Cartographic Modeling of Snow Avalanche Path Location within Glacier National Park, Montana

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ABSTRACT: Geographic information system (GIS) techniques were applied to the study of snow-avalanche path location within Glacier National Park, Montana. Snow-avalanche paths are conspicuous and important phenomena within the park: they affect geomorphic, hydrologic, and vegetative processes and distributions, and form the spatial signature of a significant natural hazard. Aerial photointerpretation and field surveys confirmed the location of 121 avalanche paths within the selected study area. Spatial and non-spatial information on each path were integrated using the ARC/INFO GIS. Lithologic, structural, hydrographic, topographic, and land-cover impacts on path location were analyzed. All path frequencies within variable classes were normalized by the area of class occurrence relative to the total area of the study area and were added to the morphometric information contained within INFO tables. The normalized values for each GIS coverage were used to cartographically model, by means of composite factor weightings, avalanche path locations. Buffers were constructed, weighted, and composited to relate distances of paths to lithologic, structural, and hydrographic features. Buffer and factor composites were intersected to determine the spatial probability of path location. The derived model was implemented and a probability map of path location was produced. The cartographic model was evaluated, initially by comparison to the 121 control paths, and secondly to 43 paths not utilized in model formation. Data organized in the GIS provided an effective approach for model development, evaluation, and variable re-weighting for performance enhancement of the model. The capability to perform spatial proximity measures of paths to selected morphological factors contained within the GIS and to add derived attribute data to INFO tables provided essential information for model building not effectively generated through other approaches.

INTRODUCTION

SNOW AVALANCHES are a widespread natural hazard. Avalanches are the most frequent catastrophic mass movement in the United States, with approximately 100,000 occurring annually. The world-wide number of fatalities from avalanche-related incidents in the 20th Century exceeds 100,000. Annual mortality rates in the United States stemming from snow avalanches are twice that due to earthquakes, and almost equal to the number of deaths from all other forms of mass movement (Voight and Ferguson, 1988).

Given the scope of the avalanche hazard, the study of snow-avalanche paths as a major landscape component was deemed important. Avalanches tend to occur in spatially-distinct locations, produce distinct landforms, and cause distinct biogeographic responses and resulting land-cover patterns. In this study a geographic information system (GIS) was used for delineation and analysis of locations subjected to snow avalanches in Glacier National Park, Montana. The objective of this paper was to utilize GIS techniques in the development of a cartographic model of snow-avalanche path location in a region widely influenced by snow avalanches. Spatial and non-spatial attribute data of 121 paths contained within the GIS were used to build the cartographic model. Spatial buffering, coverage compositing, factor weighting, and normalization of path attributes contained within INFO tables provided the analytical framework for this analysis.

BACKGROUND

A snow avalanche is defined as ". . . a mass of snow moving downslope which may also contain ice, soil, rocks, or other debris" (Fredston and Fesler, 1984, preface). Snow avalanches can flow in direct contact with the underlying slope, or they can slide or fall over an underlying snowpack, in which case vegetation might be impacted but little surface erosion will result.

Snow avalanches require steep terrain. This obvious maxim explains why the avalanche hazard is confined to mountainous environments. Specifically, most large snow avalanches begin on slopes which range between 30 and 45 degrees; most occur in the 35 to 40 degree range (LaChapelle, 1985). Smooth surfaces are much more likely to produce avalanches than are slopes of rough, irregular terrain. For the latter to experience avalanches, snow must first fill and smooth out the irregularities in the terrain. Forested slopes are much less likely to experience major avalanches than are unvegetated or grass-covered slopes, and deforestation is widely recognized as a major instigator of avalanches in terrain which had not previously experienced the hazard (Saeki *et al.*, 1982).

Steep gullies and open slopes are natural avalanche paths, whereas ridges, outcrops, and terraces are natural avalanche barriers (LaChapelle, 1985). The most typical, and dangerous, avalanche path is one with a broad starting zone that funnels downslope into a gully and ultimately debouches onto a low-angle valley bottom. Such paths are typically divided into three morphologic components: the starting zone, the track, and the runout zone (Figure 1). These paths are dangerous because the funneling effect of the gully (track) produces ". . . a deep layer of flowing snow and high velocities . . ." (LaChapelle, 1985, p. 27). Upon reaching the low-angle runout zone in a valley bottom, high velocities and powerful impact forces can potentially devastate anything in the avalanche's path.

Typical avalanche paths such as those shown in Figure 1 are common throughout mountainous regions of the world. They are strikingly visible in those alpine regions where the avalanches cut a vertical swath downhill through mature forest vegetation. These vertical swaths resemble fuel breaks cut by bulldozers (Malanson and Butler, 1984a). The swaths are visible

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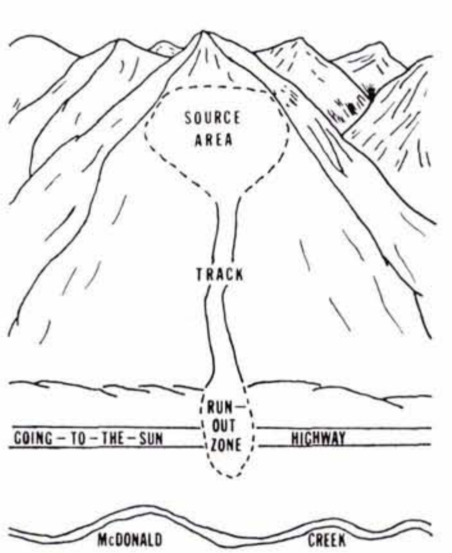

FIG. 1. Morphometric components of snow avalanche paths.

because the recurring process of avalanching on the avalanche path precludes reestablishment of the mature forest, establishing instead a variety of disclimax communities of herbs, shrubs, and flexible deciduous trees which can withstand snow-avalanche impact (Butler, 1979; Malanson and Butler, 1984b, 1986). These disclimax swaths are typically a much lighter or brighter green than the adjacent mature forest. Because of this difference, major avalanche paths are easily detectable on black-and-white or color infra-red ground-based or aerial photographs. Textural differences between the low herbaceous plants and shrub cover of avalanche paths and the adjacent mature forest are also easily detectable. Most mapping projects which delineate avalanche-hazard zones begin by outlining obvious and distinct avalanche paths.

STUDY AREA

Glacier National Park is located in the Rocky Mountains of northwestern Montana, immediately south of the Canadian border (Figure 2). Topography is typically steep, dominated by Pleistocene glacial erosional landforms. Winter precipitation is moderately heavy, and snow may fall in any month (Butler, 1986). Snow avalanches occur on all slope aspects, although Butler (1979) showed that the geomorphic alignment of Pleistocene glaciated valleys exerts a major control on the availability of certain aspects for avalanching. Avalanches in the Park include slab, dry powder, and wet snow avalanches, the latter probably the most common (Butler, 1986).

The primary study region within Glacier Park is restricted to a zone east of the Continental Divide (Figure 2) (the study area has been squared to conform to topographic map boundaries related to the processed DEM data used in this study). This area is representative of the high mountains landscape which experiences snow avalanching. It also provides maximum accessibility for ground-truth coverage utilizing an excellent set of trails and roads. Availability of panchromatic aerial photographs and remote sensing imagery was also a consideration.

The study area is deeply scoured by U-shaped glacial valleys of Pleistocene age, upon which are imprinted snow-avalanche paths. Elevations in the area range from about 1,250 m at the eastern edge of the study area to over 3,000 m at the crest of Mt. Siyeh (Figure 2). Lithology is comprised of relatively flat-lying sedimentary rocks of the Precambrian Belt Series which have been tectonically thrust eastward over Cretaceous shales and mudstones (Ross, 1959; Raup *et al.*, 1983). The Lewis Overthrust Fault marks the easternmost boundary of the thrust sheet. Associated with the tectonic thrusting were associated major and minor faults (only a few of which were mapped by Ross (1959), intense rock fracturing, and widespread folding. These structural weaknesses have been spatially linked with widespread mass movements along the eastern margins of the Park (Oelfke and Butler, 1985). These weaknesses also are thought to influence the location of snow-avalanche paths in the study area.

METHODS

During the summers of 1987 and 1988, field data were collected to confirm the location of 121 snow-avalanche paths occurring within the selected study area. These paths were initially identified on panchromatic 1:34,400-scale aerial photographs. All major basins within the study area were inventoried: terrestrial photographs were taken and index numbers were assigned to each path. The location and areal extent of each path were plotted on 1:24,000-scale topographic maps, and morphometric data were collected for each path from the topographic maps, aerial photographs, and field observations (Table 1). The morphometric variables were entered into an INFO table within the ARC/INFO GIS for defining the character of each path from a geographic and geomorphic perspective. The position and orientation of each path were graphically recorded by the digitization of all avalanche paths from the topographic maps. A GIS thematic overlay of path location was produced and merged with overlays developed for hydrography, geologic structure, lithology, topographic orientation, and land-cover type. Table 2 summarizes the data source, format, scale, and date of all variables captured and entered into the GIS.

Most of the GIS overlays were compiled by direct digitization and transformation of mapped information for precise co-registration with other thematic overlays. Land-cover type and structural lineaments, however, were characterized through the digital analysis of Landsat Thematic Mapper (TM) data. Terrain orientation was characterized by a USGS digital elevation model (DEM).

The land-cover GIS overlay was produced through an unsupervised classification of a 6 August 1986 TM scene (ID# Y5088917461XO). Ground control information for specific locations in the study area was acquired during the summers of 1987 and 1988 to aid in cluster labeling of the land-cover classification. Cover-type classes identified included water, snow and ice, bare rock, lodgepole pine (*Pinus contorta*), spruce/fir (*Picea engelmannii* and *Abies lasiocarpa*), mixed herbaceous, and mixed shrubs. The rasterized TM classification achieved through the ERDAS software was transformed into the polygon format for use in the ARC/INFO environment.

A lineament may be defined as "a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectangular or slightly curvilinear relationship and which differs distinctly from the pattern of adjacent features and presumably reflects a subsurface phenomena" (O'Leary *et al.*, 1976). Structural lineaments identified on the 1959 USGS 1:125,000-scale geology map were supplemented through the digital enhancement of the TM data for lineament detection. Walsh and Mynar (1986) indicated that the synoptic view of local and regional lineament patterns afforded through Landsat is a useful mapping technique in areas considered to be well mapped as well as in poorly mapped areas. Image enhancement of Landsat TM data increases contrast and sharpness between geologic and other landscape features and improves the recognition of subtle differences important in understanding complex landscape conditions and spatial relationships.

A combination of ratio and principal components analysis provided useful information on lineaments and suggested the

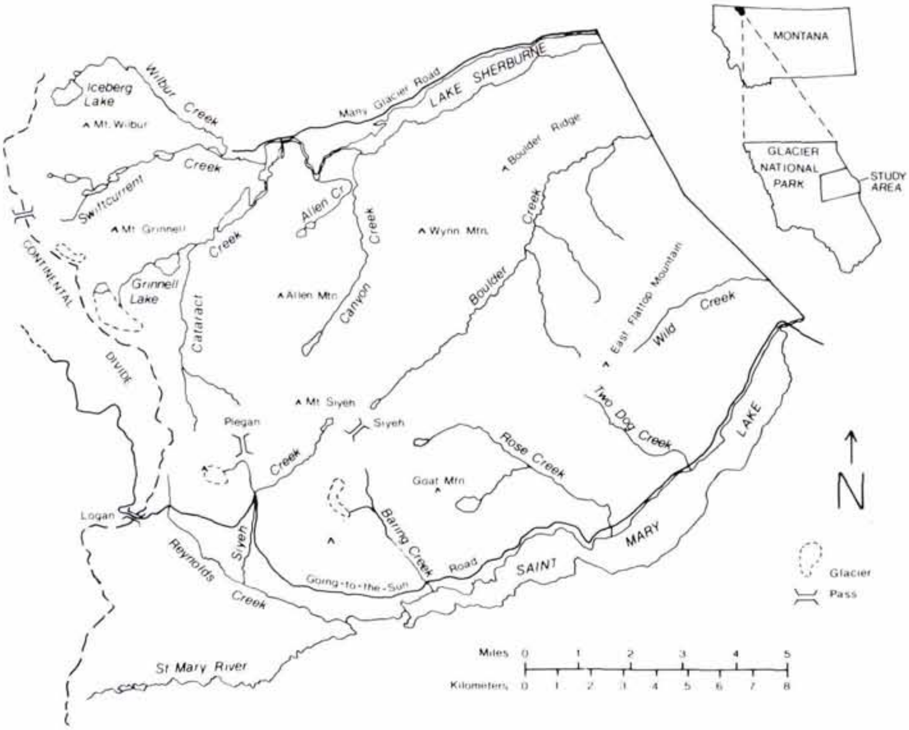

FIG. 2. Study area location within Glacier National Park, Montana.

TABLE 1. MORPHOMETRIC VARIABLES DERIVED FOR EACH OF THE SNOW-AVALANCHE PATHS (121) WITHIN THE STUDY AREA. THE ASTERISKS (*) INDICATE THOSE MORPHOMETRIC VARIABLES USED IN THIS STUDY.

INFO Table Variables
Length of path
Width of path
Length/width ratio of path
Starting elevation of path*
Ending elevation of path
Local relief of path
Slope aspect of path*
Slope angle of path*
Elevation of ridge above path location
Elevation of valley below path location
Difference between elevation of ridge and valley above and below path location
Lithology of path*
Distance of path to nearest dike*
Distance of path to nearest sill*
Distance of path to nearest fault*
Distance of path to nearest road
Landcover type in starting zone of path*
UTM easting of path head
UTM northing of path head
UTM easting of ridge above path
UTM northing of ridge above path
Source area of path
Track length of path
Runout zone area of path

TABLE 2. SUMMARY OF VARIABLES CONTAINED WITHIN THE GIS.

Variable	Source	Format	Scale	Date
Avalanche Path	Field	Air Photo & Topo maps	1:34,400 1:24,000	1966 1968
Hydrography	USGS	Topo maps	1:24,000	1968
Structural Lineaments	USGS EOSAT	Air photos & TM data	1:34,400 30 × 30m	1966 1986
Sedimentary Lithology	USGS	Geologic map	1:125,000	1959
Sills/Dikes	USGS	Geologic map	1:125,000	1959
Elevation	USGS	Topo maps & DEM	1:24,000 1:250,000	1968
Slope Angle	USGS	Topo maps & DEM	1:24,000 1:250,000	1968
Slope Aspect	USGS	Topo maps & DEM	1:24,000 1:250,000	1968
Watersheds	USGS	Topo maps	1:24,000	1968
Land Cover	EOSAT	TM data	30 × 30m	1986

association of lineaments to specific topographic and geologic features (Cwick *et al.*, 1987). TM channel ratios and principal components, viewed as single images and image composites, were utilized for lineament detection (Davis *et al.*, 1987). Subtle and conspicuous information became apparent on the color composite images by varying the ratio composite combinations and by superimposing selected principal components. Chavez and Kwarteng (1989) reported that the use of components that represented relatively minor proportions of the variability in the total TM spectral radiance contained critical information important to the interpretation of lineaments. The presence and orientation of the detected lineaments were verified in the field and through the use of aerial photography.

Band ratios reduced the effect of shadows and fluctuations in sensor-surface geometry caused by topographic orientation, and provided a method of combining the information content of multiple spectral channels into one output channel. Principal components analysis (PCA) transformed the highly correlated TM channels into statistically independent orthogonal axes on which the original satellite data were reprojected. Data subjected to PCA provided an effective data compression approach, and were capable of representing the inherent variability of the landscape contained in the seven channels of TM within generated components.

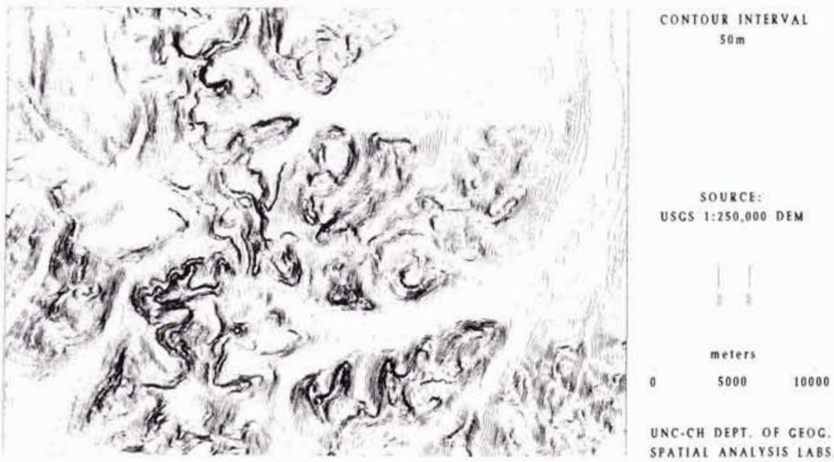

FIG. 3. Elevation contour map of the general study area from the processed DEM.

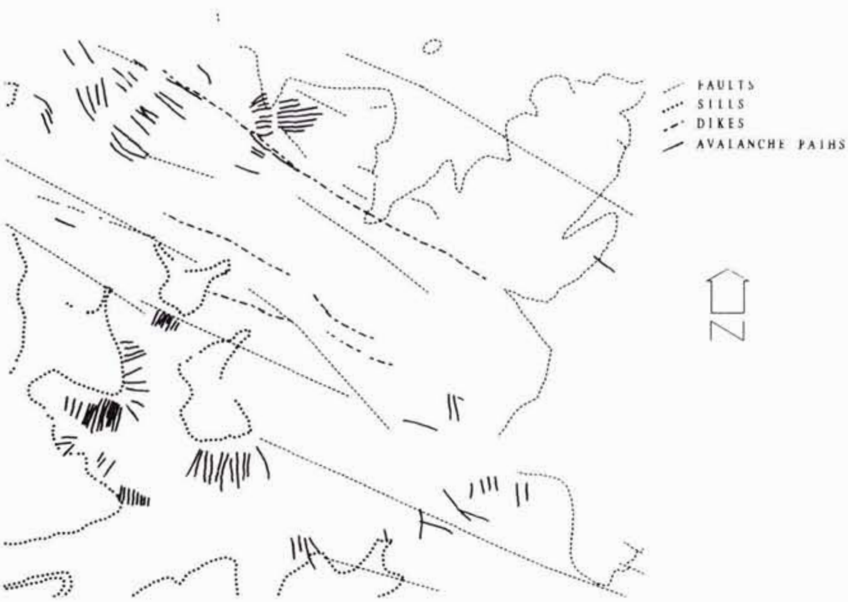

FIG. 4. GIS composite of snow-avalanche path location and structural patterns within the study area.

Topographic orientation of the study area was represented through the use of 1:250,000 base-scale digital elevation models (1:24,000 base-scale DEMs were not available for the entire study area). GIS thematic overlays of elevation, slope angle, and slope aspect were produced through the triangulated irregular network (TIN) approach offered within the ARC/INFO software.

A FORTRAN program was developed to convert the DEM data into an ARC/INFO acceptable format. The original USGS 1:250,000 base-scale DEM was constructed by sampling every three seconds of latitude and longitude (approximately 60m in an east to west direction and 90m in a north to south direction). The DEM data were transformed into UTM coordinates before the calculation of elevation, slope angle, and slope aspect overlays. Elevation data were summarized through 50-m contour lines (Figure 3). Slope angle was classified into 17 categories with five degree intervals. Slope aspect was divided into the primary eight azimuthal categories plus an additional category representing flat surfaces. The DEM data were used to produce a generalized representation of topographic orientation for the implementation of the cartographic model of path location. The measurement of terrain orientation of the paths used to generate the model was made from the 1:24,000-scale USGS topographic maps. While the use of 1:24,000 base-scale DEMs was preferable, the 1:250,000 base-scale DEM was adequate given the precision of the cartographic model and the scale of the probability map generated employing the model. In addition, the median path length of the 121 sample paths used in this study was approximately 550m - a dimension in which similar terrain was sufficiently characterized by the smaller scale DEM in the implementation of the model.

ANALYSIS

Spatial proximity to geologic structural elements and hydrologic features on the landscape was an important influence on the position of snow avalanche paths within the study area (Butler and Walsh, in review). Measurement of the distance of paths of sills, dikes, faults, and rivers and streams was carried out within the ARC/INFO environment through the generation of buffers. Buffers, as used in this analysis, are spatial zones of user-defined diameter that indicate the search/analysis distance from specified target phenomena. Distance measures of each path to the selected landscape features were calculated and added to the path morphometric database. A separate thematic overlay of buffers surrounding sills, dikes, faults, and rivers and streams was added to the GIS for integration with the other coverages. Bonham-Carter *et al.* (1988) used a similar proximity measure around structural lineaments for gold prediction.

Buffer dimensions for this study were determined by exam-

TABLE 3. NORMALIZED FREQUENCIES OF MODEL VARIABLES.

Variable	Raw Frequency (Number of Paths)	% Total Area	Normalized Frequency
LITHOLOGIC TYPE			
Altyn Limestone	4	4.4	0.909
Appekuny Argillite	32	26.7	0.834
Grinnell Argillite	21	26.3	0.798
Siyeh Limestone	58	30.7	1.889
SLOPE ANGLE			
10 - 15 degrees	1	11.16	0.09
15 - 20 degrees	0	11.19	0
20 - 25 degrees	17	9.94	1.71
25 - 30 degrees	69	8.98	7.68
30 - 35 degrees	20	8.30	2.41
35 - 40 degrees	13	8.39	1.55
40 - 45 degrees	1	7.24	0.14
SLOPE ASPECT			
Northwest	16	9.67	1.65
West	9	4.31	2.09
Southwest	9	6.88	1.31
South	29	24.93	1.16
Southeast	14	10.78	1.30
East	17	4.95	3.43
Northeast	8	6.92	1.16
North	19	25.15	0.76
ELEVATION			
Greater Than 2400 m	1	10.72	0.09
2300 - 2400 m	14	4.92	2.85
2200 - 2300 m	11	8.94	1.23
2100 - 2200 m	30	10.18	2.95
2000 - 2100 m	19	11.39	1.67
1900 - 2000 m	14	5.30	2.64
1800 - 1900 m	18	16.63	1.08
1700 - 1800 m	11	9.95	1.11
1600 - 1700 m	1	0.78	1.28
1500 - 1600 m	2	17.66	0.11
Less Than 1500 m	0	3.53	0
LANDCOVER (Starting Zone)			
Rock & Sand	89	44.1	2.02
Mixed Herbaceous	11	12.9	0.85
Mixed Brush	6	10.6	0.56
Lodgepole Pine	3	15.1	0.20
Spruce/Fir	12	12.4	0.97
HYDROGRAPHY			
Within 1 m	14	28.6	11.6
Within 50 m	11	51.0	20.7
Within 100 m	13	77.6	31.4
Within 150 m	7	91.8	37.2
Within 200 m	3	97.9	39.7
Within 250 m	0	97.9	39.7
Within 300 m	1	100.0	40.5
SILLS			
Within 100 m	11	22.0	9.1
Within 200 m	9	40.0	16.5
Within 300 m	12	64.0	26.4
Within 400 m	6	76.0	31.4
Within 500 m	9	94.0	38.8
Within 600 m	1	96.0	39.7
Within 700 m	1	98.0	40.5
Within 800 m	1	100.0	41.3
FAULTS			
Within 50 m	8	57.1	6.6
Within 100 m	1	64.3	7.4
Within 150 m	0	64.3	7.4
Within 200 m	3	85.7	9.9
Within 250 m	2	100.0	11.6
DIKES			
Within 50 m	2	50.0	1.6
Within 100 m	3	75.0	2.5
Within 200 m	4	100.0	3.3

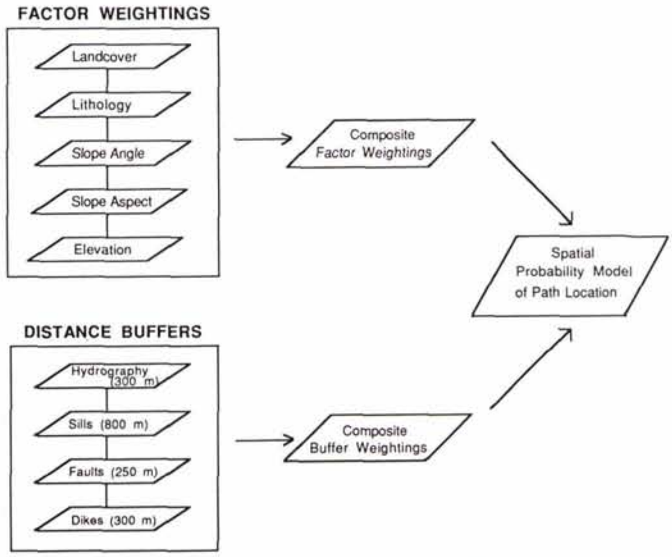

FIG. 5. Summary of spatial data integration and modeling approach.

ining the maximum distances between paths and sills, dikes, faults, and hydrography, for those paths assigned to topography, structure, or lithology as the primary forcing function of path location. Assignments were made through the compositing of GIS overlays of snow - avalanche path location against overlays of lithology, structure, and topography. The spatial clustering of paths around sills, dikes, and faults was readily apparent (Figure 4). A 300-m buffer was generated and draped onto all hydrography to determine the spatial proximity of assigned paths to rivers and streams; an 800-m buffer was used to derive distances between assigned paths and sills; a 250-m buffer was used to derive distances between assigned paths and faults; and a 300 - m buffer was used to characterize the distance between assigned paths to dikes. For all buffer applications, a 50 - m interval was used to characterize intra-buffer spatial proximities between paths and the target phenomena.

A normalized frequency weighting was calculated for each of the GIS thematic overlays to determine whether the frequency of the spatial identifiers of individual path location, i. e., preferred slope angle class and elevation zone, might be biased because of the relative abundance or paucity of such sites within the study area. All GIS overlays were normalized by the area of class occurrence relative to the total area of the study area. For example, attribute information contained within the GIS was used to determine the number of paths, out of the 121 sample paths, occurring on south facing slopes. The DEM was used to determine the total area of all south facing slopes within the study area. The frequency values of paths occurring on south facing slopes were normalized by the total area of all south facing slopes relative to the total area of the study area. Table 3 shows the raw and normalized frequency values of the 121 paths and the percent of total area of each sub-class variable used to represent lithologic, topographic, hydrographic, structural, and land-cover relationships to path location. The normalization process was achieved through use of the GIS and its capability to quickly determine the area of individual coverage components throughout the study area for each overlay. Utilizing the morphometric measures of each path contained within the INFO tables, frequency counts of paths by elevation, slope angle, slope aspect, lithology, and land-cover were determined.

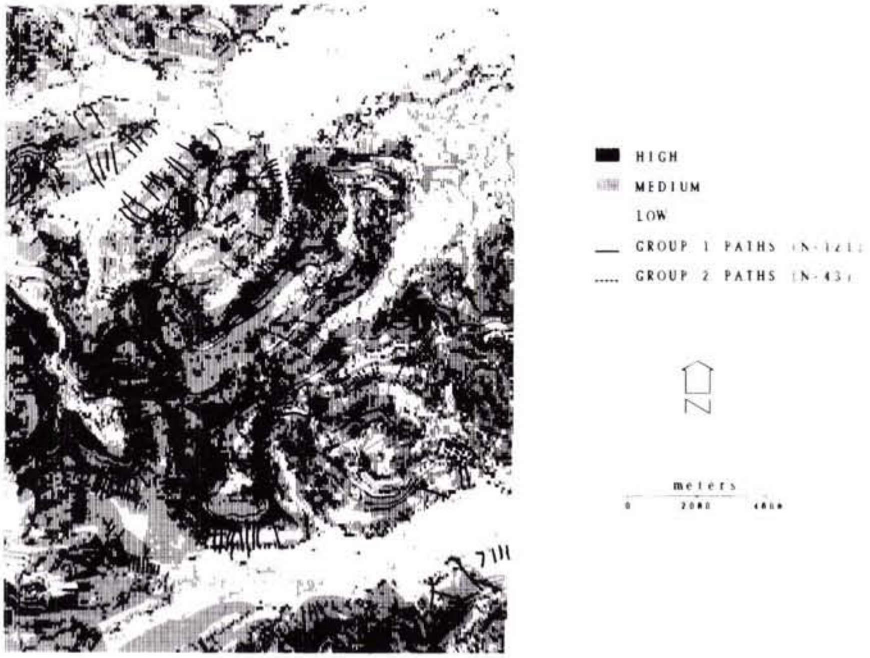

FIG. 6. Spatial probability model of path location, and overlay of two "groups" of paths for validation of the cartographic model

The frequency data for each overlay were then normalized by the weighted area measures previously calculated.

Normalized frequency weightings also were derived for the proximal measures generated through spatial buffering. Buffers were weighted by the percent of all snow avalanche paths occurring within the various buffer distance from the target feature.

Two composite maps were created as a result of combining the buffer polygon coverages and the factor weighting coverages. The two composite maps were prepared by addition of all weightings in the GIS input coverages (Figure 5). The individual factor weightings for each thematic coverage were determined by computing the relative probability of class "importance" given the distribution of the 121 paths throughout the sub-classes of that variable. If, for example, ten paths out of a possible 121 paths occurred on south facing slopes, then south facing slopes were assigned a corresponding weighting value of 0.083. The frequency distributions of the weighted values for the two composite maps were examined and grouped into three and five classes, respectively, for the buffer and the factor weighting composites. The buffer composite weightings were grouped through the natural break technique, while the factor weighting composite was grouped through the histogram equalization approach (Jensen, 1986). Data were grouped into classes to improve processing efficiency, because approximately 25,000 polygons were generated for each thematic coverage due to the size of the study area and the complexity of the environment. Intersection of that number of polygons for the number of thematic coverages utilized was computationally prohibitive. In addition, the derived final probability map was conceptualized as a classed relative probability map of path location in which aggregated data were a by-product.

In order to combine the two composite maps into one spatial probability map, the class numbers for each map (1 through 3 for the buffer composite and 1 through 5 for the factor composite) were multiplied (weighted) by the number of overlays composited to create each map. The resulting group weightings were 3, 6, and 9 for the buffer composite map and 5, 10, 15, 20, and 25 for the factor composite.

The two composite maps were overlaid and intersection polygons were created. Values were assigned to each of the intersected polygons according to the sum of the two weighted class values of the buffer and factor weighting composites, which were derived through the relative possibilities of each coverage subclass. Each thematic coverage used in the analysis had the same weight, but each coverage subclass (i. e., south facing subclass of the slope aspect coverage) was weighted according to actual path frequencies. Fifteen categories were produced which were combined into three probability categories based upon the frequency distribution of the classes formed through the intersection process. The equal interval method of data categorization was used to group the 15 intersection values into areas representing "high", "medium" and "low" probabilities of snow-avalanche path location in the study area.

The sensitivity of the cartographic model for locating snow-avalanche paths was evaluated by cartographically overlaying, within the GIS environment, two groups of avalanche paths onto the derived probability map. The 121 paths used to construct the model of path location (group 1) and 43 paths not utilized in model development (group 2) were registered to the probability map generated through the cartographic model (Figure 6). The objective was to define relative probability categories that contained specific percentages of the paths used to evaluate the model of path location. The "high" probability category was defined as that region on the map in which approximately 70 percent of the paths occurred; "medium" probability was defined as that area in which 20 percent of the paths occurred; and "low" probability was defined as that area in which 10 percent of the paths occurred.

SUMMARY AND CONCLUSION

The locations of snow-avalanche paths within eastern Glacier National Park, Montana, are controlled by lithologic, structural, and topographic factors (Butler and Walsh, 1990). The spatial correspondence of landscape elements affecting location was determined through the compositing of thematic overlays. The GIS organization of variables important to path location facilitated the assignment of each path to lithology, topography, or structure as the dominant control of path location. Descriptive information on each path, formatted within attribute tables of the GIS, permitted the construction of weighting factors for each GIS coverage that represented locational preferences of paths.

Frequency measures were normalized by area for each variable class, and appropriate weightings were derived. Distance buffers also were developed, and weights were assigned to buffer classes by utilizing normalized frequency counts calculated from the attribute tables. Finally, a location probability map of path location was produced through the intersection (addition) of buffer weighting and factor weighting composites.

The development of a map that indicates the distribution of the relative probabilities of biophysical variables affecting snow-avalanche path location is vital for hazard zone evaluation, and for incorporating information into models and related analyses on the geomorphic, hydrographic, and vegetative character of sites where paths currently exist or are likely to occur in the future. The spatial pattern of path location, display of factors controlling their distribution, and GIS approaches for modeling their spatial character have combined to provide a level of geomorphic information critical to hypothesis development and testing within a spatial domain.

The capability to submit spatial and non-spatial queries to the GIS database was a useful approach in this research. Equally as important was the capability to link the spatial and non-spatial information on the snow-avalanche paths through relationships established within the GIS data structure. The overlay, intersect, and polygon dissolve functions of the GIS software enabled the integration of information from a host of coverages into a single overlay which indicated the importance of terrain, lithology, hydrography, and land cover and their spatial proximities on path location. Iterative weighting of normalized variables and display and assessment of their distributions were an important consideration in model development.

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