Figure 10-5

BEDROCK AS A FACTOR IN LANDSLIDE OCCURRENCE
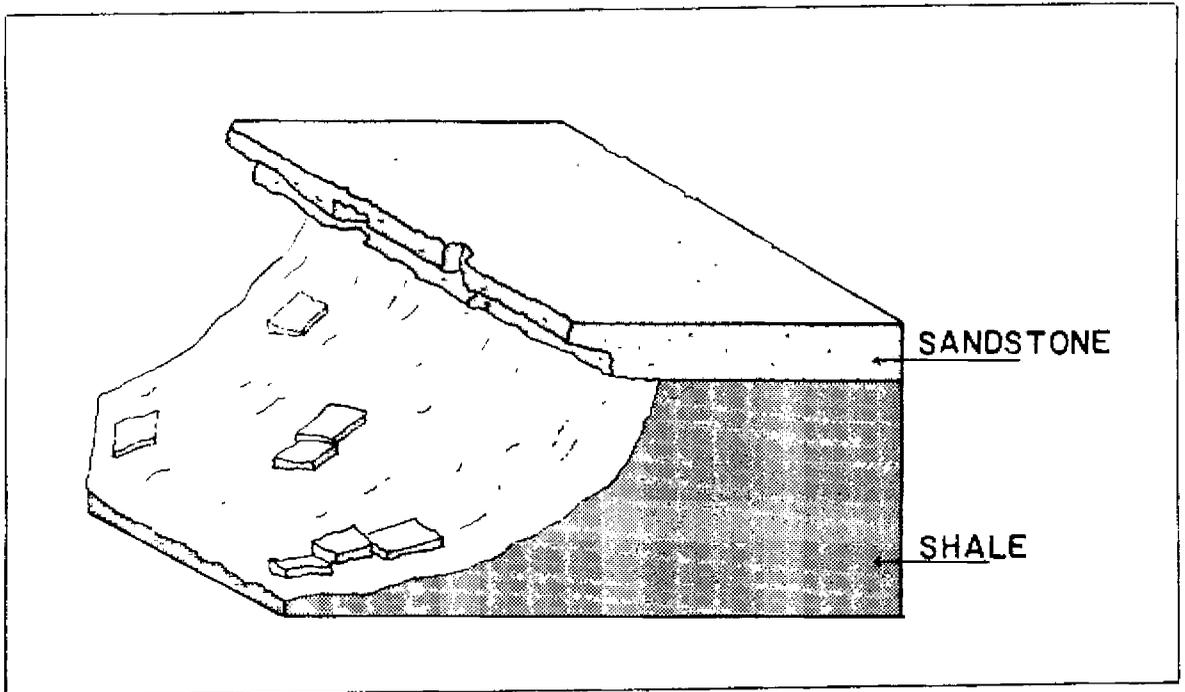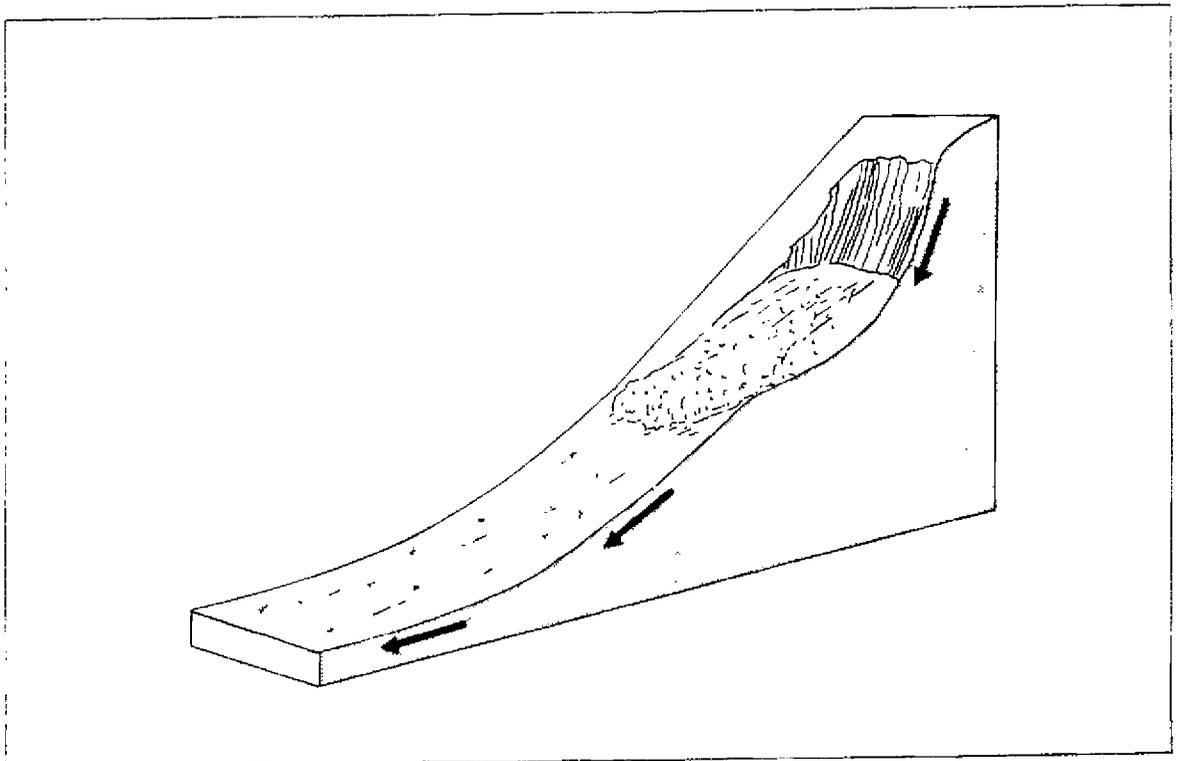

Figure 10-6

SLOPE STEEPNESS ASSOCIATED WITH LANDSLIDE ACTIVITY

Natural Hazards Primer/Part III

activities, there is usually no direct observable correlation between slope orientation and landslide hazard.

e. Human-initiated Effects

In addition to natural phenomena, human activities may increase the natural tendency for a landslide to occur. Landslides which result from development activities are usually the result of increasing moisture in the soil or changing the form of a slope. Development activities such as cutting and filling along roads and the removing of forest vegetation are capable of greatly altering slope form and ground water conditions (Swanson and Dyrness, 1975). These altered conditions may significantly increase the degree of landslide hazard present (Varnes, 1985, and Sidle, Pearce, and O'Loughlin, 1985)

For example, converting a forested area to grassland or one where crops are cultivated can increase the moisture in the soil enough to cause landslide problems (DeGraff, 1979). Or building a road which cuts off the toe of a steep slope can increase landslide susceptibility. It is possible to reduce the potential impact of natural landslide activity and limit development-initiated landslide occurrence by early consideration of these effects (Kockelman, 1985).

Now that the general points with regard to mapping the various land characteristics have been covered, the final section provides details on the techniques to do so in addition to presenting a step-by-step approach for preparing a landslide hazard map

C. Mapping Physical Factors and Preparation of a Landslide Hazard Map

A landslide inventory produces a descriptive or data map (Cotecchia, 1978) By overlaying the landslide inventory map on the maps of the type of bedrock, slope steepness, and indirect hydrologic measures, the association of past landslides with the factors controlling landslide occurrence can be recognized. The method described below employs these associations in synthesizing a landslide hazard map. Extrapolating the data to areas with characteristics similar to those found associated with past landslides is an effective tool for forecasting where, but not when, landslides are more likely to occur in the future.

This section presents the techniques used to map each of the key factors associated with landslides. With these maps, a landslide hazard map can be prepared. Hazard zonation is a means of identifying areas with differing landslide hazards. The step-by-step approach, or factor analysis, used to prepare a landslide hazard map is described.

1. MAPPING THE PHYSICAL FACTORS ASSOCIATED WITH LANDSLIDES

Each factor is mapped separately by a different technique.

a. Mapping the Inventory of Existing Landslides

A map of existing landslides serves as the basic data source for understanding conditions contributing to landslide occurrence. Normally such a map is prepared by the interpretation of aerial photography and field examination of selected locations. While this map could also be compiled by field methods alone, the time and expense involved would only be justified by the unavailability of photo coverage. Either means of map preparation requires the skills of a geologist with experience in landslide or landform interpretation.

Aerial photography can serve as the source for data on existing landslides, type of bedrock, and vegetation cover. Typically, large-scale photography is necessary to be useful for existing landslides. The photo scale depends on the size of landslides common to the study area. Small-scale photography is less of a concern where bedrock and vegetation exist, since delineating areas with similar texture and appearance is easier than recognizing discrete features. Satellite imagery is generally unsuitable for landslide mapping except where data products can be enlarged to at least 1:50,000 scale. Photographic and satellite information is valuable in mapping other spatial information and for use in conjunction with computer mapping techniques as part of the development planning study (see Chapters 4 and 5 for a more detailed discussion).

Depending on vegetative cover, photo quality, and the skill of the interpreter, overall identification accuracy of 80 to 85 percent is realistic using aerial photography (Rib and Liang, 1978). The range of useful scales of aerial photography for landslide inventory work is limited to about 1:40,000 or larger. The selected scale will depend on the size of landslides common to the study area and, to some extent, the relief of the area. Large failures of four or more square kilometers are extremely difficult to detect on aerial photography smaller than 1.40,000. Where the majority of landslides are one hectare or smaller in size, large-scale photography on the order of 1.4,800 is necessary. The usefulness of black and white,

color, or color-infrared photography for landslide inventory work will vary with local conditions and the individual making the interpretation. Each type of photography has advantages and disadvantages that will vary in their importance according to the characteristics of the area being mapped.

The map may be prepared at different levels of detail concerning existing landslides (USGS, 1982). A simple inventory identifies the definite and probable areas of existing landslides and is the minimum level required for a landslide hazard assessment. A map is produced in which each landslide is outlined and an arrow is drawn to denote the direction it moved. (See Figure 10-7 for a simple inventory map.)

More information can be provided by producing an intermediate inventory. The map produced at this level would show the outlined landslide types and distinguish between areas of landslide origin and deposit. The former is the area where material once existed as the source of the landslide and appears as a scar. The latter is deposited material from the landslide. (See Figure 10-8 for a sample intermediate inventory map.) The most information is obtained by producing a detailed inventory (Wieczorek, 1984) Large-scale features such as secondary scarps, sag ponds, and ground-crack patterns may be represented on individual landslides. (See Figure 10-9 for a detailed landslide map.)

These three types of inventories can be prepared as the development study progresses. To reiterate what was presented in Section A of this chapter: the simple inventory is adequate for Phase I development diagnosis activities; the intermediate inventory provides greater detail for an improved hazard map of a target area in Phase II, and the large-scale features of the detailed inventory are necessary for final project design in the implementation stage. Refer to Figure 10-2 for the appropriate map scales.

There are several considerations to keep in mind when gathering data on existing landslides. First, the time and effort required to conduct an inventory varies with (1) geologic and topographic complexity; (2) size of an area; and (3) desired level of inventory detail (Varnes, 1985). Figure 10-10 characterizes the relationship between the amount of time and level of effort for these three variables. Second, more detailed inventories will require larger map scales to reveal the small features of this added detail. Third, additional data gathering can add detail to an existing inventory. This enables a previously completed simple inventory to be transformed into an intermediate inventory with less time and effort than producing the intermediate inventory solely from field work and aerial photography.

b. Mapping the Types of Bedrock Contributing to Instability

By using bedrock as one factor in the landslide hazard assessment, the many different ways rock type or structure contribute to instability are represented. Comparing a bedrock map with the landslide map, one can discriminate between rock units associated with existing landslides and those devoid or largely free of landslide activity.
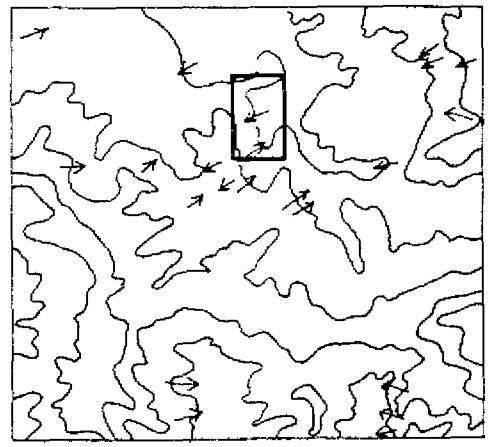
To produce a usable bedrock map for a hazard assessment, bedrock unit boundaries should be traced to produce new, more suitable units. Existing standard geologic maps define units according to factors such as age, composition or lithology (rock type), and structure (faulting, folding, etc.). For example, a standard geologic map may show a series of volcanic ash deposits of similar mineral compositions which vary only slightly in age. In most instances, these different units will affect landslide occurrence in a similar way and should be delineated as a single bedrock unit in a revised map for hazard assessment work. The geologist must use professional judgement to ensure that the number of bedrock units is sufficient to distinguish differences in their effect on landslide occurrence.

When a geologic map does not exist, a bedrock map based on aerial photography with limited field verification is needed This map may be no more detailed than a delineation of sedimentary, igneous, and metamorphic rock types. Obviously, a bedrock map generalized from a more detailed map is preferable, but this is an acceptable alternative under such circumstances Delineating areas with similar texture and appearance is easier than recognizing discrete features. Scales as small as 1:62,500 are useful for this work. Photos at scales of 1:20,000 or larger are difficult to use because the limited area shown restricts comparison with adjacent contrasting areas. It also significantly increases the number of photographs to examine in mapping the area. Black and white, color, and color infrared photography are all suitable for bedrock mapping. Satellite imagery is generally unsuitable for this mapping except when the imagery is enlarged to usable scales. For example, imagery at a 1:50,000 scale produced from satellite imagery is acceptable for this mapping (see Chapter 4).

A soils map is an inadequate substitute for a bedrock map. Soils maps are based on factors concentrated in the upper meter or less of superficial material that affects agricultural activities. Generally, there is little or no correlation between "agricultural" soil characteristics and the likelihood of failures originating along surfaces a few meters to tens of meters deep in superficial material.
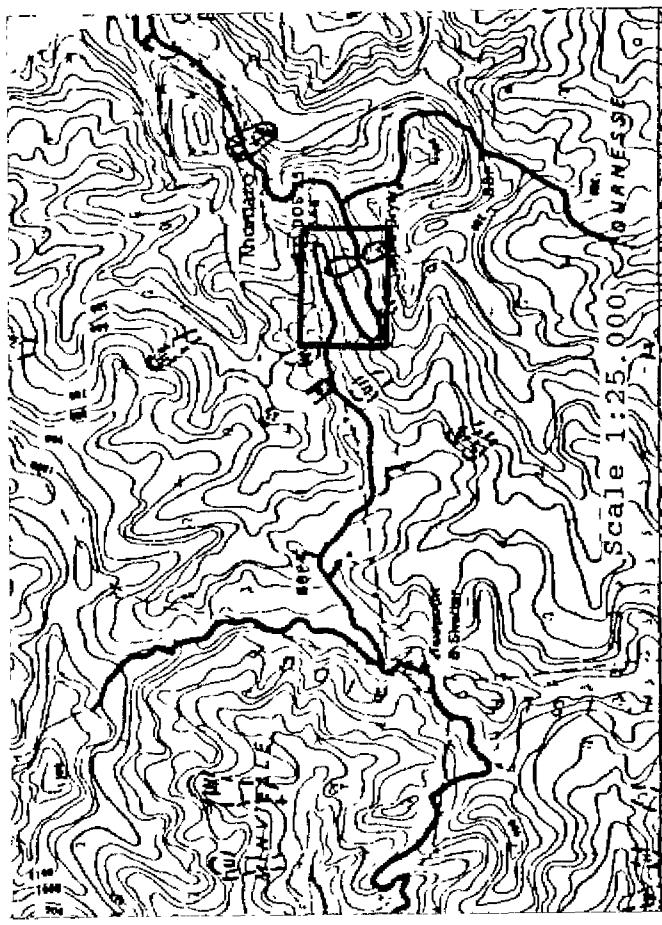
Figure 10-8

INTERMEDIATE LANDSLIDE INVENTORY MAP

Scale 1:25.000

SYMBOLS AND EXPLANATION OF INTERMEDIATE LANDSLIDE INVENTORY MAP

ROCKFALL or ROCKSLIDE	DEBRIS FLOW	DEBRIS SLIDE
scar	scar	scar
deposit	deposit	deposit

Shallow Failure

Deep-seated Failure
ROCKSLIDE or EARTH FLOW

scar

deposit

LANDSLIDE COMPLEX

May consist of many landslides too small to represent individually, an old eroded landslide feature, or a landslide displaying more than one type of movement.

NOTE

Landslides outlined with solid lines are identifiable as definite landslides
Dashed lines signify a possible landslide

Figure 10-7

SIMPLE LANDSLIDE INVENTORY MAP

Scale 1:50.000

EXPLANATION

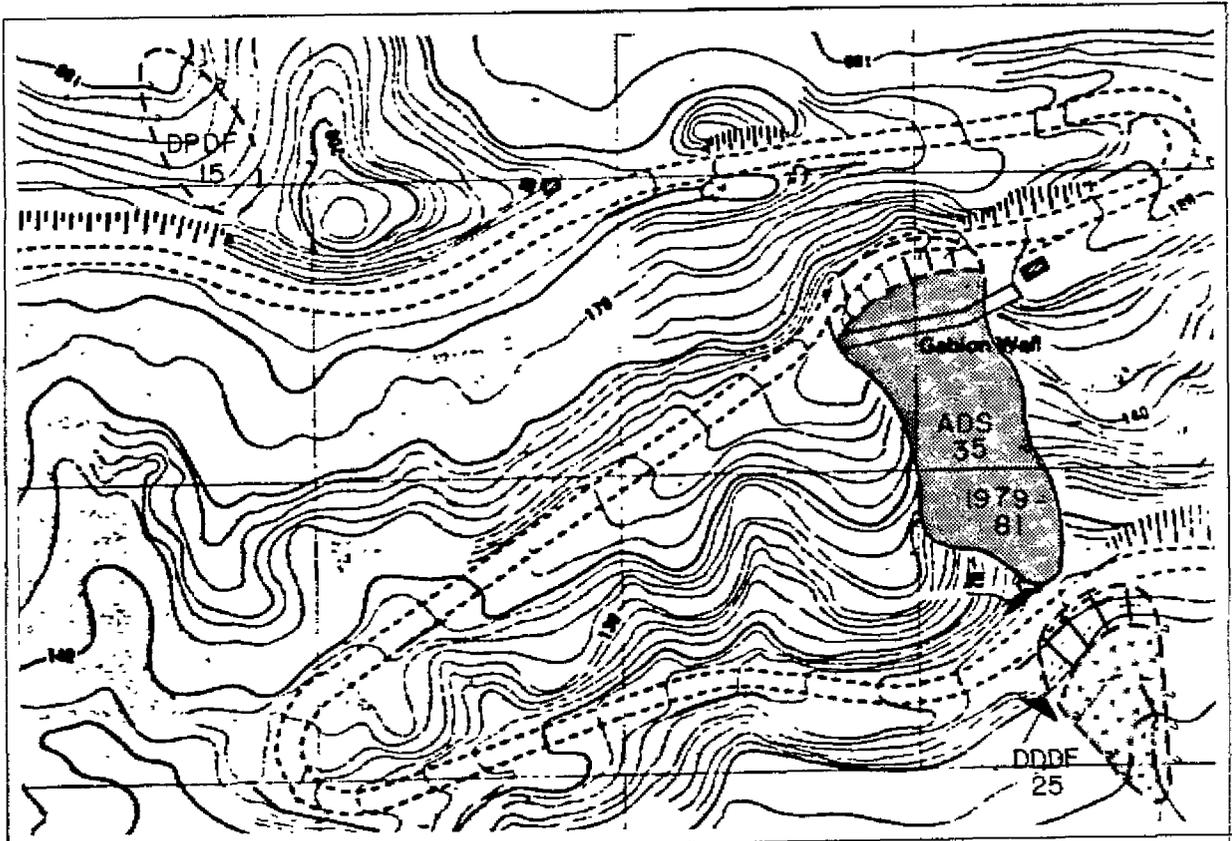↗ Landslide

Figure 10-9

DETAILED LANDSLIDE INVENTORY MAP

EXPLANATION OF LANDSLIDE SYMBOLS

Scarp area

Deposit area

Boundary of scarp and deposit area (dashed where approximate, question mark where uncertain)

First letter: state of activity
A - Active or recently activity (dark)
D - Dormant (light)

Second Letter: certainty of landslide identification
D - Definite (dotted)
P - Probable
Q - Questionable

Third and fourth letters: type of slope movement
SF - Complex slump earthflow
DS - Debris slide
DF - Debris flow
EF - Earthflow
S - Slump

Maximum depth of landslide (feet)

Year of movement

c. Mapping Slope Steepness or Inclination

Slope steepness is a factor which associates the effectiveness of gravity acting on a slope to landslide susceptibility. A topographic map is the source for preparing a slope steepness map. The slope steepness map displays the steepness values associated with the majority of existing landslides and is derived from an existing topographic map. Steepness for landslide hazard assessments is commonly expressed as a percentage rather than in degrees. The categories or grouping of steepness values for use in analyzing landslide hazards should approximate those of the slopes present in the study area. Too many classes will make it difficult to identify slopes critical to landslide occurrence and too few will be equally useless.

d. The Optional Hydrologic Factor--Mapping Indirect Measures

Since information on water table levels and fluctuations is rarely available, mapping indirect measures such as vegetation and slope orientation can reveal the influence of hydrology on an area. Any vegetation map used to represent the hydrologic factor in the landslide hazard assessment must employ units that are dependent on water. This may be as simple as representing phyreatic and non-phyreatic plant communities or as complex as distinguishing different forest types. Selection of the appropriate vegetation map units to indicate the effects of water in causing landslides requires careful field observation by the geologist.

Aerial photography is an appropriate source of data for preparing vegetation maps. In preparing vegetation maps, as in mapping bedrock, scale is less of a concern. Here, too, delineating areas with similar features is easier than recognizing discrete features. Scales of 1:62,500 are useful in identifying vegetation since 1:20,000 and larger scales do not reveal the contrasting characteristics of adjacent areas. Black and white, color, and color-infrared photography are all suitable for this mapping. Satellite imagery is acceptable only when enlarged to usable scale.

The direction in which a slope faces can also be mapped and used as an indirect indicator of the hydrologic factor. Slope orientation or aspect is described in terms of the eight cardinal directions, i.e., north, northeast, etc. For convenience in establishing a data base, slope orientation is measured in degrees of azimuth from 0 to 360 degrees. Each cardinal direction is defined by a set of azimuth values. For example, slopes facing the northeast can have an azimuth reading ranging from 22.5 degrees to 67 5 degrees.

2. INTERPRETING LANDSLIDE HAZARDS: THE LANDSLIDE HAZARD MAP

A landslide hazard map is generated to identify areas with differing landslide hazards. A hazard map is produced for each stage of the planning process, from the more generalized map in the initial stage to a detailed zonation map for specific site use. As the name suggests, this map divides the entire study area into sub-areas based on the degree of a potential hazard from landslides. The landslide hazard map is produced by interpreting the data represented by the maps of the inventoried landslides and the permanent factors found to influence the occurrence of landslides.

As with any map, scale is an important consideration. There are two points to keep in mind concerning the scale of the landslide hazard map. First, such a map should be produced at a scale capable of representing the information needed at a particular planning level. Compatibility of scale would be important when the hazard map is to be combined with other maps to yield a land capability map (see Chapter 3). Second, the landslide hazard map should be at a scale not markedly different from the data maps used to produce it. In other words, reliability may be questionable when a landslide hazard map produced at a scale of 1:50,000 has been based on a 1:250,000 slope steepness map.

Four levels of relative hazard are identified on a landslide hazard map: (1) low; (2) moderate; (3) high; and (4) extreme hazard. The level of landslide hazard is measured on the ordinal scale with this method and is a quantitative representation of differing hazard levels that shows only the order of relative hazard at a particular site and not absolute hazard. Predicting absolute hazard is impractical with current capabilities.

As a consequence, there is no way to compare hazard zones at different sites or to determine the likelihood that a high hazard area, for example, is two or ten times more likely to fail in the future than low hazard areas. It should be stressed that these relative hazard zones are based on the existing landslides and conditions influencing their occurrence in a specific area. The hazard zones which are determined for an area hold true only for the area for which they were prepared. Similar conditions found outside the assessed area may not produce the same degree of hazard because of some seemingly minor difference in one of the factors

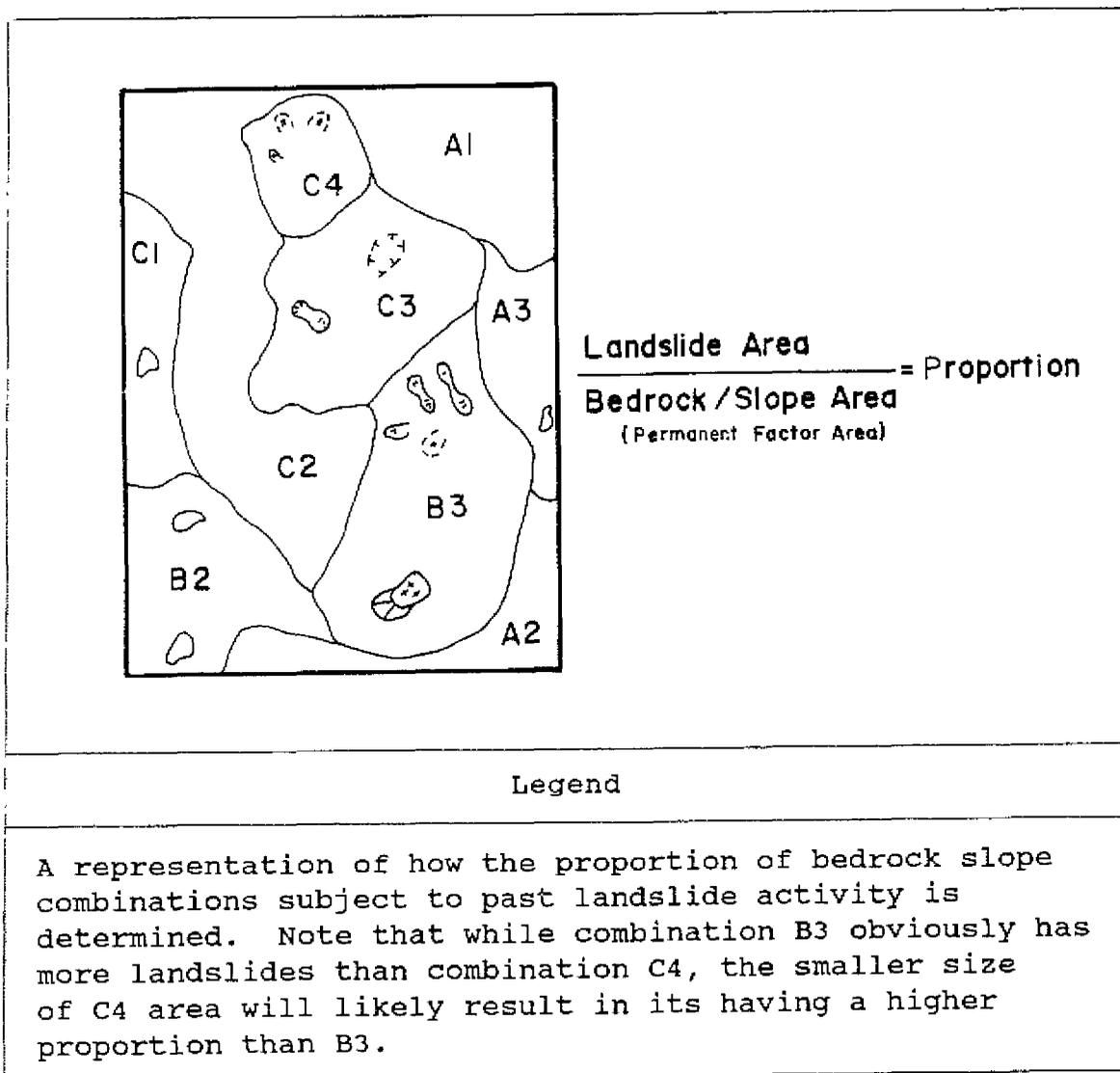## 3. FACTOR ANALYSIS: THE TECHNIQUE TO PREPARE A HAZARD MAP

A factor analysis is a step-by-step approach used to prepare a landslide hazard zonation map of an area.

There are four steps to complete the factor analysis and produce a hazard map: (1) map the existing landslides and prepare a map combining the permanent factors (bedrock, slope steepness, and, when available, the hydrologic factors) into individual map units; (2) overlay the landslide inventory on the combined factor map; (3) prepare a combined factor analysis for all combinations of the factors and group combinations of these factors in a way that defines the four levels of landslide hazard; and (4) produce a map with four landslide hazard zones from the grouped combinations.

a. Step One: Combined Map of Permanent Factors

The first step is to prepare a map of the inventoried existing landslides. Also, compile a map which combines the bedrock, slope steepness, and, when included, hydrologic factor units or categories into individual cartographic units. As an example, assume that only bedrock and slope steepness are being used. The compiled map will be composed of cartographic units delineating certain bedrock type and slope values, e.g., Bedrock B3 on slopes between 25-50 percent (see Figure 10-10).

Figure 10-10

STUDY AREA MAP

$$\frac{\text{Landslide Area}}{\text{Bedrock/Slope Area}} = \text{Proportion}$$
(Permanent Factor Area)

Legend

A representation of how the proportion of bedrock slope combinations subject to past landslide activity is determined. Note that while combination B3 obviously has more landslides than combination C4, the smaller size of C4 area will likely result in its having a higher proportion than B3.

b. Step Two: Overlay of Landslide Inventory

The second step is to overlay the landslide inventory map with this combined factor map This will identify which combinations are associated with past landslides and which are not. A landslide inventory table is developed indicating total area of landslides occurring on each specific bedrock unit and slope steepness combination (and other factors, if considered) (see Figure 10-12) When a hydrologic factor such as vegetative zone or slope orientation is used, the table will include the area of landslides for each specific combinations of bedrock. slope steepness, and the hydrologic factor Summing the areas from all combinations found in the table will yield the total area of landslides in the study area. This is a way to check that all combinations are included in the analysis. Figure 10-11 shows the extent to which each combination is present in the study area. For example, Bedrock B on slopes between 25 and 50 percent has 784 hectares of landslides.

c. Step Three: Group Combinations Using a Factor Analysis

The third step is to group combinations of these factors in a way that will define four levels of landslide hazard. This grouping is achieved by performing a combined factor analysis or matrix assessment (DeGraff and Romesburg, 1980). This analysis permits incorporating the interaction among factors affecting landslide occurrence without explicitly understanding those interactions.

To start, measure the total area for every combination of bedrock, slope steepness, and hydrologic factors in the study area represented in the table prepared in Step 2. The total area with these combinations is to be calculated, not just those associated with landslide activity. Continuing with the example, assume a total area of 2,327 hectares of bedrock B on slopes greater than 25 percent but less than 50 percent was found. The landslide inventory table prepared in Step 2 shows only the area of past landslides present for each combination. Then the total area for every combination associated with landslides found in the landslide inventory table is divided by the area for the same combination of factors found in the study area (see Figure 10-12). In the example, this would be 784 divided by 2,327. This yields a proportion of each combination which is subject to past landslide occurrence, e.g., 0.34. This represents the proportion of the combination disturbed by past landslides in that area (see Figure 10-11).

The combination of bedrock, slope steepness, and hydrologic factors associated with the largest area disturbed by landslides may not, in fact, be the most
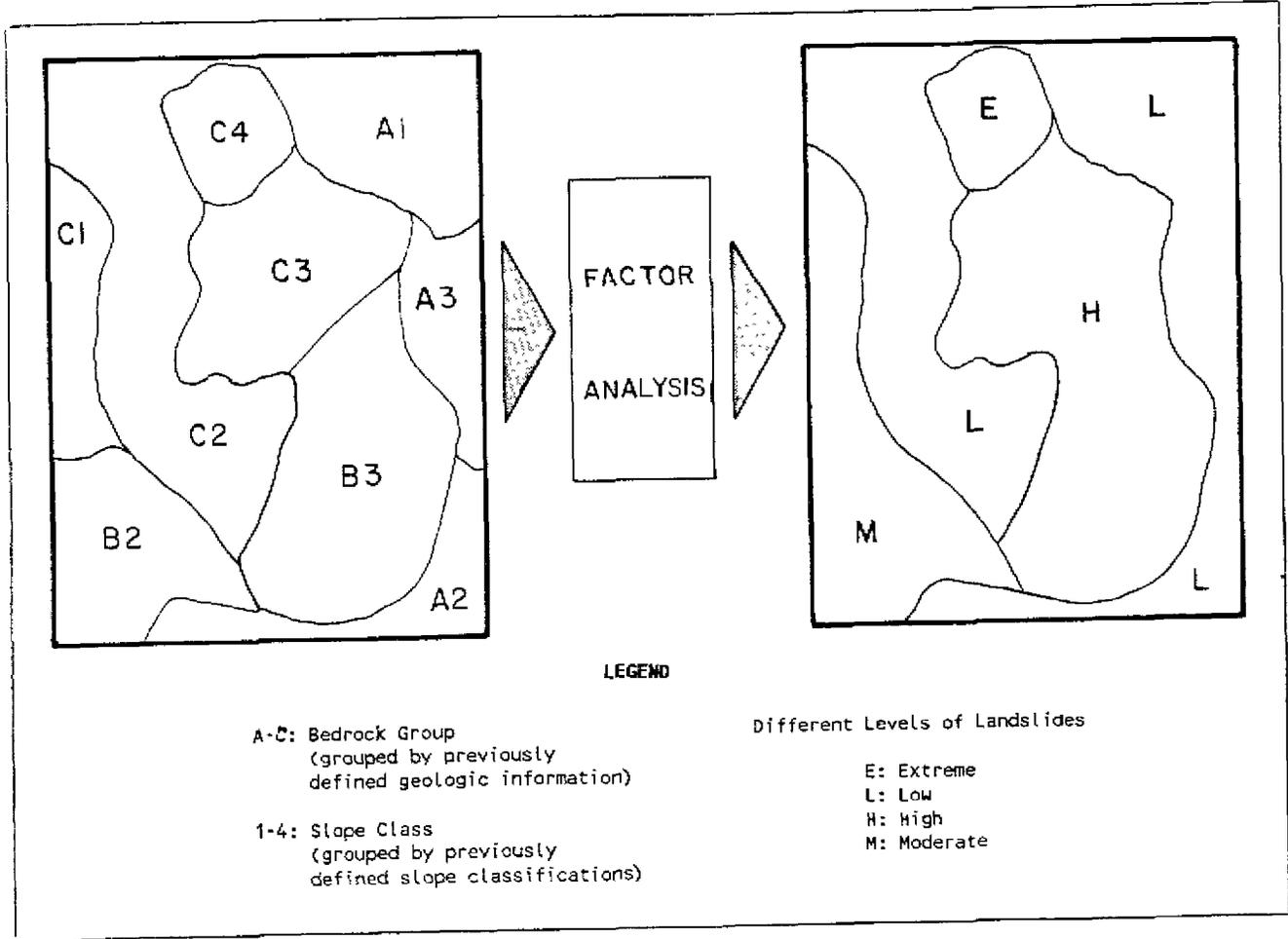
Figure 10-11

COMBINED PERMANENT FACTOR (SAMPLE BEDROCK AND SLOPE CLASS) AND LAND AREA COVERAGE (IN HECTARES)

BEDROCK GROUP	--------- SLOPE CLASS ---------				TOTAL AREA (HA)
	0<12% (1)	12<25% (2)	25<50% (3)	>50% (4)	
A	-- 1,570	52 722	78 512	-- 237	130 Landslide Area 3,041 Combined Area[a]
B	-- --	301 1,776	784 2,327	-- --	1,085 Landslide Area 4,103 Combined Area[a]
C	78 673	-- 2,450	351 1,790	180 793	609 Landslide Area 5,706 Combined Area[a]

[a] Combined Area = Combined Permanent Factor Area

Figure 10-12

LANDSLIDE HAZARD ZONES

LEGEND

A-C: Bedrock Group
(grouped by previously
defined geologic information)

1-4: Slope Class
(grouped by previously
defined slope classifications)

Different Levels of Landslides

E: Extreme
L: Low
H: High
M: Moderate

hazardous it may simply be the combination which is most common to the study area. Since such an area is the most prevalent combination, it has the greatest chance for being associated with past landslides rather than being most hazardous. The process described above ensures that comparison of landslide hazard among different combinations takes place on an equal basis.

There will be a proportional value for each combination of bedrock, slope steepness, and other factors associated with existing landslides ranging from 01 to 1.0. The proportions are sorted from the smallest to the largest. This range of values is broken into three groups to represent the relative landslide hazard in the study area. To ensure that the points used to define the three groups are determined objectively, a non-hierarchical cluster analysis is used (See the Appendix of this chapter for a sample computation.)

An initial division into three groups is achieved by breaking equally the range of proportional values present. The upper and lower boundaries of each group are retained or adjusted to ensure that the final division represents the minimum sum of the squared deviations around the three group means. This is based on the W function (Anderberg, 1973).

d. Step Four: Producing Landslide Hazard Zones

The fourth, and final, step uses the grouped combinations to produce landslide hazard zones--extreme, high, moderate, and low. Once the proportions are divided into three groups. bedrock, slope steepness, and hydrologic factor combinations representing different degrees of relative landslide hazard are identified. The group of proportions with the larger values, i.e., toward the 1.0 end of the range, represent combinations defining extreme landslide hazard The group of proportions with the next

$$W = \sum_{i=1}^{i=3} \sum_{j=1}^{j=n_i} (X_{ij} - X_i)^2 = W_1 + W_2 + W_3$$

smaller values represents combinations defining high landslide hazard. The group of proportions with the smallest values, i.e., toward the 0.1 end of the range, represents combinations defining moderate landslide hazard. All bedrock, slope, and hydrologic factors not found to be associated at all with existing landslides define low landslide hazard.

The map overlays used to determine areas of bedrock, slope steepness, and hydrologic factor present in the entire study area can now be revised to make the hazard zonation map. Figure 10-12 shows the original maps redrawn into hazard zones. Combinations with extreme hazard are redrawn and relabeled as extreme hazard zones Redrawing and relabeling for combinations representing other hazard zones produces a completed hazard zonation map displaying four levels of relative hazard. The empirical relationship of the physical factors, as defined by the factor analysis, is valid for only the area evaluated, and cannot be extrapolated to cover additional areas.

Once these hazard areas are identified, a decision can be made regarding the appropriate development activities, type of mitigation measures to be included in the process, or the areas which should be avoided. It is important to note that the essential bedrock and slope steepness maps are not always available. Without these maps, an isopleth map can be produced which is an acceptable substitute

4. COMPENSATING FOR INSUFFICIENT DATA: THE ISOPLETH MAP

In the absence of bedrock and slope steepness maps, the landslide inventory map can be used to produce an analytical map suitable for representing landslide activity in an area. An isopleth map of landslide frequency is recommended for this purpose. An isopleth or any other analytic map can only serve as an initial assessment of landslide activity and not as a substitute for a landslide hazard map. The underlying conditions producing landslides will remain unknown and prevent making the distinction between the relative degrees of landslide hazard.
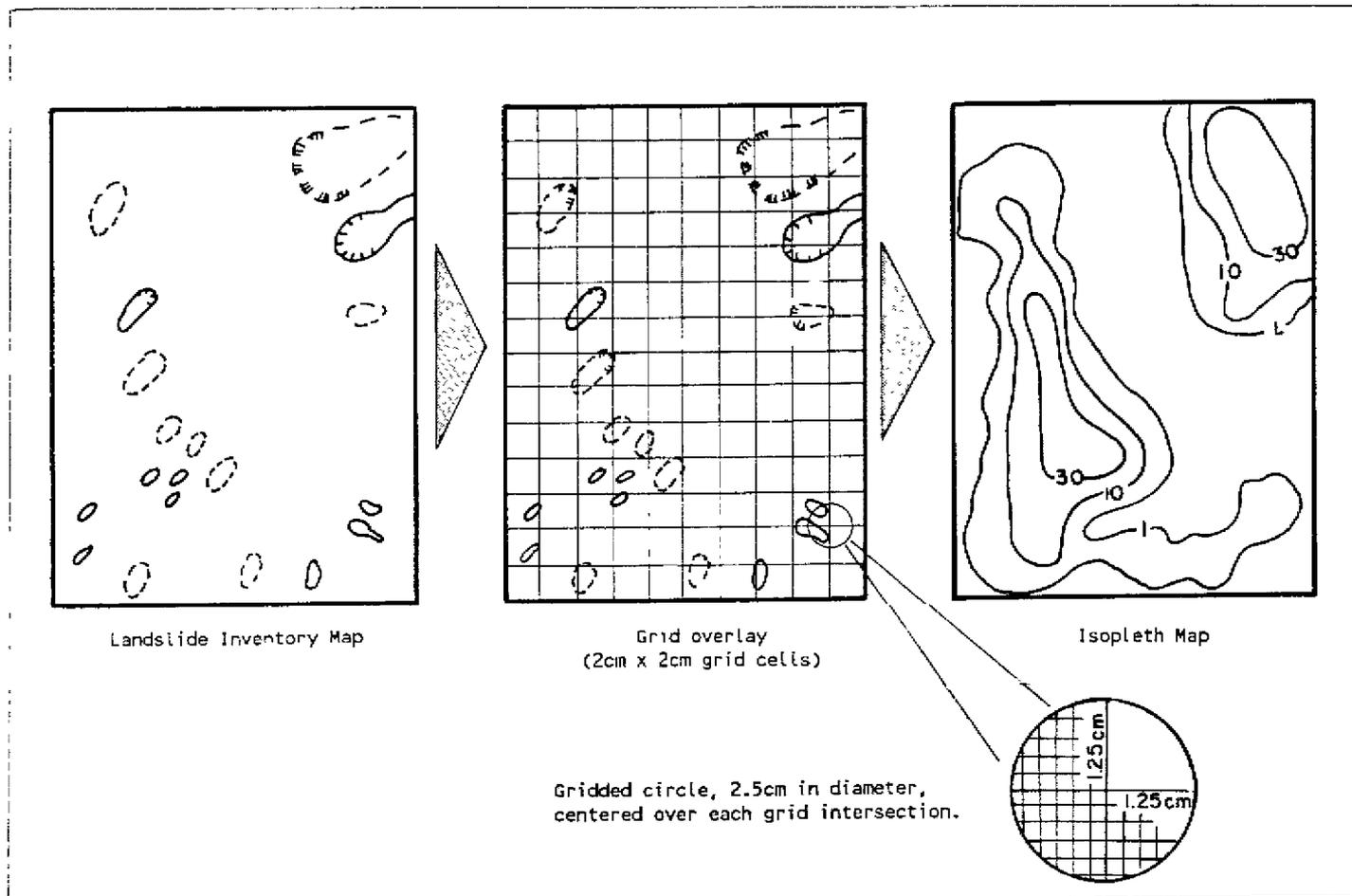
It is reasonable to assume that areas with a high frequency of landslide activity represent areas with a greater chance of future landslides than those areas with a low frequency. An isopleth map can be made based on this assumption. Preparing an isopleth map begins with the map of inventoried landslides (Wright et al., 1974). A transparent overlay with a 2cm x 2cm grid is placed over the landslide inventory map. (See Figure 10-13 for a graphic depiction of each step.) At each grid intersection a transparent gridded circle 2.5cm in diameter is centered on each grid intersection on the transparent overlay. The number of grid squares in the circle through which landslide deposits are visible is counted. Divide this number by the total number of grid squares within the inscribed circle. This yields the proportion of the unit area within the circle that is underlain by landslide deposits. This proportion is multiplied by 100 and rounded off to the nearest whole number to compute the percentage of landslide-disturbed terrain. The percent value is written on the gridded overlay next to the grid intersection.

Once all grid intersections are marked with percent values, the isopleth lines can be drawn. Isopleth lines connect the points of equal value. These show the generalized frequency of landslide activity as represented by the percent of landslide-disturbed area. The interval between isopleths drawn to produce the map will depend on the proposed use A single value representing a boundary between areas of frequent landsliding and infrequent landsliding shows areas where this phenomenon is a major factor in shaping the landscape and areas where it is not. This serves as an initial assessment of areas subject to landslide problems when additional factors are not available for a study area. It is important to remember that this is an analytic technique producing a limited assessment of an area rather than a technique developed by an interpretative process.

During Phase II of the planning process, in addition to the intermediate landslide inventory, the preparation of an isopleth map which would enhance the information available to planners is recommended. Using the technique described above, preparation is

Figure 10-13

STEPS TO PREPARATION OF AN ISOPLETH MAP

Landslide Inventory Map

Grid overlay
(2cm x 2cm grid cells)

Isopleth Map

Gridded circle, 2.5cm in diameter,
centered over each grid intersection.

1.25 cm

1.25 cm

altered in two ways: (1) only the specific landslide types identified in the intermediate inventory which are likely to be initiated by the land use proposed would be used in compiling this isopleth map; the choice of landslide types should be governed by the information on landslide activity developed by the geologist completing the intermediate inventory of existing landslides and by existing and proposed land use; and (2) isopleths are drawn at regular intervals similar to the way elevation is represented by a contour interval instead of the single value used in the isopleth map For example, an interval of 10 percent has been used with some isopleth maps applied to land-use planning (Campbell, 1980, and Pomeroy, 1978). This produces a map representing the intensity of past landslide occurrence in a form resembling a topographic map. The isopleth lines would appear like the contour line showing elevation. The final isopleth map is used as an overlay on the landslide hazard map.

5. COMPUTER-GENERATED MAPPING

The method described in this chapter can be readily adapted to computer-generated mapping (Brabb, 1984). The factor maps used to generate the landslide hazard map can be encoded to a geographic information system (GIS) and manipulated by a computer. (See Chapter 5 for a discussion of computer mapping applications and GIS.) This enables the rapid preparation of tables showing the area for different factor combinations In some cases, data maps used in landslide hazard assessment may be part of the GIS created for generated land-use planning, for instance a vegetation map. A second advantage of this approach is that the scales for maps to be overlaid in a landslide hazard assessment can be matched regardless of their original scale. For example, the scale of a published bedrock map may differ from the other factor maps. Using manual

techniques, redrafting the bedrock map at the same scale would be necessary, whereas a computer-based system permits the matching of map scales regardless of their original scale and the maps can be overlaid.

Computerized matching of map scales requires that certain reference points on each map be identified to ensure proper registration of points between maps. Once maps are computerized, they are capable of being updated or used to improve landslide hazard assessments. A more detailed landslide inventory map could be encoded and used to produce an improved hazard zonation map with the already encoded data maps.

The single major limitation of using a computer-based system is the amount of time and expense that is required to encode the maps and establish the data base for a landslide hazard assessment at a scale sufficiently large to permit the calculation of the percentage of the area covered by existing landslides. Creating such a data base usually dictates that a major project or series of projects be planned to justify this commitment of resources, or that a data base of computerized maps already exists. One final consideration is the ability to gain access to computer equipment, since computers may be scarce or in great demand for many uses. Nevertheless, readily available and relatively inexpensive micro-computers and software programs which are adequate for a landslide hazard assessment make it possible for some planning studies to have their own system.

Conclusion

Areas susceptible to landslides can be projected, based on the physical factors associated with landslide activity: past landslide history, bedrock, slope steepness, and hydrology Predicting where and when landslides are going to occur is not possible even with the best available information. It is, however, possible to identify landslide-susceptible areas. This chapter has discussed some of the concepts related to landslide susceptibility. the different types of landslides; the relative nature of landslide hazard zonation; its relationship to development activity; and ways to mitigate the effects of landslides The essential point has been to demonstrate the importance of considering landslides early in the planning study and to provide one technique which can be used at all stages of the planning process. The different questions that need to be asked at the different planning stages were highlighted. Many answers can be generated from the use of landslide hazard zonation at each stage of the planning study The step-by-step combined factor analysis to prepare hazard maps was presented All of this will enable the

planner to have a working knowledge of terms, concepts, and the important considerations related to landslides and landslide hazard mapping.

References

Anderberg, M.R. Cluster Analysis for Applications (New York: Academic Press, 1973).

Brabb, E.E. "Innovative Approaches to Landslide Hazard and Risk Mapping" in IV International Symposium on Landslides, vol. 1 (Toronto, 1984), pp. 307-323.

Campbell, R.H. Landslide Maps Showing Field Classifications, Point Dume Quadrangle, California, U.S. Geological Survey Field Studies Map MF-1167 (Reston, Virginia: U.S Geological Survey, 1980).

Carrara, A., and Merenda, L. "Landslide Inventory in Northern Calabria, Southern Italy" in Geological Society of America Bulletin, vol. 87 (1976), pp. 1153-1162.

Cotecchia, V. "Systematic Reconnaissance Mapping and Registration of Slope Movements" in Bulletin of the International Association of Engineering Geology, no. 17 (1978), pp. 5-37.

DeGraff, J.V. "Regional Landslide Evaluation: Two Utah Examples" in Environmental Geology, vol. 2 (1978), pp. 203-214.

-- "Initiation of Shallow Mass Movement by Vegetative-type Conversion" in Geology, vol. 7 (1979), pp. 426-429.

-- "Quantitative Approach to Assessing Landslide Hazard to Transportation Corridors on a National Forest" in Transportation Research Record 892 (1982), pp. 64-68.

DeGraff, J.V., and Romesburg, H C.   "Regional Landslide-Susceptibility Assessment for Wildland Management: A Matrix Approach" in D.R. Coates, and J. Vitek (eds.), Thresholds in Geomorphology (Boston. George Allen & Unwin, 1980), pp. 401-414.

Hutchinson, J.N., and Kogan, E. "The Mayunmarca Landslide of 25 April 1974" in UNESCO Serial No. 3124/RMO.RD/SCE (Paris: UNESCO, February, 1975).

Hopkins, L.D. "Methods for Generating Land Suitability Maps: A Comparative Evaluation" in American Institute of Planning Journal, vol. 43 (1977), pp. 386-400.

Kockelman, W.J. "Some Techniques for Reducing Landslide Hazards" in Bulletin of the Association of Engineering Geologists (vol. 22, 1985).

Morgenstern, N.R., and Sangrey, D.A. "Methods of Stability Analysis" in R.L. Schuster, and R.J. Krizek (eds.), Landslides, Analysis, and Control, Special Report 176 (Washington, D C.: Transportation Research Board, 1978), pp. 155-171

Organization of American States. Integrated Regional Development Planning: Guidelines and Case Studies From OAS Experience (Washington, D C. Organization of American States, 1984).

Pomeroy, J.S. Isopleth Map of Landslide Deposits, Washington County, Pennsylvania, U.S. Geological Survey Field Studies Map MF-1010 (Reston, Virginia. U.S. Geological Survey, 1978)

-- Map Showing Landslides and Areas Most Susceptible to Sliding in Beaver County, Pennsylvania, U.S. Geological Survey Miscellaneous Investigations Series Map I-1160 (Reston, Virginia· U.S Geological Survey, 1979).

Rib, H.T., and Liang, T. "Recognition and Identification" in R L. Schuster and R.J. Krizek (eds.), Landslides, Analysis, and Control, Special Report 176 (Washington, D.C.: Transportation Research Board, 1978), pp. 34-80

Sharpe, C.F.S. Landslides and Related Phenomena (New York: Columbia University Press, 1938).

Sidle, R.C., Pearce, A.J., and O'Loughlin, C.L. Hillslope Stability and Land Use, Water Resources Monograph Series No. 11 (Washington, D.C.: American Geophysical Union, 1985).

Swanson, F.J., and Dyrness, C.T. "Impact of Clearcutting and Road Construction on Soil Erosion by Landslides in the Western Cascade Range, Oregon" in Geology, vol. 3 (1975), pp 393-396.

U.S. Geological Survey Goals and Tasks of the Landslide Part of a Ground-Failure Hazards Reduction Program, U.S. Geological Survey Circular 880 (Reston, Virginia: U S. Geological Survey, 1982).

Varnes, D.J. "Slope Movement Types and Processes" in R.L. Schuster and R.J Krizek (eds.), Landslides, Analysis, and Control, Special Report 176 (Washington, D.C.: Transportation Research Board, 1978), pp. 12-33.

-- Landslide Hazard Zonation: A Review of Principles and Practices, UNESCO Natural Hazards Series No. 3 (Paris. UNESCO, 1985).

Wieczorek, G.F. "Preparing a Detailed Landslide-Inventory Map for Hazard Evaluation and Reduction" in Bulletin of the Association of Engineering Geologists, vol. 21 (1984).

Wright, R.H., Campbell, R.H., and Nilson, T.H. "Preparation and Use of Isopleth Maps of Landslide Deposits" in Geology, vol. 2 (1974), pp. 483-385.

Appendix

SAMPLE COMPUTATION OF W FUNCTION

As noted in Section C-3, Factor Analysis, the W function is computed from the formula:

$$W = \sum_{i=1}^{i=3} \sum_{j=1}^{j=n_i} (X_{ij} - X_i)^2 = W_1 + W_2 + W_3$$

where: X_{ij} = j^{th} observation i^{th} group
n_i = number of observations in the ith group

For the example, it is assumed the combined factor analysis yielded the following sixteen proportions:

.53, .01, .19, .03, .39, .04, .05, .88, .11, .01, .21, .03, .61, .01, .04, .11

Step 1: The proportions are then arranged in ascending order:

.01, .01, 01, 03, .03, 04, .04, 05, .11, 11, 19, .21, 39, 53, 61, .88

The data range from .01 to .88. This range is divided equally to form three groups based on an equal interval partition: $.01 \le X < .29$, $.29 \le X < .58$, and $.58 \le X < .88$.

Step 2: The W factor is computed using the values in each group formed under the initial equal interval partition:

[.01 ≤ X < .29]	[.29 ≤ X < .58]	[.58 ≤ X < .88]
.01, .01, 01, .03, .03, .04, .04, .05, .11, .11, 19, .21	.39, .53	.61, .88
X1 = .07	X2 = .46	X3 = .745
W1 = .0534	W2 = .0098	W3 = 0365

W = W1 + W2 + W3 = 0534 + .0098 + .0365 = .0996

The objective is to minimize the value of W. In other words, find the smallest W values that can be computed for three groups of the proportional values. This applies the principle of least squares, a common statistical approach, to this one-dimensional problem through minimizing the sum of squared deviations about the group means.

Step 3: The boundary is shifted to the right to seek the desired decrease in W function:

[.01≤X<.39]	[.39≤X<.58]	[.58≤X<.88]
.01, .01, .01, .03, .03, .04, 04, .05. .11. .11, .19, .21, 39	.53	.61, .88
X1 = .0946	X2 = .53	X3 = .745
W1 = .1479	W2 = 0	W3 = .0365

$$W = W1 + W2 + W3 = .1479 + 0 + .0365 = .18435$$

Because the recomputed value is more than the W value initially computed, this is the wrong direction move. The boundary will be shifted to the left of the initial boundary seeking a decrease in the W value.

Step 4: The left-most boundary is moved to the left by one value. The W function is recomputed and compared to the initial W value to determine whether the desired decrease occurred:

[.01≤X<.19]	[.19≤X<.58]	[.58≤X<.88]
.01, .01, .01, 03, .03, .04, .04, .05, .11, .11, .19	21, .39, .53	.61, .88
X1 = .0573	X2 = .3767	X3 = .745
W1 = .0320	W2 = .0515	W3 = .0365

$$W = W1 + W2 + W3 = 0320 + .0515 + 0365 = .12$$

This is not a decrease. Therefore, the partition for the left-most boundary is kept at the initial value

Step 5: Now the second or right-most boundary is moved to the right:

[.01≤X<.29]	[.29≤X<.61]	[.61≤X<.88]
.01, .01, 01, .03. 03. .04, .04, .05, .11, .11, .19, 21	.39, 53, .61	.88
X1 = 07	X2 = 51	X3 = .88
W1 = 0534	W2 = .0248	W3 = 0

$$W = W1 + W2 + W3 = .0534 + 0248 + 0 = 0782$$

This is a decrease in the W value. If any other values remained in the third group, the boundary would be shifted in single moves to the right until no further decrease in W values was obtained With no other values present, this minimizes the sum of squared deviations about the group means to the greatest extent possible and

retains three groups. If the shift to the right had resulted in an increased W value, a move to the left on the right-most boundary would have been tried. Having determined the boundaries for obtaining the smallest W value, the best grouping of the proportional values present is achieved.

As a result of this iterative process, the initial partition into groups with the following ranges:

$$.10 < X < .29$$
$$.29 \leq X < .58$$
$$.58 \leq X < .88$$

is changed to a grouping more consistent with the proportional values involved based on the range of values below:

$$.01 < X < .29$$
$$.29 \leq X < .61$$
$$.61 \leq X < .88$$