the Bull Run was overlaid on the maps showing "exposed" and "protected" areas.

5.3.1.2 Use of logistic regression results

A second approach to predicting windthrow hazard incorporated the results from a study of windthrow patterns. Windthrow from three storms in the Bull Run were mapped, and a sample of points from each storm pattern were subjected to a logistic regression to assess the relative importance of topography, soils, and edges in the forest canopy in influencing the location of windthrow (Sinton 1996a, unpublished). The odds ratios generated by the logistic regressions were used to weight the variables and produce three windthrow risk maps, one for each pre-storm condition (Table 5.3). To evaluate the maps, all known windthrow locations were compared to the predicted zones of low, medium, or high windthrow risk.

5.3.2 Windthrow risk maps for present and future vegetation conditions

Based on the results from the two approaches to estimating windthrow risk, multiple data sources were combined to generate windthrow risk maps for 1995 conditions in the Bull Run watershed, as well as two time steps in the future, the years 2010 and 2075.

Table 5.3 Use of logistic regression results to establish relative rankings of variables for 1931, 1973 and 1983 windthrow susceptibility maps. The weightings were summed for each storm, and divided into three groups of low, medium, and high windthrow risk.

	variable	category	weighting
1931 storm	soil	no hazard	1
		slight hazard	10
		moderate hazard	2
		severe hazard	17
	aspect	northeast	6
		southeast	3
		southwest	1
		northwest	2
1973 storm	aspect	northeast	3
		southeast	1
		southwest	2
		northwest	1
	soils < 150 m of ephemeral opening	no hazard	0
		slight hazard	1
		moderate hazard	1
		severe hazard	10
	soils > 150 m of ephemeral opening	no hazard	0
		slight hazard	4
		moderate hazard	1
		severe hazard	3
1983 storm	soils	no hazard	1
		slight hazard	2
		moderate hazard	1
		severe hazard	7
	ephemeral opening	< 150 m	3
		> 150 m	1

All vegetation data were based on a 1988 Landsat 5 TM satellite image classified into groups of varying vegetation type and age (Cohen *et al.* 1995). All conifer stands were placed in broad age groups of young forest (< 80 years), mature (80-200 years) and old-growth (> 200 years). Following a procedure developed for the windthrow pattern analysis, the vegetation data layer was reclassified to reflect 1995 vegetation conditions (Sinton 1996b, unpublished). Specifically, locations known to have been clearcut in the intervening years were reclassified as such. Certain variables included in the susceptibility mapping are dynamic (e.g., vegetation type by age and recent clearcut edges), and the first susceptibility map was based on their conditions in 1995. For the 2010 and 2075 vegetation layers, forests were "grown" and when appropriate, reclassified to the next older age class (Table 5.4). Table 5.5 describes the variables that were used to generate future susceptibility maps, as well as the relative rankings of each variable.

A reconstruction of windthrow patterns from storms throughout the 20th century shows that virtually all windthrow in the Bull Run has been generated by northern, northeastern, or eastern winds (Sinton 1996a, unpublished). Therefore, the ranking of the aspect variable was based on exposure to a northeast wind.

5.3.3 Overall susceptibility of the Bull Run to windthrow

Since the 1890s, at least eight storms have generated windthrow in the Bull Run (Sinton 1996a, unpublished), yet little or nothing is known about many of the storm events themselves. Wind and other climate data from the period 1948-1994 were used to characterize windthrow-generating storms in the Bull Run (Sinton 1996c, unpublished). Based on these analyses, a mean return interval for severe, east wind events was calculated and this information is incorporated into a description of the overall risk of windthrow in the Bull Run.

The probability, or risk, of windthrow occurring at any given time is a function of both hazard (spatial) and exposure (temporal) variables. In the Bull Run this combination of spatial and temporal risk for windthrow involves the proportion of forested area that is available to be windthrown by a given storm. To assess this dynamic relationship, certain assumptions were incorporated into

Table 5.4 Criteria followed to modify susceptibility rankings between the years 1995, 2010, and 2075. All topographic and edaphic variables remain the same; only vegetation and edge-related variables are modified. Young conifers are less than 80 years old, and mature conifers are 80 - 200 years old.

year	1995	2010	2045
1. Vegetation			
	young conifer	no changes	mature conifer
	clearcuts	no changes	mature conifer
2. Locations < 150 m from clearcuts less than 25 years old	high risk	low risk	no risk

Table 5.5 Weighting of hazard and exposure variables for a northeast-wind windthrow risk classification of the Bull Run watershed. Weightings are based both on results of a statistical analysis of past windthrow patterns in the Bull Run (Sinton 1996a, unpublished), as well as information gleaned from published literature on windthrow risk classifications. To generate an overall windthrow risk map, these values are summed and the resulting numbers are divided into three risk groups (low, medium and high).

year	1995		2010		2075	
variable	ranking	score	ranking	score	ranking	score
1) aspect						
north	medium	2	medium	2	medium	2
northeast	high	3	high	3	high	3
east	medium	2	medium	2	medium	2
southeast	low	1	low	1	low	1
south	low	1	low	1	low	1
southwest	medium	2	medium	2	medium	2
west	low	1	low	1	low	1
northwest	low	1	low	1	low	1
2) hillslope position						
valley bottom	low	1	low	1	low	1
mid-slope	medium	2	medium	2	medium	2
upper slope, ridges	high	3	high	3	high	3
3) soil type by windthrow hazard						
none	none	0	none	0	none	0
slight	medium	2	medium	2	medium	2
moderate	low	1	low	1	low	1
severe	high	3	high	3	high	3
4) vegetation						
old-growth conifer (> 200 y.o.)	high	3	high	3	high	3
mature conifer(80-200 y.o.)	medium	2	medium	2	medium	2
all other vegetation	low	1	low	1	low	1
water, perennial openings	none	0	none	0	none	0
5) proximity to ephemeral opening						
< 150 meters	high	3	low	1	low	1
> 150 meters	none	0	none	0	none	0
6) proximity to perennial opening						
< 150 meters	low	1	low	1	low	1
> 150 meters	none	0	none	0	none	0

another simple model, including the age (or height) of trees that can be windthrown (Table 5.6).

5.3.4 How to include uncertainty

"Uncertainty" is increasingly recognized as an integral component of hazard assessments (Haness and Warwick 1991; Reckhow 1994). Maps of windthrow risk generated for the Bull Run were designed to describe relative probabilities of windthrow, rather than represent actual predicted locations of future windthrow. Specifically, the use of logistic regression analyses, rather than other statistical methods, dictates that the results (i.e., the odds ratios) can be used to estimate probabilities, but not actual population proportions (Ramsey and Schafer, 1993 unpublished).

5.4 Results and Discussion

5.4.1 The modified EXPOS model

The watershed as divided by the modified EXPOS model is shown in Fig. 5.2 and Fig. 5.3. Varying the deflection degrees did not greatly affect the amount of the landscape designated as protected vs. exposed (Table 5.7). In the 1931 storm, more windthrow occurred in the protected zone rather than the areas defined by the model to be exposed to winds. Windthrow from the 1973 and 1983 storm events occurred slightly more frequently in the exposed zones than the protected ones.

Several explanations are possible for the mixed results obtained from the EXPOS model, including issues related to the GIS, topography, and the winds themselves. Arc/Info does not provide an automated procedure for generating an accurate or comprehensive coverage of ridgelines or prominent landforms, a crucial element for adaptation of the EXPOS model for use with Arc/Info. The model was originally designed, with an IDRISI GIS, for use with hurricanes,

Table 5.6 Data and assumptions on which the windthrow-susceptible forests areal analysis was performed.

decade	total possible forested area (ha)[1]	fires (ha)[2]	clearcuts (ha)[3]	windthrow (ha)[4]	total forest available to be windthrown (ha)[5]	total forest available to be windthrown (ha)[6]
1850s	25173	0	0	0	25173	25173
1860s	25173	0	0	0	25173	25173
1870s	25173	3820	0	0	21353	21353
1880s	25173	865	0	0	20488	20488
1890s	25173	0	0	106	20382	20382
1900s	25173	0	0	20	20362	20362
1910s	25173	530	0	3	19829	19829
1920s	25173	190	0	0	19613	19613
1930s	25004	0	0	26	19027	19027
1940s	25004	0	0	417	19027	19027
1950s	25004	0	0	0	22786	18966
1960s	24820	0	171	0	21672	16987
1970s	24820	619	1663	55	19368	14577
1980s	24820	0	1815	411	18506	13695
1990s	24820	0	439	0	18810	13466
2000s	24820	0	0	0	19026	13466
2010s	24820	0	0	0	19443	13466
2020s	24820	0	0	0	19443	17286
2030s	24820	0	0	0	19504	18151
2040s	24820	0	0	0	21299	18257
2050s	24820	0	0	0	23709	18277

1 Includes total area of watershed (26494 ha), minus the areas covered by perinneal openings in the forest canopy: meadows, talus slopes, shrub fields and small lakes (1321 ha); and the addition of Reservoir #1 in 1927 (169 ha) and Reservoir #2 in 1964 (184 ha).

2 Assumes fire severe enough to kill all trees. Fire in 1873 equals the total burned area (4241 ha) minus the area that burned subsequently in 1928 and 1971 (combined 421 ha).

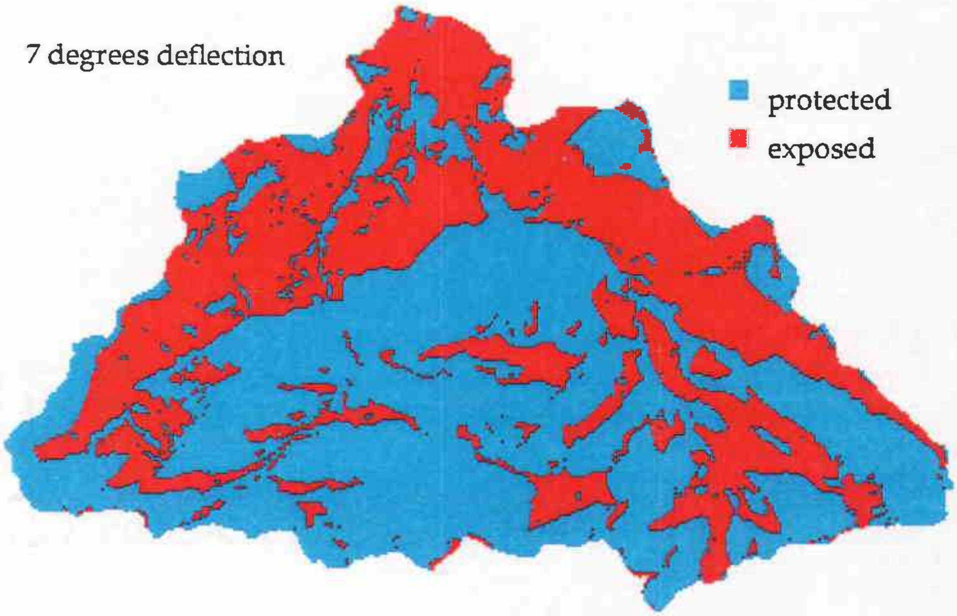
3 Includes salvage logging and assumes all vegetation cleared.

4 Assumes windthrow severe enough to remove all canopy trees. Windthrow in 1973 equals only 10% of total area blowndown (554 ha); the other 90% was salvage logged and included in clearcut numbers. Windthrow in 1983 equals only 30% of total area blowndown (1369 ha); other 70% was salvage logged and included in clearcut numbers.

5 Includes all forested areas that were neither burned, logged, or windthrown over the course of each decade. Once locations that were burned, cut, or blowndown reach the age of 80 years, they are assumed to be revegetated by trees tall enough to be windthrown and are re-included in the available forest.

6 Same as previous column, except a 150-year regrowth time to windthrow-vulnerability is assumed.

Figure 5.2 Adaptation of the EXPOS model, 1931 storm.



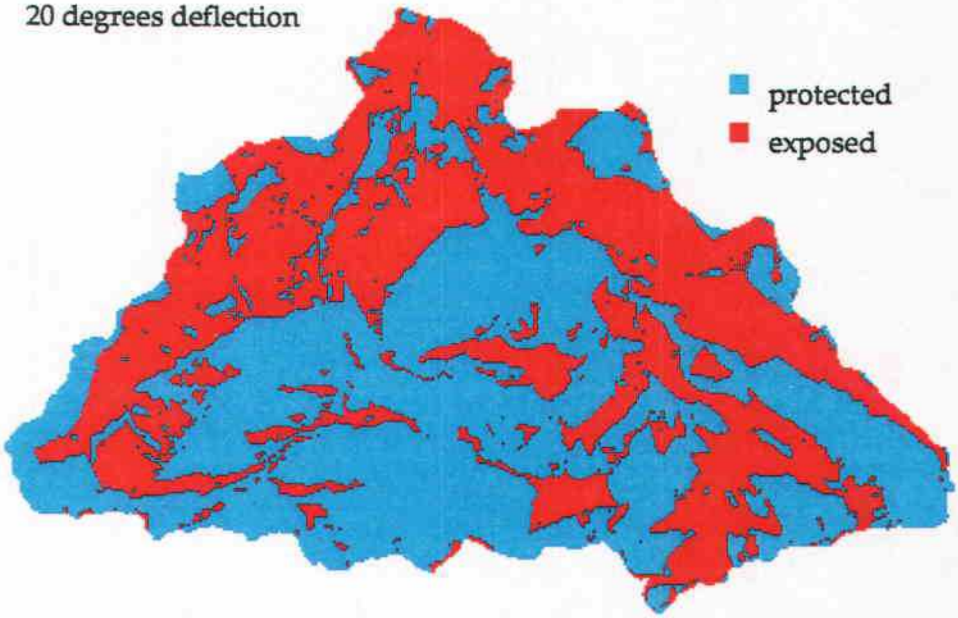


Figure 5.3 Adaptation of the EXPOS model, 1973 and 1983 storms.

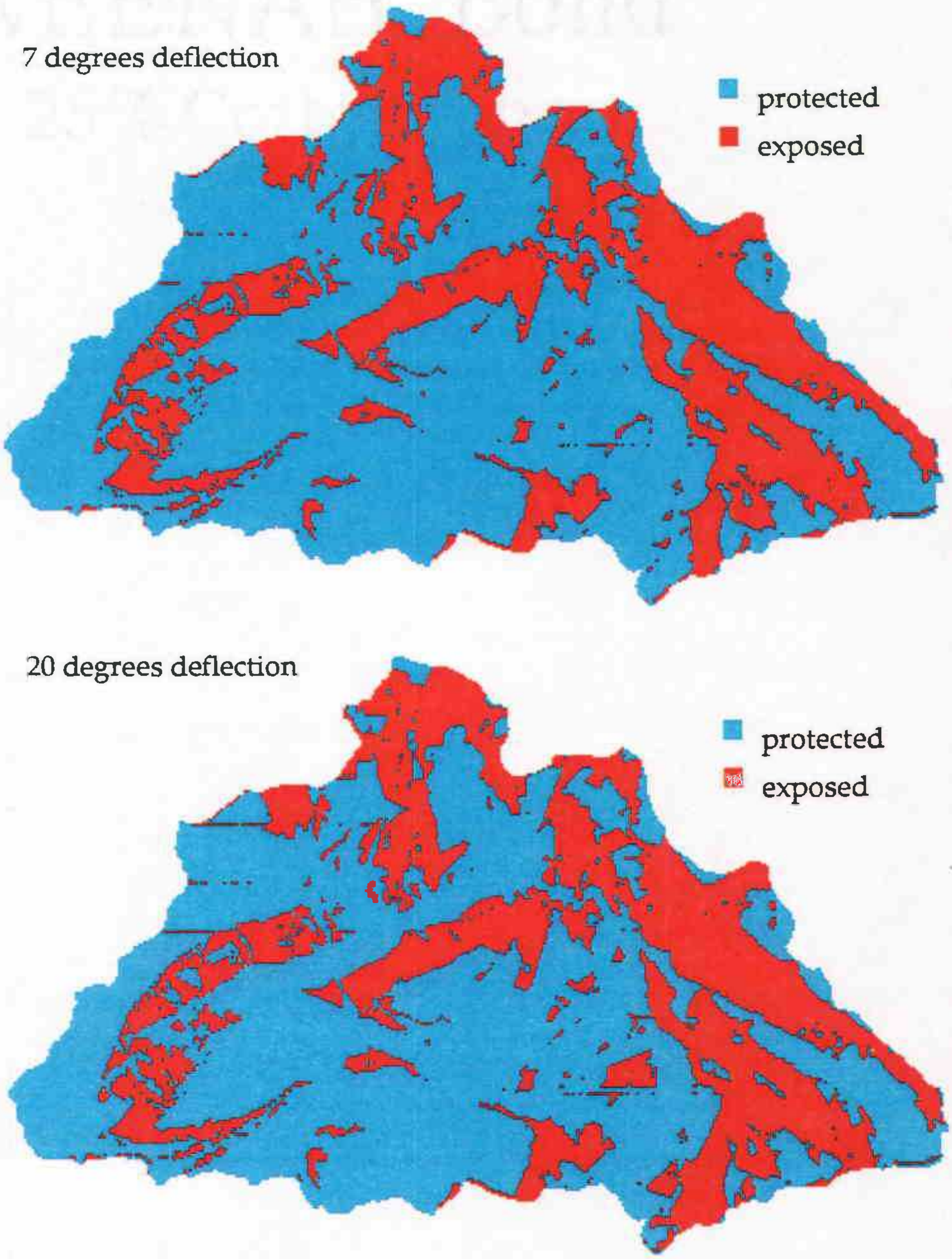


Table 5.7 Adaptation of the EXPOS model for the Bull Run watershed and the observed distribution of 1931, 1973 and 1983 windthrow on protected and exposed zones.

storms	deflection degrees			
	7°	11°	15°	20°
1931				
area protected (%)	57	55	55	54
area exposed (%)	43	45	45	46
windthrow in protected (%)	78	75	75	75
windthrow in exposed (%)	22	25	25	25
1973				
area in protected (%)	66	65	64	64
area exposed (%)	34	35	36	36
windthrow in protected (%)	46	45	45	45
windthrow in exposed (%)	54	55	55	55
1983				
area in protected (%)	66	65	64	64
area exposed (%)	34	35	36	36
windthrow in protected (%)	49	48	48	48
windthrow in exposed (%)	51	52	52	52

when wind direction is relatively constant (E. Boose, Harvard Forest, pers. comm.). Local effects on wind direction created by topography were not accounted for by the model (Boose *et al.* 1994), a limitation that may greatly have influenced its ability to accurately predict exposed or protected locations in steep terrain, such as in the Bull Run.

The insignificant changes between exposed and protected proportions of the landscape, despite a two-fold increase in the deflection angle, suggests that either the generated ridgeline coverage did not did not adequately represent landform features in the Bull Run, or the steep topography in the Bull Run is insensitive to relatively small variations in deflection angles . Similar changes in deflection angles with the EXPOS model run for an area in central Massachusetts, with gentle topography, decreased protected zones from over 50% to less than 10%, but in an area of Puerto Rico, with terrain more similar in steepness and dissection to that of the Bull Run, the effects of varying the deflection angle were not as profound (Boose *et al.* 1994).

Current approaches to modeling windthrow disturbances are attempting to incorporate local topographic effects on wind variability (D. Mladenoff, Univ. Wisconsin, pers. comm.). Until these approaches are better developed, the usefulness of deterministic models for exposure prediction seems limited.

5.4.2 Windthrow susceptibility maps for past events in the Bull Run

The use of logistic regression results generated windthrow susceptibility maps that looked very different from one storm event to another (Figs. 5.4 - 5.6). The predicted risk zones matched well with the location of windthrow from 1931, 1973 and 1983 storms in the Bull Run. In each case, windthrow was observed significantly less than expected in low risk zones, and more frequently than expected in the high risk areas (Table 5.8). Overall, more than 70% of the windthrow in each storm occurred in medium and high risk zones.

Each storm's susceptibility map was based on statistical results from a sample of the total data from the same storm, so the results were not unexpected. However, the model did not explain all variability in the patterns. There are two reasons fór why an even better fit to the model was not evident. First, the sampled data used for the logistic regressions represented between 5 and 11% of

Figure 5.4 Windthrow risk in the Bull Run watershed calculated with logistic regression results, 1931.

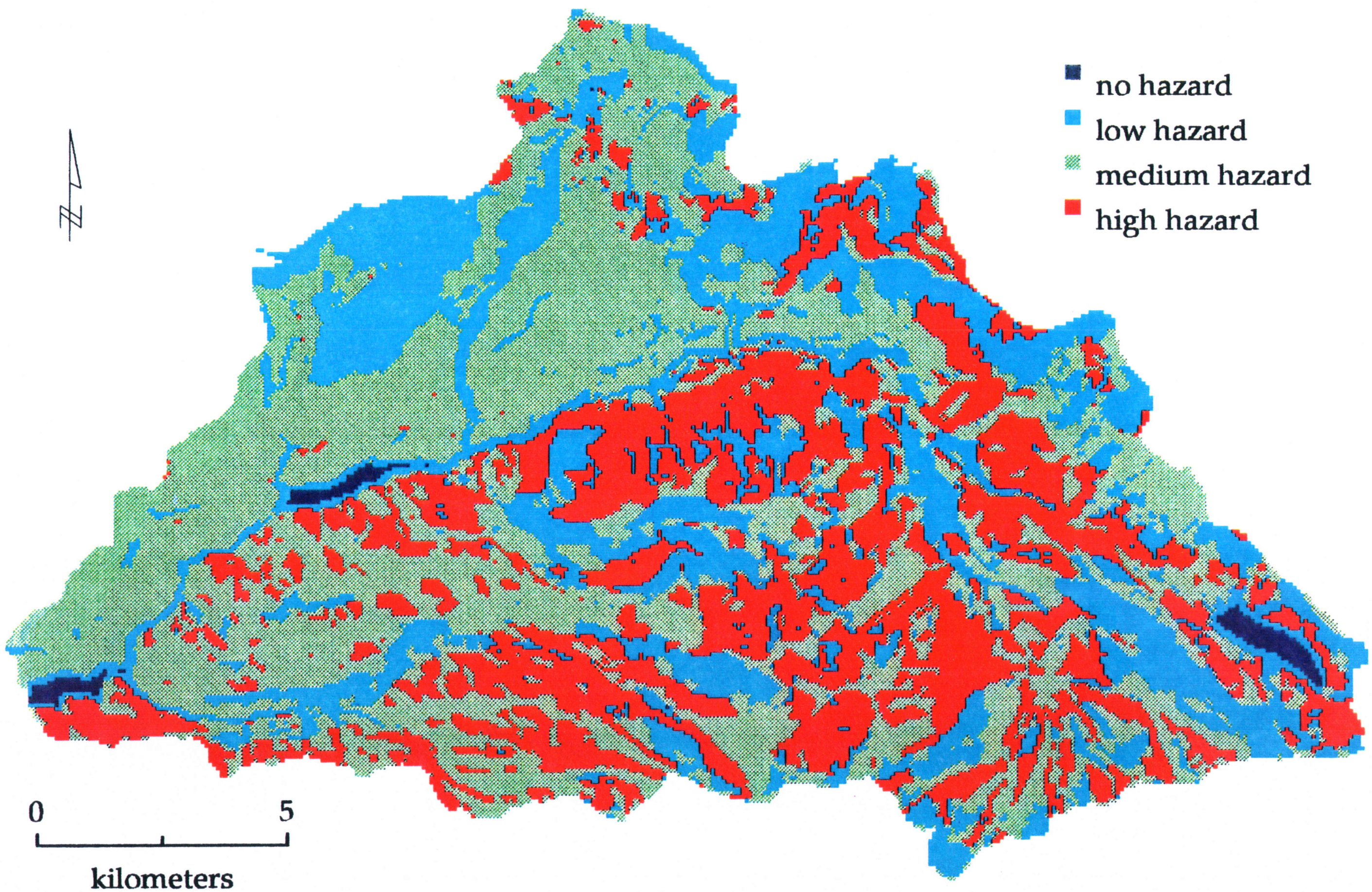


Figure 5.5 Windthrow risk in the Bull Run watershed calculated with logistic regression results, 1973.

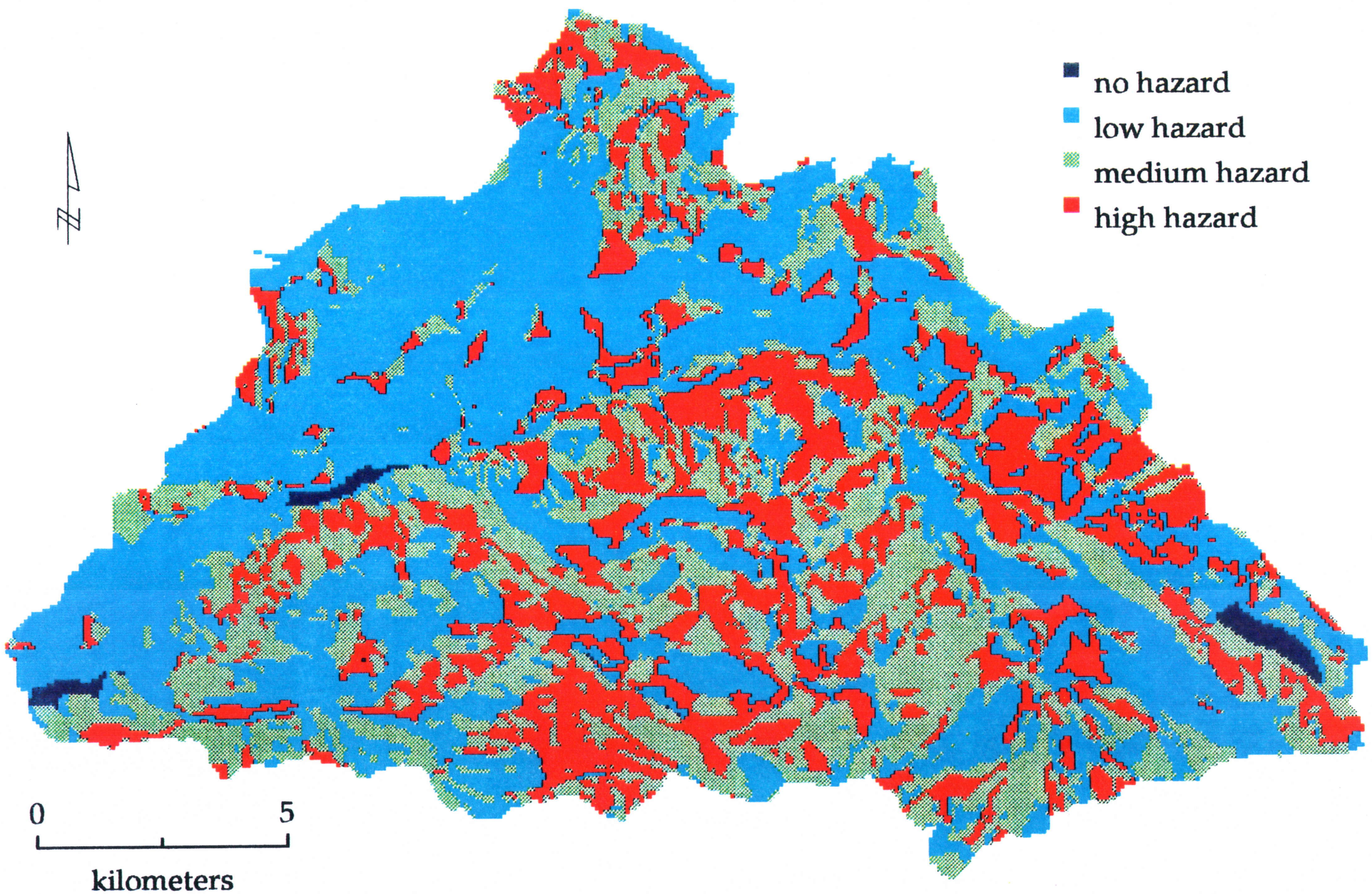


Figure 5.6 Windthrow risk in the Bull Run watershed calculated with logistic regression results, 1983.

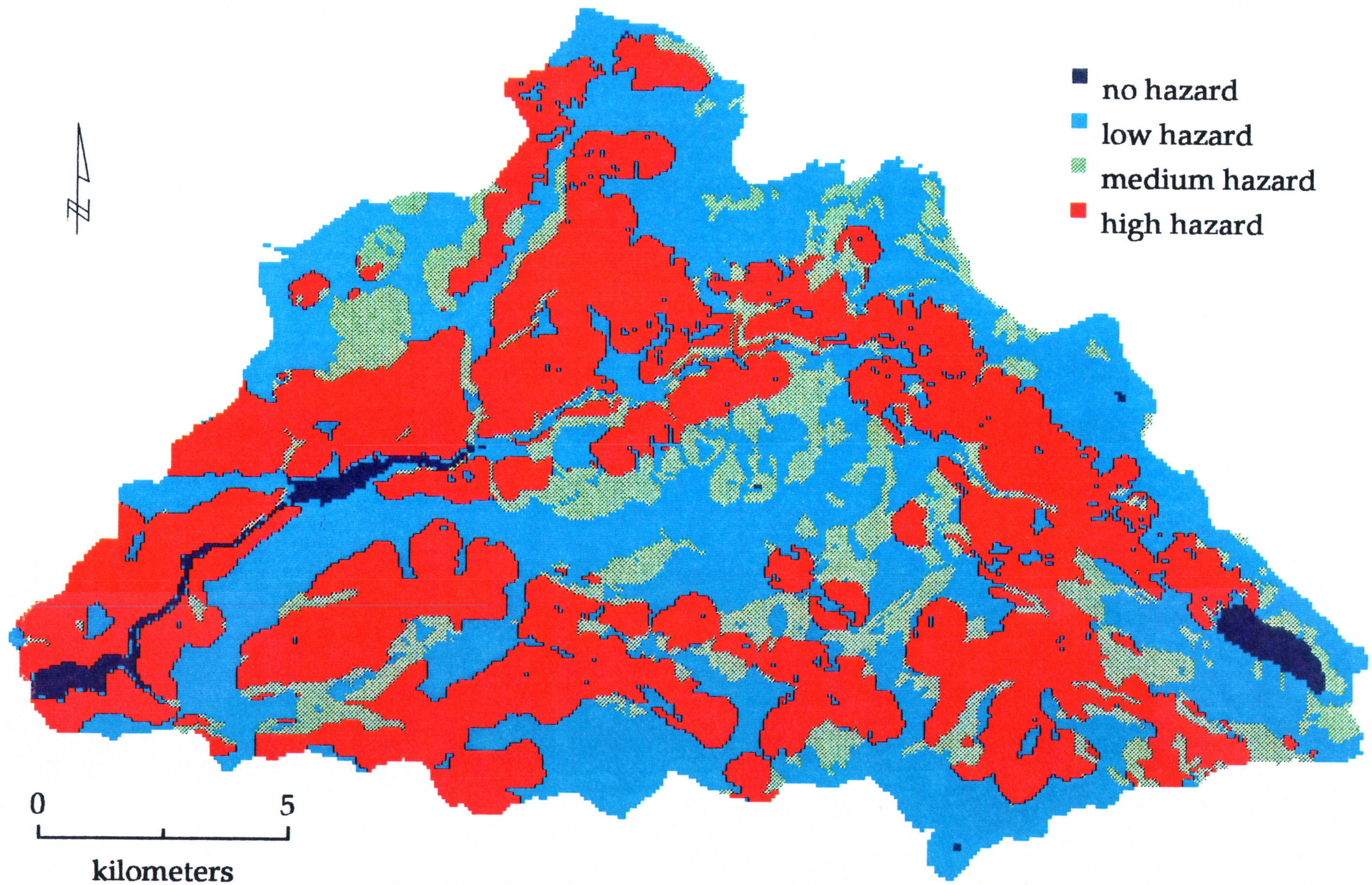


Table 5.8 Comparison of windthrow risk maps generated with logistic regression results for 1931, 1973 and 1983 pre-storm conditions with the location of windthrow for the three events in the Bull Run watershed. Results from logistic regressions performed on data sets from three storms were used to identify variables that significantly influenced windthrow in each storm, and the odds ratios for each set of variables were directly used to weight the variables for their relative windthrow risk. All logistic regression results and odds ratios can be found in Tables 2.23 - 2.25.

1931 risk	1931 windthrow (%) (observed)	watershed (%) (expected)	Chi square = 303.23 df = 3, $p < 0.001$
none	0	1	
low	5	26	
medium	45	46	
high	50	27	

1973 risk	1973 windthrow (%) (observed)	watershed (%) (expected)	Chi square =204.57 df = 3, $p < 0.001$
none	0	1	
low	29	45	
medium	30	32	
high	41	22	

1983 risk	1983 windthrow (%) (observed)	watershed (%) (expected)	Chi square = 632.64 df = 3, $p < 0.001$
none	0	1	
low	19	40	
medium	14	15	
high	67	44	

the total data from each storm event, selected to compensate for spatial autocorrelation among the data (Sinton 1996b, unpublished). If the sampled data used to generate the susceptibility maps were not truly representative of the storm as a whole, the discrepancy would be reflected in the occurrence of windthrow in locations other than the high risk zones.

A second reason involves the inadequacy of any attempt to thoroughly model a disturbance as variable as windthrow. Neither of the models tested in this study (EXPOS and that based on logistic regression results) was able to thoroughly explain the 1931, 1973 and 1983 windthrow patterns in the Bull Run, though the logistic regression model worked significantly better than EXPOS. Unexplained variance in each pattern resulted from contributing factors that were overlooked or mapped inadequately. Soil moisture, drainage and thickness influence windthrow, yet the available map describing those conditions shows that the majority of all 1931, 1973 and 1983 windthrow occurred on soils assigned only a "slight" hazard for windthrow (Sinton 1996a, unpublished). Furthermore, detailed information on other factors that could affect windthrow, such as root rot, ice loading in tree canopies, or road networks, fell below the minimum mapping resolution or was not available.

5.4.3 Windthrow susceptibility maps for present and future conditions in the Bull Run

Based on the attempts to predict known windthrow locations, the approach to predicting future windthrow in the Bull Run incorporated factors that have affected windthrow in the past, as well as an understanding of other contributing factors discussed in windthrow literature (Ruth and Yoder 1953; Gratkowski 1956; Stathers *et al.* 1994).

Locations with relatively low, medium, and high risk for windthrow, based on 1995 vegetation conditions and a northeast storm event, are shown in Fig. 5.7. The greatest proportion of the watershed was designated as having a moderate windthrow risk (Table 5.9). Windthrow risk probabilities were also mapped for the years 2010 (Fig. 5.8) and 2075 (Fig. 5.9), and in each case, more area was classified with a moderate risk than any other category (Table 5.9). The fluctuations in the amount of landscape designated as having a high risk are the

Figure 5.7 Windthrow risk in the Bull Run watershed, 1995.

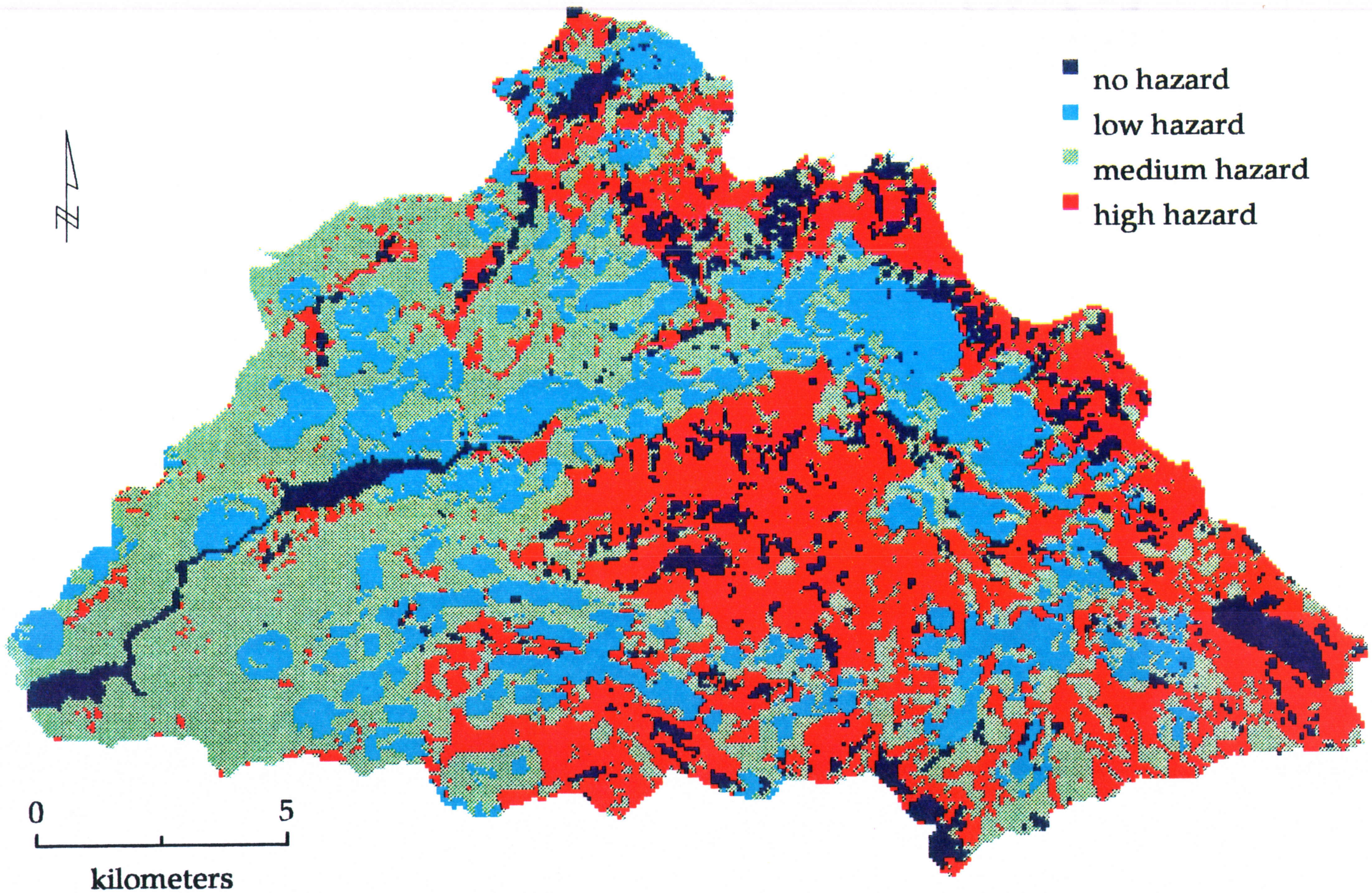


Figure 5.8 Windthrow risk in the Bull Run watershed, 2010.

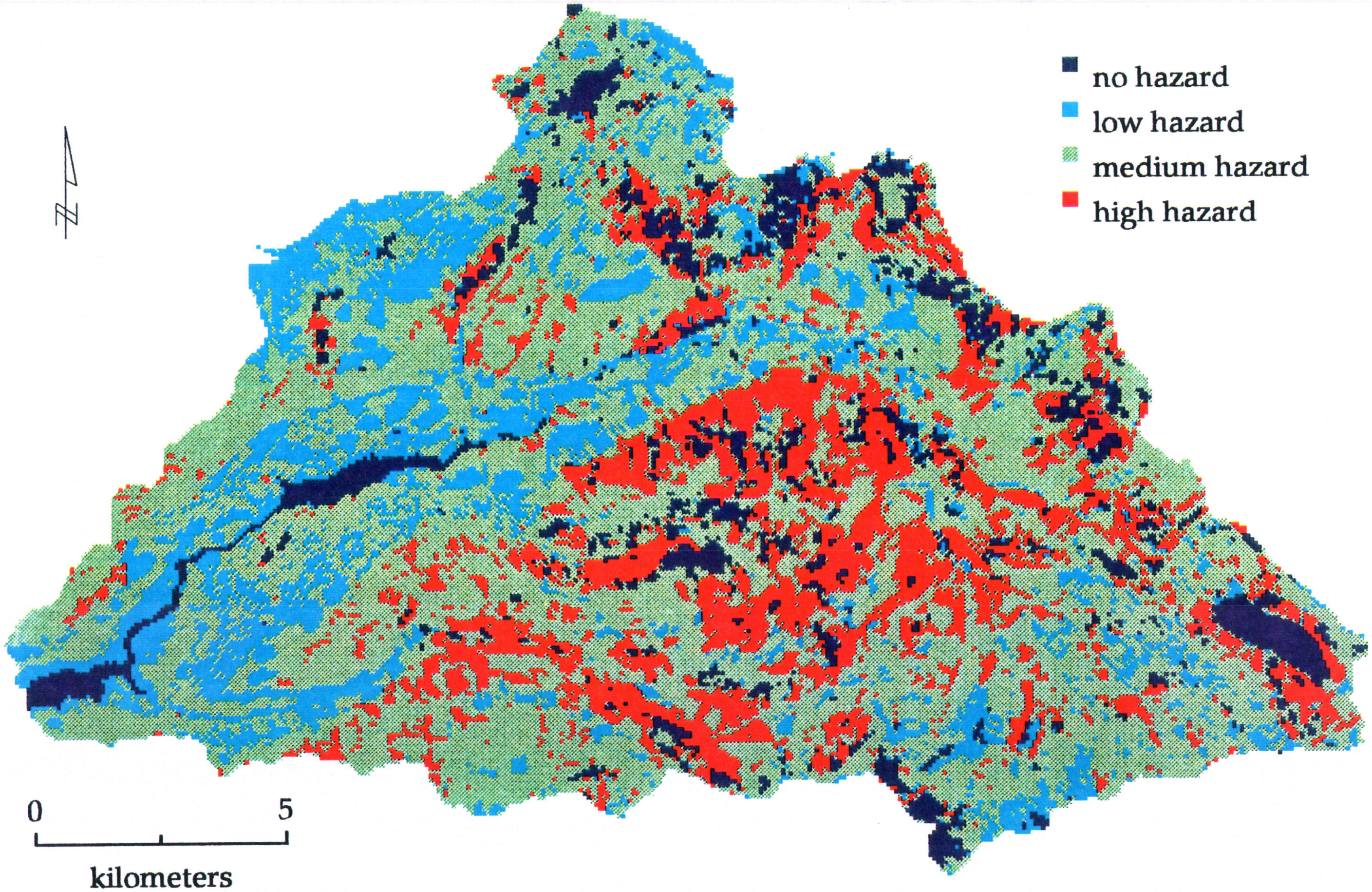


Figure 5.9 Windthrow risk in the Bull Run watershed, 2075.

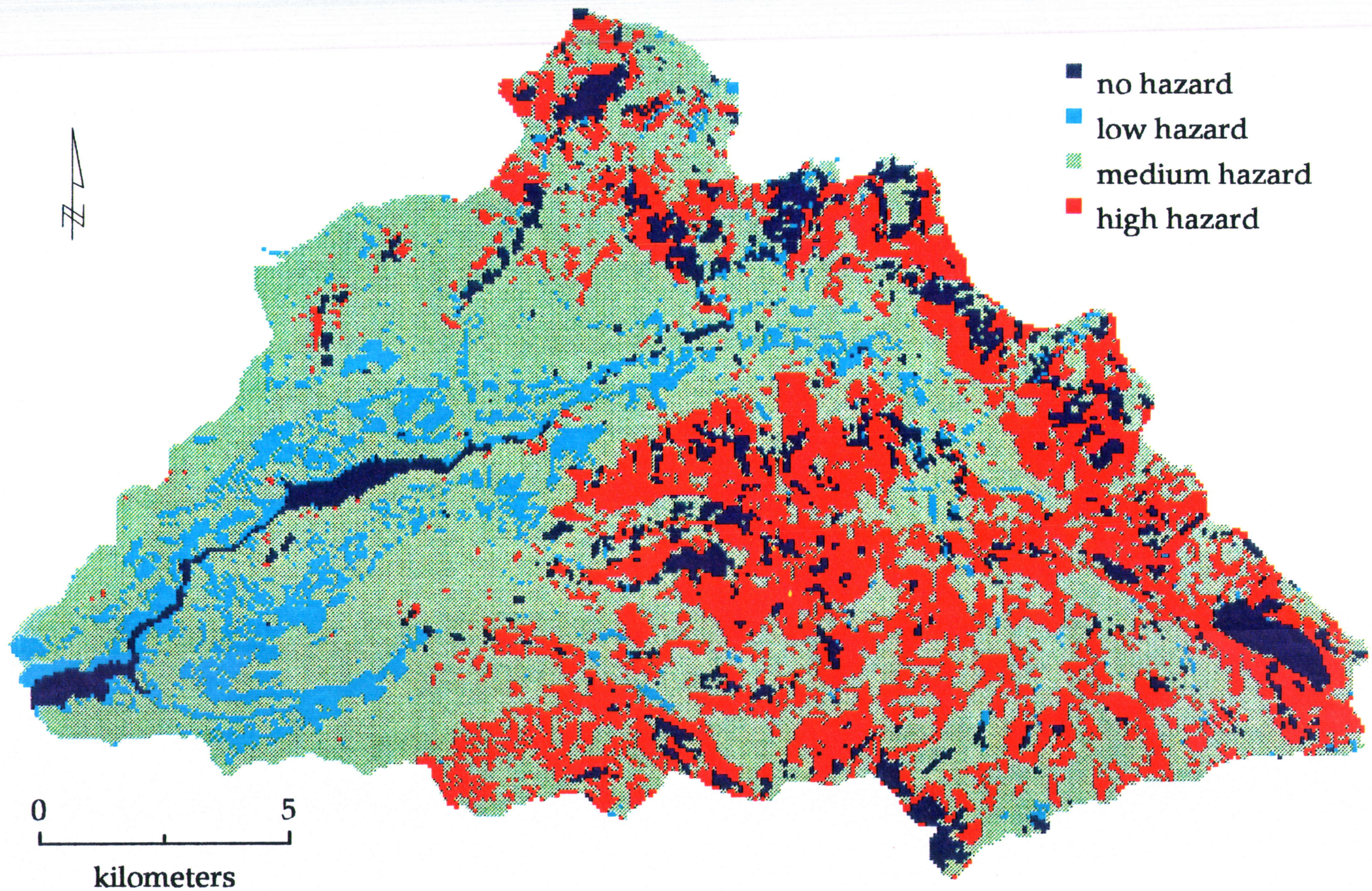


Table 5.9 Proportions of landscape mapped by windthrow risk for the years 1995, 2010, and 2075 in the Bull Run watershed, Oregon.

windthrow risk	year 1995	year 2010	year 2075
none (%)	9	9	9
low (%)	20	16	8
medium (%)	42	57	57
high (%)	29	18	25

result of clearcut edges losing vulnerability by 2010, but other forest stands increasing in height and susceptibility by 2075.

The areas most likely to experience windthrow during the next decade or so include forested locations near ephemeral openings, such as clearcuts. The spatial arrangement of clearcuts influenced windthrow during storms in 1973 and 1983, even though there were also severe wind storms in 1989 and 1996 that did not generate windthrow along cutting lines. As a conservative measure, areas within a 150-m buffer of younger clearcuts remain classified as having a high risk potential for windthrow.

In contrast, these high risk sites near ephemeral edges are likely to have been mitigated by the year 2010, and the arrangement of "high risk" windthrow locales is then projected to reflect more inherent topographical risk: ridges and upper slopes on aspects directly exposed to winds from the northeast and east. By the year 2075, younger conifer stands will have reached a stage of increased windthrow risk, and the patterns of windthrow risk varies again. In a "shifting mosaic" of landscape patterns (Bormann and Likens 1979), future windthrow patterns may more closely resemble those that occurred prior to timber harvesting, once trees at clearcut edges lose their particular vulnerability to being windthrown.

The Bull Run susceptibility maps were not designed to identify site-specific locations of future windthrow. The most accurate prediction models work in systems where winds are constant in speed and direction, the topography is gentle, and the forests are plantations, with single-species trees row-planted into shallow soils having a high moisture content (Miller 1985; Quine and White 1993). Other types of models that have proven successful involve detailed information on tree species and height (Foster and Boose 1992). Factors in the Pacific Northwest such as variability of wind speed and direction, mountainous terrain, and mixed forest composition and structure, add complexity that challenges attempts to definitively predict future windthrow location.

5.4.4 Overall windthrow risk in the Bull Run

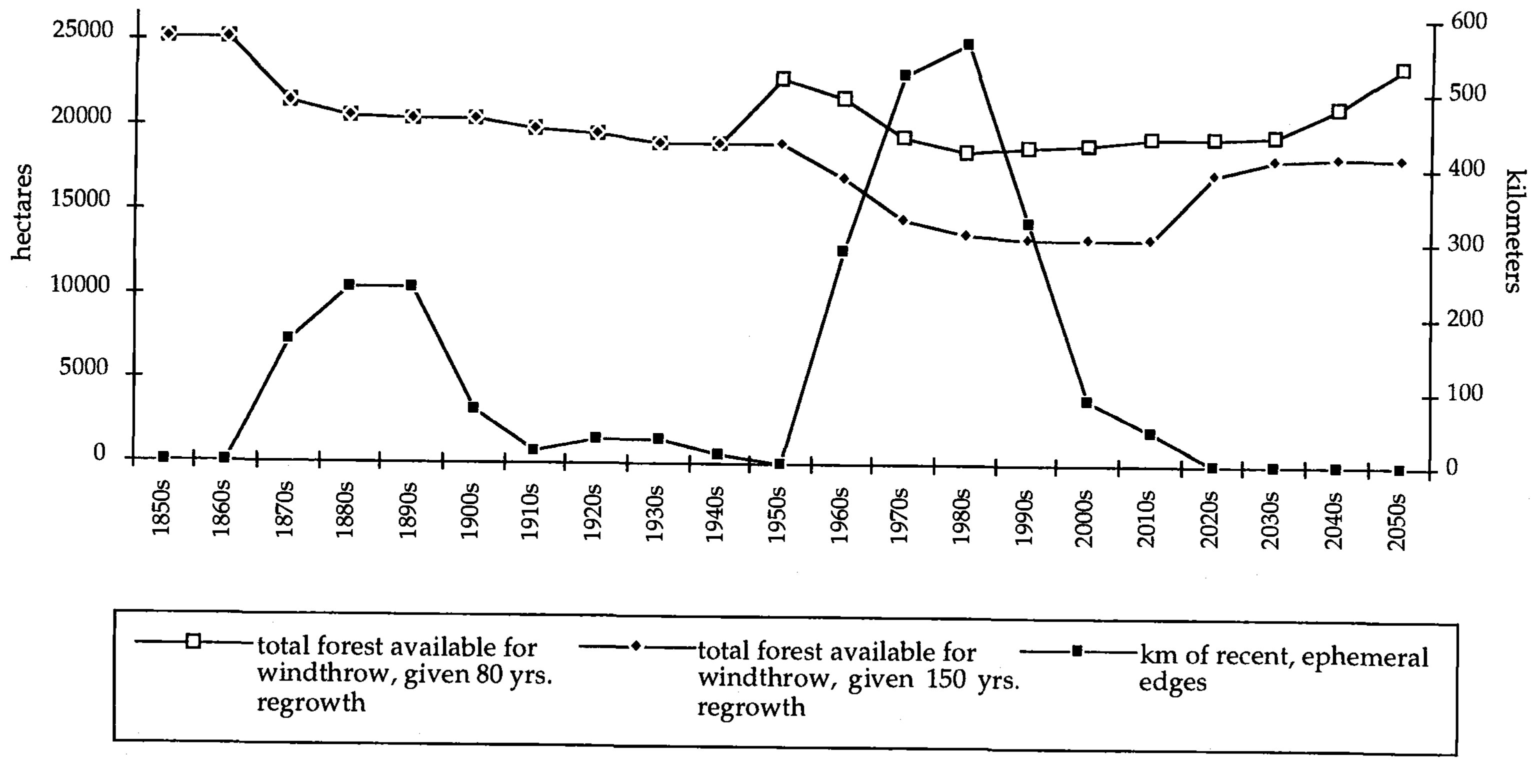
The most general way to evaluate windthrow risk in the Bull Run is to consider the area of forest that is available to be windthrown at any particular time. Fires, clearcutting, and windthrow have reduced the amount of forest in the Bull Run by over 40% since the 1870s, while the total amount of newly created edges may have peaked (Fig. 5.10). With continued fire suppression and a cessation of logging activities, the current younger forest stands will age, resulting in an increasingly older and taller forest across the landscape. Under these assumptions, the windthrow risk is currently at a low point, and will increase over the next several decades as more forest becomes vulnerable to windthrow.

Over the period 1948-1994, a mean return interval for windthrow generating storms in the Bull Run was approximated at three years, but the storm events were not uniformly distributed in time (Sinton 1996c, unpublished). Furthermore, a model designed to forecast windthrow-generating storms of two- or more days duration was only able to predict 50% of the known events that occurred between 1948 and 1994 (Sinton 1996c, unpublished). The model would predicted windthrow from a storm in January, 1996, yet no measurable windthrow was detected.

The shifting directionality of severe storm events may be part of a larger cyclical pattern in the region. In the Bull Run, windthrow was found from at least five events that occurred between 1893 and 1931, and then no measurable windthrow was identified until the 1973 event, followed by windthrow in 1975 and 1983 as well (Sinton 1996a, unpublished). Field observations and published records show that windthrow from all of these events resulted from northerly, northeasterly, or easterly winds. Therefore, it is possible that 1893-1931 was a period when severe east winds in the area were common, a temporal pattern that may have begun again in the 1960s. If this were the case, it is uncertain how long the apparent cycle would last, but with an overall mean return interval as short as three years, it is highly probable that more east wind events can be expected. However, severe east wind storms do not always produce windthrow, as was evident with the 1989 and more recent 1996 storm events.

Overall windthrow susceptibility or risk is the product of the dynamic exposure (temporal) pattern of both severe winds and trees exposed (by height or

Figure 5.10 Amount of forest available to be windthrown and the total length of recent fire and clearcut edges by decade, 1850-2050. The forest proportions vary by decade depending on the area removed from windthrow risk by fire, clearcutting, or windthrow itself. The assumptions on which this model is based are described in Table 5.6.



edges), in conjunction with static hazard (spatial) patterns of shallow soils located in vulnerable landscape positions. Under the presumption that no further clearcutting, for salvage or otherwise, occurs in the Bull Run, the locales of highest susceptibility will change in a matter of years, as revegetation occurs in openings and individual trees are pruned or culled from the edges. Thus the 2010 susceptibility map differs from the 1995 version on the basis of clearcut edges only, while the 2075 susceptibility map reflects both the absence of clearcut edges and the succession of all forested stands.

Forest stands in the Bull Run may already be increasingly windfirm, as suggested by the lack of windthrow from severe, east wind storms in 1989 and 1996. Evidence from the analysis of 1973 and 1983 windthrow suggests that in as little as ten years, clearcut edges may become more windfirm (Sinton 1996a, unpublished). Furthermore, care was taken by the Forest Service during the 1983 salvage operations to exclude from salvage stands in which salvage activity might propagate future windthrow, and in other cases salvage units were designed to have feathered or rough edges, characteristics that might increase the windfirmness of the edge.

5.4.5 Legal and management implications of risk prediction

Risk prediction is a risky business. Rarely can all possible contributing factors be identified, much less ranked and weighted. Moreover, to measure predictive success it is often necessary to wait and see where the earthquake occurs, who gets heart disease, or which trees blow down, for example. A systematic method of evaluating predictive accuracy is lacking from current risk assessment techniques (Burger 1994).

A comparison of expected to observed results is a common way to assess the accuracy of a model. Yet with retrospective studies, such as this windthrow one and others, the model is designed with a priori knowledge of the windthrow location (Foster and Boose 1992; Sinton 1996a, unpublished), thus biasing the model and limiting its applicability elsewhere.

In a location as politically-charged as the Bull Run watershed, issues surrounding windthrow and other disturbances are guaranteed to be controversial. Windthrow itself does not represent a major threat to water quality or quantity; its greatest risks are its association with insect infestations, fire fuels, and loss of old-growth forest habitat, among other things (U.S.D.A. Forest Service 1987). The Final Environmental Impact Statement prepared by the Forest Service for the salvage of 1983 windthrow stated that removal of windthrow and residual trees in windthrown stands "should not result in an increase in windthrow in adjacent stands" (U.S.D.A. Forest Service 1987, p. summary-16). While many 1983 windthrown sites were adjacent to the salvage clearcut units from the 1973 storm, little or no windthrow has yet occurred adjacent to any 1983 salvage sites (Sinton 1996a, unpublished). There is evidence that the salvage of windthrow can exacerbate further windthrow, particularly when there is clearcut salvage in areas where topographic and edaphic variables already contribute to a higher windthrow risk. However, the precautions taken during the 1983 salvage to exclude the highest risk sites may have prevented a windthrow/clearcut/windthrow pattern from continuing.

The usefulness of windthrow susceptibility maps for forest managers is restricted by the limited actions that can be taken to prevent future windthrow. For example, it has been suggested that by limiting the total length of clearcut edge that lies perpendicular to the prevailing wind direction, windthrow risk can be lessened (Gratkowski 1956; Stathers *et al.* 1994). However, the direct upwind and downwind edges of clearcuts in the Bull Run (i.e., the northeastern and southwestern edges, based on a northeasterly wind) already represent the smallest proportion of clearcut edge length (Sinton 1996a, unpublished).

One approach to utilizing the risk maps involves actions both by managers and scientists (Fig. 5.11) (Burger 1994). Forest managers should not only be concerned about management activities in high risk sites, but should also be wary of lower risk sites where the management activities could interact with other factors and inadvertently increase windthrow risk. This represents the situation where the predicted risk is low, and the actual outcome is high: an example would be the area surrounding the 1973 clearcut salvage operations near Log Creek in the Bull Run, which experienced unusually high amounts of windthrow in 1983 (Sinton 1996a, unpublished). In locations such as this, a more prudent measure might be the removal of only windthrown trees, rather than the additional removal of residual standing trees.

Figure 5.11 Various options available for managers and scientists based on accuracy of predicted risk (Burger 1994).

actual outcome	predicted risk: low	predicted risk: high
low	Managers: Low priority for risk reduction.	Managers and Scientists: Evaluate reasons for disagreement to improve future risk analysis.
high	Managers: Reduce risk. Scientists: Evaluate reasons for disagreement; evaluate methods of original prediction.	Managers: Take precautionary actions to reduce further risks.

5.5 Conclusions

Windthrow risk in the Bull Run was estimated by using spatial, hazard variables such as hillslope position, aspect, and knowledge of shallow soil locations, in conjunction with temporal, exposure variables such as the age or height of vegetation and the age of clearcut edges. Attempts to model windthrow risk in other ways, including deterministic exposure models and the use of statistical results from windthrow pattern analyses, generated mixed results.

A thorough and comprehensive windthrow risk classification, such as that used in Great Britain, is not feasible given the limited wind data, rough terrain, and complex forest stand structures in the Pacific Northwest. However, an approach similar to the Canadian Forest Service's methods of assessing windthrow risk in British Columbia might prove to be applicable in the western Cascades region.

As a conservative measure, the estimated risk for windthrow near clearcut edges remains relatively high in the Bull Run throughout the 1990s. Evidence from previous windthrow events suggests that these edges become more windfirm in as little as a decade, so it is projected that as early as the year 2010, there will be a shift in higher windthrow risk from areas dominated by ephemeral clearcut edges to areas where windthrow is controlled by topographic and edaphic factors. The result may be future windthrow patterns similar to those observed in the century before logging.

Chapter 6. Conclusions

Natural disturbances, such as windthrow, fire, and landslides, have contributed to the spatial heterogeneity of forests in the Bull Run watershed (Schulz 1980, unpublished; Krusemark *et al.* 1996). The Bull Run experiences winds funneled westward along the Columbia River Gorge, and although physical evidence of windthrow has only been found dating to the 1890s, it is likely that windthrow has been a chronic influence on the forests of the Bull Run.

Patterns of historic windthrow in the Bull Run were most strongly influenced by topographic exposure, while more recent storms generated windthrow in patterns that primarily reflected the geographic distribution of clearcuts and roads (U.S.D.A. Forest Service 1987; Sinton 1996a, unpublished). Windthrow from a 1931 storm was found most often on north and northeast aspects, locations that are consistent with storm winds from those directions. In contrast, 1973 and 1983 northeasterly storms created windthrow most frequently on south and southwest aspects, a pattern that can be explained by the existence of many ephemeral and perennial openings located on those aspects, as well as a possible lee-effect of wind turbulence over a ridgeline. However, when clearcut-edge-related windthrow from the recent storms was excluded from analyses, the remaining windthrow exhibited a geographic distribution similar to the older, pre-cutting windthrow patterns, with topographic exposure and certain edaphic factors controlling windthrow location.

The analysis of windthrow patterns involved the use of a GIS in conjunction with numerous data layers that were both created for this study and inherited from other sources. The use of such systems to interpret a disturbance pattern is not free from errors, both subjective and generated during computer analyses. However, with a landscape study, other approaches are impractical. Furthermore, the GIS provided opportunities to manipulate data in a format appropriate for multivariate statistics, a fundamental step for an analysis of a pattern that involved multiple variables as well as their interactions.

Extensive windthrow in the Bull Run is uncommon. Since 1948, only two events (January 1973 and December 1983) have generated windthrow covering more than 2% of the forest. Using wind and temperature criteria, a mean return interval for the type of storm events likely to cause windthrow was calculated at approximately three years. However, this technique predicted windthrow on days when it did not occur, and failed to predict known events such as a minor November, 1975, storm. Wind and climate data alone, particularly wind data that were not from within the Bull Run watershed itself, are inadequate predictors of windthrow events.

Windthrow can be described as a function of spatial and temporal factors, or in terms of risk assessment, a product of hazard and exposure. Certain contributing factors to windthrow do not change over time, such as topographic exposure to an east wind or the existence of shallow, moisture-laden soils, that affect a tree's rooting abilities. Other variables, such as the height of trees and clearcut edges, are transitory. Furthermore, while a tree's growth increases its susceptibility to windthrow, the aging of clearcut edges decreases the risk to adjacent trees. By incorporating these factors into a model, probable future windthrow risk can be mapped, though no model can claim accurate, site-specific prediction for a disturbance as spatially and temporally variable as windthrow.

The spatial and temporal patterns of windthrow since the 1890s in the Bull Run watershed demonstrated a range of disturbance frequencies, sizes, and severities, corroborating the theory of a natural range of disturbance variability (Swanson *et al.* 1993). The most recent windthrow in the Bull Run exhibited a correlation with forest fragmentation patterns, yet underlying the edge-related windthrow were reflections of earlier, pre-logging patterns. The windthrow disturbance regime in the Bull Run is dynamic and will change as future vegetation patterns are inevitably altered by events foreseen and unforeseen, such as succession and forest fires.

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