A SYSTEMS CLASSIFICATION
OF WATERSHEDS AND STREAMS

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AN ABSTRACT OF THE THESIS OF

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Adequate management and scientific investigation of ecosystems depends on classification of landscape systems based on all significant bio-physical and associated cultural properties. The present classification is a hierarchical systems design that can be modeled in terms of a natural system interacting with its level-specific environment. A watershed system in this context is embedded in a landscape environment organized into, for example, zonal and regional systems. A system at any level is classified by its capacity and the capacity of its environment, capacity defining temporally the scope of possible system performances relative to the components, substrate, climate, biota, culture, and water.

This theoretical framework for examining systems was translated into methods suitable for integrating the full capacities of watersheds and for displaying the discrete and continuous nature of watershed and stream system similarities. Classification of land to a sub-zonal level with a full capacity description coupled with analysis of watershed substrate variables provided an adequate representation of watershed capacity. This was demonstrated by empirical correlations of system components described in the literature, and by the ability to predict soil properties from topographic characteristics of land facets that are formed on a grid system overlaid on the watershed. Watershed classes were shown to be a good surrogate for differentiation of stream classes.

Watersheds were analyzed by facet on a grid system according to several substrate variables. Slope, aspect, altitude, radiation intensity on the winter solstice and equinox, and soil series occurrence by facet effectively sorted watershed and stream classes. These same classes were also revealed by a more extensive set of variables describing the statistical distribution of these primary variables and some variables describing topographic roughness, form, and drainage development. Spatial organization of the basin is a significant factor determining solar radiation distribution on slope facets and in segments of the drainage network. A gravity model of spatial organization of soils is potentially a useful model for stream reach performances, considering the reach environment as the upstream segment, network, and watershed system.

A Systems Classification of Watersheds and Streams

by

Dale A. McCullough

A THESIS

submitted to

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APPROVED:

Professor of Fisheries

Chairman of Department of Fisheries and Wildlife

Dean of Graduate School

Date thesis is presented ___June 2, 1987___

Typed by ___Dale A. McCullough___

The Columbia River Inter-Tribal Fish Commission (CRITFC) is the coordinating fisheries agency for the Nez Perce, Umatilla, Warm Springs, and Yakama tribes–four Columbia River tribes that reserved fishing rights in 1855 treaties with the United States government.

Since time immemorial, Indian people have lived and fished in the Columbia River's vast basin, and salmon and steelhead have always been central to the culture and lifestyles of these native Americans. Anadromous fish, in addition to being the mainstay of the diet, have great religious significance. Salmon and steelhead, which in prehistoric times were dried for trading to other tribes, have also been of great economic importance.

Court decisions in the 1960s and 1970s reaffirmed not only the tribes' right to fish, but also their right to co-manage this once plentiful renewable resource. To fulfill their responsibilities as co-managers, the Nez Perce, Umatilla, Warm Springs, and Yakama tribes formed CRITFC in 1977 to be these tribes' coordinating technical arm on fisheries issues. CRITFC, through its staff of biologists, policy analysts, law enforcement officers, and other specialists, works closely with state and federal agencies, citizen groups, and other tribes to help restore the Columbia Basin's salmon and steelhead.

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A SYSTEMS CLASSIFICATION OF WATERSHEDS AND STREAMS

I. INTRODUCTION

Despite the acknowledgment that streams and their valleys are a unit and should be treated as integrated systems, few aquatic studies frame stream biological/physical properties on a template of land type. Hynes' (1975) evaluation of classification systems as fruitless because of the multiplicity of types possible given all the variables involved (e.g. current speed, temperature, water chemistry, etc.) is unnecessarily pessimistic and ignores the utility of integrating streams and their watersheds. Because there have been few biological studies done on streams smaller than fourth order relative to the numbers of such streams in the United States, a classification of watershed/stream types would be useful. Such a classification would serve many needs. It would be (1) a framework for associating geographic units that have common properties, (2) a basis for extrapolating existing knowledge from one unit to others of similar character, (3) a means for identification of units of similar potential even when the present states of the units are not identical, (4) a framework for understanding system behavior in terms of interacting biological/physical parts, and (5) a means to generate hypotheses regarding behavior of similar units, which could serve to refine the classification.

There are abundant data in the literature to indicate a close relationship between watershed physical characteristics and hydrological properties of streams. In addition, studies show a correlation between hydrological properties and channel physical characteristics. Consequently, the correlation between watershed and stream physical properties is established (Kabir and Orsborn 1980). Such correlations integrate the fields of watershed hydrology and topography, network topology, and channel hydraulics.

Prediction of hydrological properties of streams draining watersheds with similar geomorphic properties has been successful within a region, but the extrapolation of relationships obtained from streams in one region to streams in other regions has not been successful (Vorst and Bell 1977, Pilgrim 1983). Improvement in predictive ability is possible by extension of variables used in regionalization to include biota, climate, substrate, culture, and water relations for land systems incorporating the stream. This should be done by constructing fully classified hierarchical levels of interest from regional levels to the watershed, the stream network, and down to stream reach or habitat. This hierarchical system creates the needed spatial framework for understanding system processes. Systems should not be compared out of context, for they derive their character from their relation to their environments.

A. OBJECTIVES OF PRESENT STUDY

The first objective of this study was to extend a theoretical framework of Warren (1979) for classification of land systems at any scale. This classification integrates environments down to the level of streams and provides a conceptual basis for scientific studies and management of natural systems. The second objective of this study was to provide a set of methods and variables for classification articulating with the theory.

These methods are illustrated by classification of 11 watersheds.

B. HISTORICAL REVIEW

Regional classifications have taken many forms. Some biophysical land classifications may be considered large in scope because they incorporate vegetation, soil, topography, and lithology in regionalization (Sukachev 1945, 1960, Hills 1961, Krajina 1965). Recent classifications of this type are the system of Bailey (1976) and the Land Resource Inventory (Wertz and Arnold 1972, Wendt, Thompson and Larson 1975). Most existing classifications deal with land regions, watersheds, or streams, not with all levels. For example, Bailey's system (1976, 1980) for land classification deals with land systems not necessarily delineated by watershed boundaries. Units are hierarchically defined by emphasizing at each level a different major variable, i.e. landform, potential natural vegetation, climate, or soil type. This system fails to link stream types with land systems at any level, and it does not deal with watersheds of relatively small area (i.e. <25 mi^2). It was elaborated only to the Section level, a level considered suitable for national or regional planning in Bailey's own system and the Land System Inventory.

Major system components (e.g. climate, topography, lithology) have been classified at various spatio-temporal scales of resolution. The classifications have been used as a tool for regionalizing the expression of related parameters. For example, climatic classifications have used data intensive multivariate methods (Newnham 1968, Ayoade 1977, Wilmott 1977), low dimensionality systems expressing long-term averages of temperature and moisture (Koppen 1931, see Trewartha 1943, Thornthwaite 1948, Holdridge 1959, Curran 1979), and large scale genetic classifications describing temporal patterns of air mass systems (Oliver 1970). Regional regimes of solar radiation input on a 12-month basis have been mapped globally (Terjung 1970, Krieder and Kreith 1981).

Topography at a small map scale has usually been treated qualitatively as physiographic zones (Highsmith and Kimerling 1979); on a large scale, topography has been described mathematically (Hobson 1967, Evans 1972). Landforms have been regionalized (Astle, Webster, and Lawrance 1969, Lewis 1969, Webster and Beckett 1970, also see Mitchell 1973, Chap.8) and statistical classifications of morphometric data have been used to identify watersheds of similar type (Mather and Doornkamp 1970, Abrahams 1972, Eyles 1973, Rice 1973, Gardiner 1978, Ebisemiju 1979). At the site level, slopes have been classified by morphologic type (Young 1964, Blong 1975, and Parsons 1978).

There have been numerous soil classification systems (Finkl 1982). Multivariate classifications of soils have been developed that employ up to 66 soil variables (Arkley 1971). The present USDA 7th Approximation (Soil Survey Staff 1975) has been widely adopted. Previous systems of soil classification emphasized genetic relationships between zonal soils, made up of great soil groups, and a regional climate in which soil development took place (Dokuchaev 1967). This zonal concept was reinforced by Clements' (1916) view of vegetation distribution. The 7th Approximation, a hierarchical classification with six categories, relies primarily on existing morphological and physical properties of the pedons. According to the hierarchical nature of this system, two soil series in the same family are expected to be more similar with respect to all diagnostic soil properties than two series in different families. A single purpose soil classification, for example, one designed to predict water infiltration rates, typically emphasizes a limited set of soil properties. Consequently, these classifications do not necessarily group soils having other properties in common.

Lithologies are classified by mineralogic composition, but even within a given major rock type (e.g. basalt) there are apt to be many geomorphically significant variations. Some properties of importance in watershed dynamics, such as rock hardness, dip, degree of fracturing, chemical weathering properties, can be ranked on an ordinal scale (Goudie 1981). However, the implications of given properties vary with environmental setting. For example, rock hardness is not necessarily an index of resistance to chemical weathering, although it may be for physical weathering. Mineralogic hardness reveals little about resistance of sedimentary rock to chemical weathering if the cementing particles are not resistant. Lithology controls the expression of geomorphic properties (Tandon 1974), soil genesis (Chesworth 1973), stream water chemistry (Miller 1961), hydrologic properties (Musiake et al. 1975), and mineralogy of transported sediment (Spigai 1969, Scheidegger et al. 1971).

Vegetation zones have been regionalized for Oregon by Franklin and Dyrness (1973). The relationship of vegetation and climate has been expressed on a regional level by Daubenmire (1956) and at the site level by Waring (1969) within the Pacific Northwest area.

Water relations for a region have been dealt with in classifications as depth to groundwater, percentage of area in lakes, etc. (Winter 1977). Hydrological classifications of watersheds emphasize basin physical properties that reflect the ability of the land to transport water. Multivariate classifications of watersheds have focused primarily on basin morphometry to define hydrologic regions (Blake et al. 1973, Gottschalk et al. 1979, Mosley 1981). Regional analysis of hydrologic properties has also dealt with low flow (Orsborn 1975, Chang and Boyer 1977, Bingham 1982), peak flows (Patton and Baker 1976) and groups of flow parameters (Thomas and Benson 1970, Riggs 1973).

C. STREAM CLASSIFICATIONS

Stream networks have been classified primarily by drainage density or frequency, bifurcation ratios, and planar morphology (e.g. dendritic, trellis, radial) (Horton 1945, Mitchell 1973, p.20-21) whereas segment classification by planar morphology often emphasizes the straight, braided, and meandering form in relation to segment slope (Leopold and Wolman 1957, Schumm 1963, Mollard 1973, Galay, Kellerhals, and Bray 1973, Kellerhals, Church, and Bray 1976). Topologic analysis of channel networks has been suggested as a mathematical tool for classification (Werner and Smart 1973, Jarvis 1977), although the relationship of network classes so-defined to hydrologic response has not been well established (cf. Surkan 1969). Longitudinal profiles within networks exhibit regularities relative to their valleys (Hack 1957, Gregory 1976, Lee and Henson 1978) and also discontinuities when transition in lithology occurs (Hack 1973, Keller and Tally 1979). Longitudinal trends in parameters of hydraulic geometry have been explored on a global basis (Park 1977) and more intensively on individual streams (Onesti and Miller 1974, Pickup 1975, Richards 1977). Temporal variations in morphometry at a site also occur (Knighton 1975, Richards 1977). Consistency of trends in hydraulic geometry downstream in relation to watershed class and drainage area suggests the possibility of inferring network properties from properties of the basin drained.

Stream networks have been classified according to longitudinal biological zonation. Biological stream classifications have generally emphasized fish zones (Kuehne 1962, Illies and Botosaneanu 1963, Smith 1971, Hawkes 1975, 1977). Longitudinal trends in the biota of drainages have been examined in terms of changes in aquatic plant (Haslam 1978) and animal communities (Cushing et al. 1983). Gradient (continuum) views of longitudinal community changes are not necessarily preferable to zonation (cf. Minshall et al. 1985). Both views are derivable from the same systems model by adjustment of scale.

Stream segment physical classifications have relied on simple measures such as channel width, slope, mean depth, and order (Ricker 1934, Huet 1946, Whiteside and McNatt 1972, Vannote et al. 1980) as well as large sets of variables (Pennak 1971). Channel parameters and associated fish distributions can be explained in relation to their geomorphic setting (Platts 1974). Form factors have been used to represent cross-sectional, planar, and longitudinal variations in stream segments. Because of the close relationship between channel form and hydrology, measures of hydrologic regime are intimately tied to channel behavior for given drainage areas.

D. SIGNIFICANT INTERRELATIONSHIPS AMONG MAJOR CAPACITY ELEMENTS

Schumm (1977) identified the dependent/independent nature of major system variables on various time scales. Although the functional relations among variables can be qualitatively described (Jenny 1961), analytical value is not usually ascribed to such description because of the current incomplete understanding of the forms of families of soil functions under changing topographic and climatic conditions and different lithologies (Yaalon 1975). Cause-effect relationships among variables need not be assigned for advancement in understanding but at least interdependence should be sought. Melton (1958) explored correlation structures among watershed variables. Strong interdependence among variables suggests a mutual adjustment to equilibrium environmental conditions. A careful selection of variables may adequately represent system character without substantial loss of information attributed to reduction of dimensionality.

Many examples of interdependence of major variables can be given. Lithology and age of the rock unit control drainage density (Jansen and Painter 1974). Age is an index of resistivity to erosion. Given a certain substrate, drainage density varies with time of geomorphic development (Ruhe 1952). Water chemistry from basins having only one rock type is highly predictable (Miller 1961, Wallace and Cooper 1970). Mixtures of rock types in a basin produce a composite water chemistry predictable by weighting the areas of the different rock types (Ponce et al. 1979). Zonation of water chemistry class varies in relation to geologic type, precipitation/evaporation regime, Mg/Na balance, etc. (Gorham 1955, Gibbs 1970, Newcomb 1972). Stream bed substrate size and composition are predictable from local geology and bed slope (Hack 1957). Longitudinal distributions of aquatic macrophytes are predictable from the upstream mixtures of rock units (Haslam 1978).

Climatic zonation has long been recognized as correlated with vegetation distribution (Daubenmire 1956) and with landform (Derbyshire 1976). Climatic geomorphology is, however, hindered by the assumptions that must be made about the nature and stability of past climate over a region and the rate of response of landform to climatic changes. Assumed linkages between climate and geomorphological processes have been investigated with the use of mean climatic data (Peltier 1950) as well as magnitude and frequency of extreme events (Wolman and Miller 1960, Starkel 1976, Wolman and Gerson 1978). In a given region, processes characteristic of the interactions of climate, lithology, soils, vegetation, etc. result in classifiable landscape morphologies. Climate provides a major determinant of soil clay content (Jenny 1935). Drainage density is the most frequently measured landscape expression of a climatic type (Carlston 1966, Gregory and Gardiner 1975). Drainage density also varies with lithology (Day 1980), drainage area (Morgan 1973), vegetation (Jansen and Painter

1974), and time (Ruhe 1952). Stream channel classes have been related to climatic zones on a global scale (Sundborg 1978).

Regional vegetation and temperature act as regulators of soil organic matter content in a drainage basin (Meentmeyer, Gardner, and Box 1985). Vegetation density is related to regional rates of erosion, given lithology and associated climate (Wilson 1977, Schumm 1977). At the site level, vegetation type and density regulate soluble mineral retention and export (Likens et al. 1977, Karr and Schlosser 1977, Vitousek and Reiners 1977) and is intimately associated with soil development (Stein and Ludwig 1979, Whittaker et al. 1968). Vegetation modifies the expression of channel morphology (Zimmerman et al. 1967, Heede 1972, Wolman and Gerson 1978).

Water in a drainage basin can be classified according to its chemistry, temperature, sediment load, position (altitude in a basin, depth in soil), and magnitude, frequency, and seasonality of flow. Water chemistry is a function of lithology (Miller 1961, Wallace and Cooper 1970), vegetation (Vitousek and Reiners 1977), soils (Smith and Dunne 1977), stream order (Moeller et al. 1978), forest management (Likens et al. 1977), precipitation chemistry (Douglas 1968), and proximity to oceanic air masses (Likens et al. 1977). Multivariate methods have been employed in water chemistry classification (Dawdy and Feth 1967). Flow regimes have been classified on global scales as a function of flow patterns related to sources of water (Beckinsale 1969) and on regional scales in relation to topography (Orsborn 1980, Mimikou and Kaemake 1985). Peak flows have been correlated with basin and network morphometry (White 1975, Patton and Baker 1976, Newson 1978) and climatic parameters such as precipitation intensity (Hewlett, Fortson, and Cunningham 1977). Hydrologic recession rates have been related to soil character (Jones and McGillchrist 1978) and low flows can be related to basin topography (Orsborn 1975), lithology (Farvolden 1963, Schneider 1965), and soil properties (Gustard 1983). Stream temperatures are a function of climate (i.e., air temperature, potential solar radiation) (Smith 1981), topographic shading through basin morphology, ground water vs. surface water flow volumes, degree of riparian canopy shading (Levno and Rothacher 1967), and percentage of bedrock exposed in the channel (Brown 1969).

Stream biota have been used as primary means of classifying stream type, biotic response often being described as a function of watershed or stream character. Fish production has been related to geomorphological parameters (Ziemer 1973, Swanston et al. 1977) and more specifically to flow fluctuation (White 1975, Wesche 1984). Fish distribution was shown to vary according to increasing stream order or size (Lotrich 1973, Platts 1974, Horowitz 1978). More extensive ecosystem studies along river continua have shown changes in plant/animal community types (Vannote et al. 1980, Cushing et al. 1983, Minshall et al. 1983).

II THEORETICAL NATURE OF THE CLASSIFICATION

A. OVERVIEW OF CLASSIFICATION

Any classification system should be determined by its objective, its theoretical perspective, and the nature of the objects to be classified. Objectives vary greatly in scope. The theoretical perspective employed produces the unique conceptual structure of a classification. This helps to make apparent the organization of the natural systems and makes interpretation possible. Variables and data sets have meaning only in the context of a theory or conceptual framework. The true nature of the object and its interrelations with other objects in its environment can never be known entirely and cannot be disassociated from preconceived theoretical perspectives. Nonetheless, the nature of the object must in some way and in some degree be entailed if a classification is to be effective.

Common to all classifications is recognition of an object. This involves observation at a given spatio-temporal scale, within a standard hierarchy of systems (e.g. organism-population-community). Object-environment boundaries vary in clarity. For example, distinguishing a squirrel from a forest is unambiguous, but distinguishing a soil unit or land type from its surroundings is not so clear, this making apparent the larger role of theory or convention in distinguishing some boundaries. Regardless of the ease in identifying boundaries of objects, objects vary by gradations from similar objects in terms of one or more variables, which may be taken as differentiating characteristics. Some variables are assumed to be of greater importance in differentiating types of objects, and these vary together with "less important" variables or accessory characteristics (Grigg 1967). The properties and behavior of objects of similar differentiae are usually assumed to be similar. It is generally accepted that no single classification can be universal (Grigg 1967). That is, no single set of differentiating characters of a system can represent similarity of all possible behaviors. Special purpose classifications emphasize particular variables, tending to group objects in special or different ways. The classification system to be considered here is not supposed to be universal but is believed to be quite general and useful for most scientific and management applications.

The classification to be here developed and employed is based on a system of classification proposed by Warren (1979). Hierarchical structuring of land units incorporates each level in all higher level systems, which comprise its environment. The next higher level forms its immediate environment, whereas even higher incorporating levels form its generative environment. Any watershed system has its maximum degree of association (similarity and strength of interaction) with other systems in its own immediate environment. Larger environmental systems incorporate more dissimilarity, individual watersheds in these systems having weaker associations, the stronger boundaries separating them. Over geologic time a watershed and its immediate environment maintain integrity as a system, subsystems achieving a degree of mutual adjustment (e.g. adjustment to the regional tectonic forces, oceanic base level, climatic forces). Generative environment applies to a more regional land system acting as an entity over geologic development, incorporating the immediate environment of a watershed system, and contributing to the behavior and maintenance of that system. For example, the gene pool of any system is partially maintained by the system itself, partially by its immediate environment, and more completely by the region to which the system belongs.

In the classification system proposed by Warren (1979), every hierarchical level is defined by the same set of capacity components. These components (water, biota, substrate, culture, climate) entail major categories of variables that describe the potential of a system (Fig. 1). Any performance of a system is taken to be the result of an interaction of a system with its environment. The potential capacity of a system and the potential capacity of its environment determine all that a system can do over time under all possible environmental states or performances. System and environmental capacities determine system class. Conversely, the set of all possible performances of a system over time (i.e. all performances in response to all possible environmental performances over time) defines the potential capacity of the system. Realized system capacity refers to a set of system performances in relation to a set of environmental performances within a particular time frame such as vegetative successional time (Fig. 1). Potential and realized capacities are related on a time scale. As environmental capacity (capacity of a land system at a specified hierarchical level using the five capacity components) relative to any system changes through development, the environmental regimes for a system of a given capacity vary. Predictive models of system performance in the time frame of vegetative succession (e.g. 1000 years) often assume stable environmental systems, although this may be inadequate for given objectives. On a greater time scale, the degree of variation of the environmental system is understandable in terms of other parameters varying even more slowly in time, but the cumulative environmental change may be greater.

It is impossible to observe all performances of any system over time. Consequently, we can never know with certainty whether any two systems are identical. According to the hierarchical structure employed in this systems classification, no two systems could have exactly the same potential capacity because it is impossible for

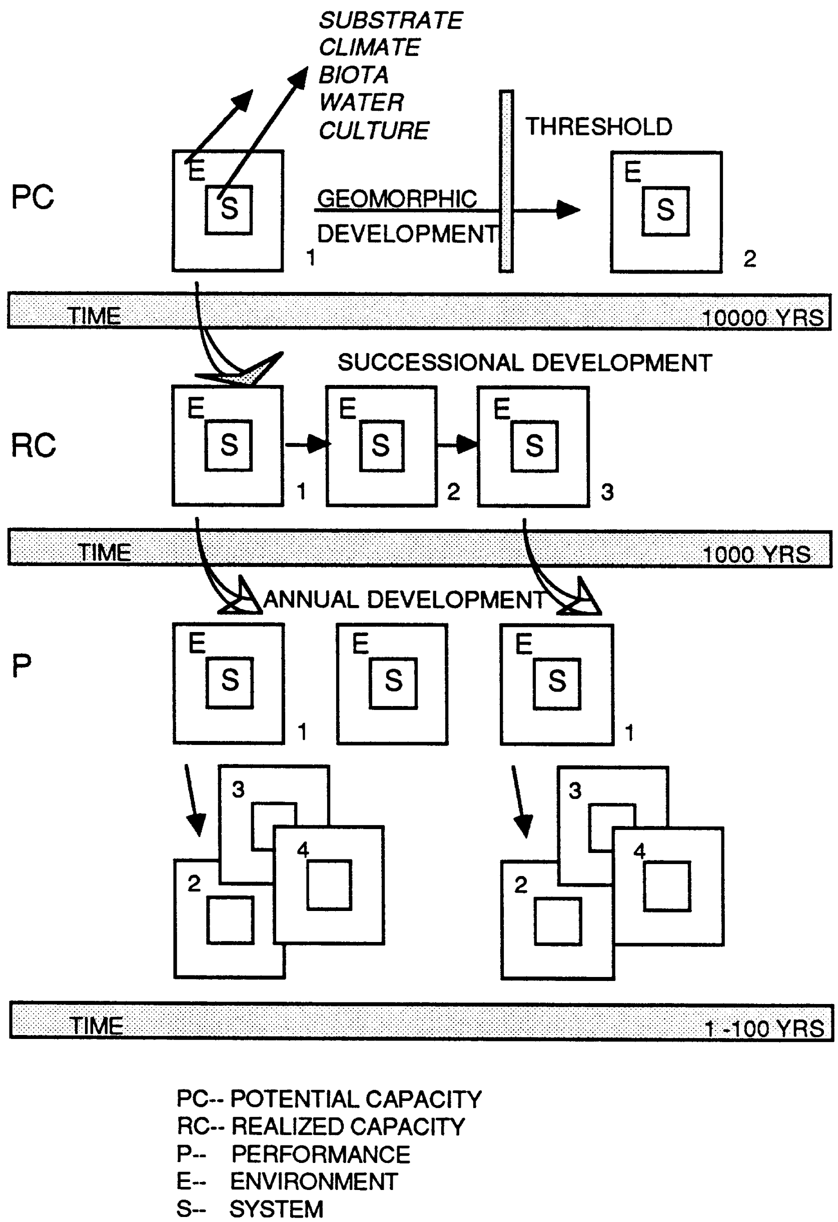


Figure 1. Concepts of system/environmental capacities and performances on different scales of time.

different systems to have exactly the same environment. For example, a system at a boundary of a given region has a different group of surrounding systems than a similar system toward the center of a region.

An alternative to observing performances of any system through time is to observe performances of similar systems in different stages of development (the so-called ergodic theorem)(Hall and Knight 1981, Chorley, Schumm, and Sugden 1984). The most appropriate indices or proxies for system capacity are performances that vary slowly over time (Table 1). Watershed classification by capacity, then, is relative to a time frame. The concepts of relative rates of change of system attributes over time periods and of dependent/independent variables in a continuum of time frames were expounded by Schumm and Lichty (1965) and Schumm (1977). Their meta-stable state may well apply to natural systems whose behavior over long time periods can be characterized by a set of capacity proxy variables. When system thresholds are exceeded, even potential capacity may change, this indicating a new kind or class of system, which must then be characterized by a new set of capacity proxies. These variables are termed proxies because, being measurements of (slowly changing) performances, they represent capacity only indirectly. Capacity, being a theoretical concept, cannot be directly or completely determined observationally. Any regime is defined with respect to a time frame. Capacity of a watershed entails possible interactions of system morphology, physical and biological materials of the watershed as a whole and its parts, regime of physical inputs, and spatial organization of system parts. The time frame selected in identifying watersheds must be longer than for the performances of interest. For example, if watershed development is to be understood over geological time, watersheds must be conceived to extend over that time, state changes within that time frame then being understood as watershed performances.

Table 1. Some variables of interest in the classification and modeling of natural hierarchical systems.

	Substrate	Climate	Water	Biota	Culture
Continent or Region	Proximity to sea floor spreading centers; subduction zones; uplift/subsidence; volcanism; Age of rock masses Major soil forming processes--aeolian, fluvial, colluvial Soil orders and sub-orders Fault zones Major valleys, mountain ranges, plateaus, divides, drainages Glaciation history	Ocean temperatures Spatial/aerial relationship of ocean to land masses. Interaction of wind fields with those to N and S. cP, mT, cT, and mP air masses. Jet stream patterns Orographic effects Rain shadows	Area, depth, volume, temperature of major water bodies--ocean, stream, lakes, groundwater Spatial relation of water body to air flow direction Hydrologic regime for stream systems--domination by spring snowmelt, winter rain, summer drought, etc.	Biomes Species pools Biogeography	Economic Governmental Aesthetic, moral, legal Technology

Zone or Subzone	Soil great groups, families Lithology, stratigraphy Fault lines Trends in altitude and drainage lines with respect to wind flow regimes and regional climate	Proximity to ocean Regional climate modified by zonal topography Mean annual precipitation as rain/snow Mean monthly precipitation and maximum intensity of various durations (1h, 6h, 12h, 24h) Mean monthly temperature range Monthly temperature duration frequency curve Humidity, mean monthly relative humidity Solar radiation--potential radiation for given latitude Monthly wind speed--duration curve; monthly direction frequency distribution.		Species pool Ecosystems Spatial linkage of habitat types	

Watershed	(Geographic position) Latitude Proximity to bodies of water or topographic barriers with respect to mean monthly wind direction (Topographic) Slope, aspect, altitude for all triangular land facets Hypsometric integral Mean percentage change of elevation from point to point on altitude grid in N-S and E-W directions. Number of changes in direction of slope on N-W and E-W axes per 100 altitude points on grid system. Basin orientation and slope.	Regional air mass types; seasonal occurrence. Solar radiation distribution with respect to slope, aspect, altitude, and topographic shading using mean atmospheric transmissivity on cloudless day for watershed.	Depth to groundwater Mean annual discharge. 7 day low flow with 10-year recurrence interval. Peak flow with 10, 50, 100 year recurrence intervals. Area, volume of lakes.	Polyclimax Community organization Formation types	Miles of road % of area logged % of area burned Fire history. % of area affected by mass erosion. Glaciation history. Industries--timber, mining, livestock. Management decisions, landuse, zoning.

Watershed (cont.)	Distribution of rock and soil types with respect to altitude and distance upstream from mouth (gravity model of spatial organization). (Geology) Stratigraphy Mineralogy Geomorphic age, landscape history, rate of uplift or downwarp, seismic activity. Lithology with respect to altitude. (Soil) Depth Texture Clay type and content				
Stream System	(Topographic) Longitudinal profile of mainstem and blue line tributaries. Increase in cumulative total stream length (or area) vs. cumulative length down mainstem. Cumulative total length of stream vs. distance from a point on main-stem, traced along mainstem and outward along blue line tributaries. Drainage density				

Stream Segment or Reach	(Geographic position) Proximity to other stream segments or of same and different orders (Topographic) Mean channel width to bankfull Channel width when depth is 10% greater than mean annual bankfull depth (capacity to expand laterally with bankfull depth); lower bank slope; upper bank slope. Drainage area Roughness elements-sinuosity; large structural elements,boulders, large wood; bedform; bedrock falls; channel constrictions or variability of bankfull width. Map-derived slope of reach. Habitat characterization by area, volume, length, quality. (Geologic) Bedrock type or material potentially exposed in a 100 year flood. Bank material-texture, clay content. Substrate size composition.				

One component of system capacity is its substrate capacity. If performances relative to two substrate capacity proxies could be recorded through time in two stream systems, one might observe some degree of overlap in the performance field of points (Fig. 2). This field in two dimensions represents a portion of substrate capacity. The fact that two streams could have similar sets of substrate performances at points in their developments through time does not mean they belong to the same class. Dissimilar substrate performances through time could arise from the fact that the streams have different substrate capacities or their environments have different capacities.

Every performance of an object (e.g. stream morphology) partially sets the realized capacity of the object for future performances. That is, a meta-stable state in channel morphology establishes a threshold of response to internal or external forces (Schumm 1977, Wolman and Gerson 1978). Because of this incremental behavior, a present performance can shape system realized capacity for future performances varying on shorter time scales and operating within threshold limits.

B. PRESENT SYSTEM

The systems classification here to be presented is based on that of Warren (1979), in which each hierarchical level is characterized by all five components (substrate, climate, water, biota, and culture). When small watersheds and their stream networks are the objects of study, detailed information usually does not exist for all capacity components at this hierarchical level. For this reason, in this study, only one component of capacity (substrate) was emphasized for small watersheds. This treatment is more akin to the general scheme of Bailey (1976) in which only one component is used as a distinguishing criterion at each hierarchical level.

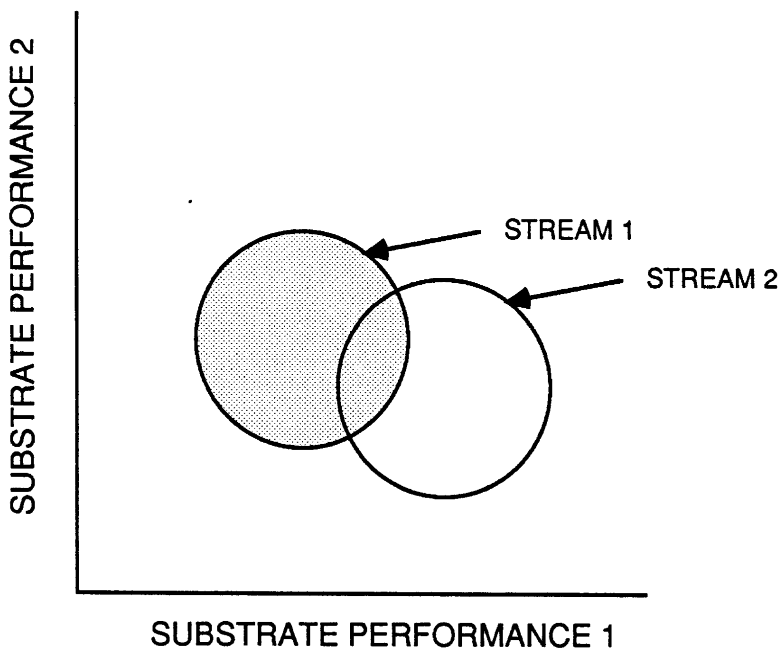


Figure 2. Overlap of clouds of two stream substrate performance parameters as monitored through developmental time in two stream classes.

Singling out substrate for classification at lower levels of the hierarchy is not likely to seriously misrepresent total system potentials. In the present study, proxies for watershed substrate capacity were relatively general, invariant, and determining performances of topography and soils. Soils data were preferred to lithology because geologic surveying was neither so extensive nor so detailed as soil surveys for the study area. Stream networks were classified with capacity proxies based on substrate morphology, geology, and solar radiation load. Stream network classes are entailed in the watershed classification.

The stream (system) is considered here to be the network. Parts of the network of any given drainage area may be termed segments or reaches. A segment is the mainstem channel between the consecutive points of entry of two tributaries. Segments may be comprised of different types of reaches, each of which is characterized by overall bed slope, cross-sectional form, and meander form. Reaches are decomposable into bed form types, or habitat types when physical form is associated with community type (Frissell et al. 1986). It is a matter of convention as to how large a stream is to be termed a tributary. This definition of segment serves as a means of denoting a part of the stream having relatively constant drainage area over its extent. The point of entry of a tributary at the downstream end of a segment marks a rapid change in stream system size and environment. That is, drainage area increases abruptly at nodes (points of tributary entry to the mainstem) and more smoothly between nodes. Inclusion of this idea in "River Continuum" concepts (Vannote et al. 1980) implies that stream habitats have continuous as well as discrete dimensions.

The environment of the network is the next higher hierarchical level, the watershed. This system-environment relationship is appropriate when the entire network is the object of study. Each major tributary of the network has its own watershed. Any given network has a downstream reach that is a direct expression of the cumulative effects of all upstream subsystems. When the downstream segment or reach, as opposed to the network, becomes the object of study, as opposed to the network, the watershed is still considered to be its environmental shell. A downstream reach may be heavily influenced by local features, but it is also a product of whole basin behavior.

Structure of the environment of a reach is primarily oriented on drainage lines, whereas many terrestrial systems would have environments isotropically structured. The strength of environmental influence of any part of the watershed on a downstream reach may be modeled by spatial proximity, size, and land type of that part. Owing to its proximity, the riparian corridor of a downstream reach of a watershed can be considered as part of the effective environment of the reach. But land-water interactions between riparian zone and stream reach generally decrease with increasing drainage area, except where overbank flow is significant. The whole watershed might be considered part of the generative environment of the reach, including drainage area, reach bed slope and geology, and higher level environments.

There is no clear land-to-water discontinuity in the hierarchy descending from watershed to stream when stream is taken to be the network. The network is characterized by capacity components water and substrate (topography, geology, soils) as used in watershed classification. In the network, water is flowing primarily over rather than through the substrate. Also, soil dynamics are different, but a network can be thought of as an extended land unit with complex interactions with its environment. Networks have capacities that change directionally downstream with increasing drainage area and abruptly at nodes, rather than randomly from facet to facet on land surfaces.

C. IDENTIFICATION OF SYSTEMS WITHIN A HIERARCHICAL FRAMEWORK

For any two watershed systems to be considered the same, the capacities of the watersheds and the capacities of their environments must be the same. Watershed environment is a general term for all hierarchical levels above that of the watershed. Environment may be conceptually structured as an infinite series of subdivided units or it may be structured by coarser geographic divisions. If two watersheds have the same capacity E, but one is located in environment C and the other in D, then the class of these watersheds is different (Fig. 3).

If units C and D are each found in unit B, then watersheds with capacity E have environment in common at the level of B but not at the C and D level. This illustrates that environment could be subdivided to the point that watersheds of capacity E are shown not to be in the same class (due to their different environments). Conversely, at some level in the hierarchy, two systems are part of the same geographic unit. Theoretically, it must be assumed that each watershed is unique. No two objects could have exactly the same spatial organization of units surrounding them. However, finding that two watersheds have the same environment at some hierarchical level only implies a certain degree of similarity in the classes. On average, performances of systems of capacity E should be more similar if they were found to have level C in common rather than level B. The higher the level, the greater the degree of heterogeneity and range of variability encompassed.

Even if watersheds of the same capacity (A) are found in the same environmental shell (E), the spatial position of a watershed inside this shell is apt to be important in determining its class at a finer level of resolution. This situation is

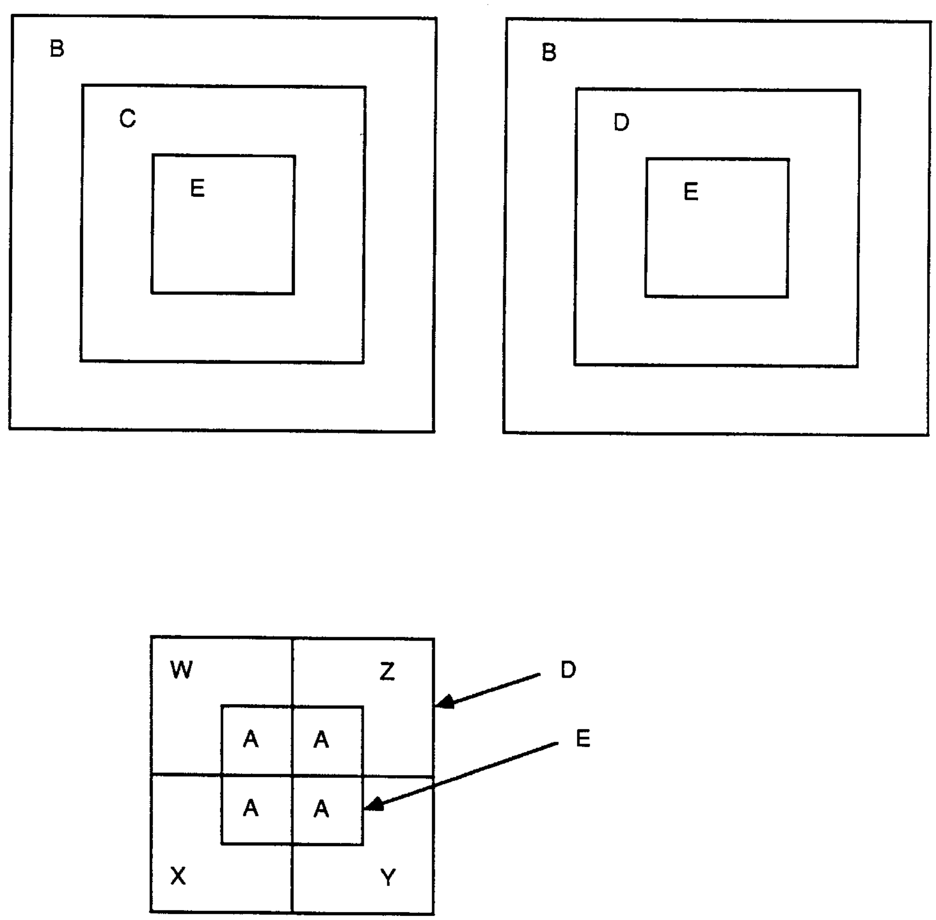


Figure 3. Conceptualization of system/environment relationships and boundary problems.

illustrated in Figure 3. Units W, X, Y, and Z each have unit A as an inclusion. Each unit A has a different immediate environment but the same environment at the next higher level, since unit D includes W+X+Y+Z. Each small unit A has a different spatial position within D. Because all small A units are contiguous, they may be grouped into a large unit (E). The practical problem in classification is to determine whether unit D is a system of the same hierarchical rank as W, X, Y, and Z. If unit D has no integrity as a system and its components are heterogeneous, then each component should be a subsystem of W, X, Y, and Z respectively. This implies that the four quadrants of D depicted are not similar enough to be called class A or that W, X, Y, and Z have more system integrity than does a system D.

This example emphasizes certain points relative to watershed classification: (1) If the small A subunits are grouped to form a larger unit, this unit would no longer be labeled A. Capacity is a function of size, so the large contiguous cluster has a distinctive capacity; (2) capacity of a system is a function of the capacities of the five interactive components of capacity (substrate, climate, etc.); 3) class of a system is a function of the capacity of the system and the capacity of its environment; (4) environment of a system is a higher order geographical unit comprising watershed units of different classes (partially distinguished by drainage area and topographic differences); (5) the character of any such geographic unit is an expression of the degree of homogeneity of subsystems of a given size (or the spatio-temporal co-distribution of all capacity proxies); (6) although two basins may be said to have the same environment if found within a geographic unit, their unique character may result partially from their spatial relationships to other nearby basins within the unit; (7) the capacity of any basin is partially derived from the capacity of its environment, the biota or climate of a single basin being a sub-set of the environmental biota or climate, that is modified on a topographic template (Southwood 1977); (8) owing to joint control of system performances by watershed and environmental capacities as well as the theoretical uniqueness of all watersheds, basins can be more nearly described by multidimensional continua rather than as discrete groups.

The preceding points highlight the need for a formal system of identifying units at all hierarchical levels. Despite the multivariate nature of systems, discrete classes are useful as tools of understanding and management. Watershed boundaries will here be the primary physical delimiters of geographic units for units less than 25 mi^2. Larger units may be distinguished by physiography or vegetation zones. Essentially, ecosystem boundaries are formed in this latter way.

D. ABILITY TO SUBSTITUTE TOPOGRAPHIC AND SOIL CLASSIFICATION FOR FULL CLASSIFICATION AT THE WATERSHED LEVEL

Although use of all major system capacity variables for classification is proposed at the regional, sectional, and district levels of Bailey, it is often impractical to attempt this at the watershed, network, and stream segment levels, owing to lack of requisite data. Numerous studies show the utility of topographic and soils parameters in representing potentials of watersheds. If the watershed is embedded in higher level classes defined by climate, lithology, vegetation, and culture, it is proposed that, in the absence of more refined data, topography and soils define adequately the site level expression of these other variables.

Soil data at the soil series level is the most detailed information afforded by the new Comprehensive Soil Survey system. Variations in soil character reflect differences in lithology and slope (Swan 1970), aspect (Reid 1973), and basin geomorphology (King 1975). Clay mineralogy reflects lithology and also the time of soil development. Slope gradient and vegetation zone control the time period of soil development (clay formation and soil horizonation) on a site.

Measures of basin topography (slope, aspect, altitude) can be derived for classification at the basin level by statistically summarizing topography at many representative sites. At the site level, these variables are often used to infer boundaries of soil units when data are not available. Landform concavity and convexity are additional topographic variables that describe the developmental environment (Goudie 1981), but the coarseness of topographic resolution used in this study makes these variables of little use. The ability of a soil to retain water is a function of soil depth, texture, and clay type, and the local slope, concavity, and convexity (O'Loughlin 1981, Anderson and Burt 1978). Soil temperature is a function of vegetative cover, air temperature regime, the ability of slope and aspect to control solar radiation load at a given latitude, and topographic shading. Because soil temperature is closely related to air temperature, site altitude is also a key factor determining soil temperature. The tendency for soils to experience drying of surface horizons or freeze-thaw action is also related to these same variables. Spatial variability of snowmelt (Rawls and Jackson 1979) and soil temperatures (Green and Harding 1980)is predictable based on topographic factors. At the basin and network levels, these topographic and soil factors control the rate of runoff, formation of flood peaks, low flow magnitude, channel morphometry, sediment yield, potential for mass movement and debris avalanches, solar radiation loading, and lower atmospheric wind flow patterns.

III METHODS

This classification of watersheds proceeded from a regional scale down through zone, subzone, major drainage system, watershed, and stream network. The hierarchy established below the level of network is segment, reach, habitat cluster, habitat, and microhabitat although these levels were not addressed here. At the watershed and stream network levels, a set of methods was developed to analyze structure.

Basin structure was examined with the aid of a grid system of cells. The grid was laid over topographic and soil maps for data extraction (Fig. 4). The distance between points on the grid was 880 feet in a N-S and E-W direction. Grid cells or facets were the smallest triangles (area= 0.5 x 880 x 880 ft^2) created by selecting groups of points consecutively across the grid, provided points all fell within watershed boundaries. In each facet the predominant soil type present was recorded. If two soil types were present in equal abundance, only one type was recorded per cell but if the same combination ever occurred again in a basin, the other soil type was recorded.

Altitudes of all grid points were recorded as integers obtained by dividing each altitude (ft) by contour interval (80 ft). A FORTRAN program (ALTXYZ)(see Appendix A) was developed for the Quasar QDP-100 microcomputer to calculate the maximum slope gradient, aspect or the direction of steepest descent, and mean altitude (AVALT) of each triangular facet on the landscape covered by the grid and to produce a frequency distribution of these data.

The grid system formed the basis for statistical analysis of topography. Given the x, y, and z coordinates (x and y being planar Cartesian coordinates and z being altitude), the maximum slope gradient, mean altitude, and direction of steepest descent

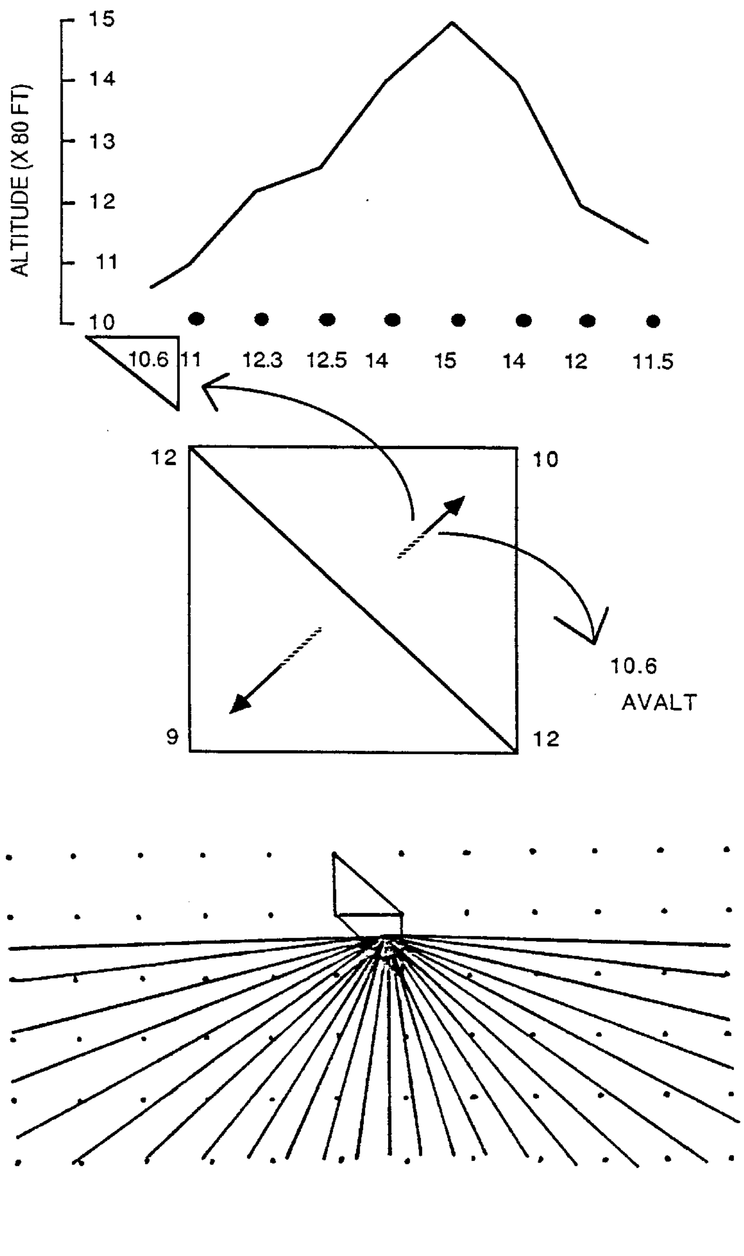


Figure 4. Computer search through the altitude grid for topographic ridges providing maximum shading factor at increments (7.5 degrees) of solar movement along meridian. A search on the equinox is diagrammed.

were calculated for each triangular slope facet by vector analysis.

Corners of triangles (i.e. grid points) are designated as A, B, and C. The x, y, and z coordinates of, for example, point A are often labeled A(1), A(2), and A(3), but could also be labeled x_1, y_1, and z_1. Mean altitude of the triangle was calculated as 1/3 $[z_1 + z_2 + z_3]$. Vector AB= $(x_2-x_1)i + (y_2- y_1)j + (z_2- z_1)k$. In shortened form vector AB= $a_i + b_j + c_k = AB_i + AB_j + AB_k$. The normal vector also has three components, N(1), N(2), and N(3) or a, b, and c. The length of a vector is d = sqrt($a^2 + b^2 + c^2$). Direction cosines are a/d, b/d, and c/d; direction numbers are a, b, and c. The normal vector to the plane defined by the points A, B, and C is defined by the cross-product of the vectors AB and AC. By this procedure, the "a" component of the normal vector is $(AB_j * AC_k - AB_k * AC_j)$; the "b" component is $(AB_k * AC_i - AB_j * AC_i)$; the "c" component is $(AB_i * AC_j - AB_j * AC_i)$. Taking the a, b, and c components of the normal vector, the gradient vector of the plane is expressed as (-a/c, -b/c). The angle of steepest ascent is then calculated as arctan [sqrt($a^2 + b^2$)/ !c!]. The direction of steepest ascent (angle in radians counterclockwise of east) is given by arctan[abs(b/a)].

The direction cosines of the normal vector to a triangular facet were labeled L, M, and N by Watson (1956) and Watson and Irving (1957), Koch and Link (1971) (p.140) and Taff (1981) and x, y, and z by Pincus (1953, 1956). L = sin(slope) * cos(BEAR + 180 degrees), M = sin (slope) * sin(BEAR + 180 degrees), and N = cos(slope), where slope is the maximum slope gradient and BEAR is the compass bearing in the direction of steepest descent. In program SUN (Appendix B), which performs solar radiation calculations, the formulas for direction cosines L, M, and N are modified from the standard ones cited because compass directions with north at 0 degrees are converted to the azimuth system with north at 180 degrees and the slope gradient = (90 degrees - z) where z is the zenith distance.

In program SUN a solar constant of 2.00 $cal/cm^2/min$ (Williams, Barry, and

Andrews 1972) was converted to 83680 $J/m^2/min$ (CRC 1979) for radiation calculations. Atmospheric transmissivity (P) of 0.75 was selected (Garnier and Ohmura 1968) as representative of the study area, which is located at 45.5 degrees latitude. Solar declination at the winter solstice was taken as -23.44 degrees (Air Almanac 1984) and the equinox as 0 degrees.

Various astronomical functions were determined using equations in Sellers (1965) and Holbo (unpubl. MS): h- hour angle, H- half-day length, z- solar zenith angle, l- latitude, d- solar declination, and az- azimuth angle. Formulas for some of these calculations are given below.

cos H = -tan l * tan d

cos z = sin l * sin d + cos l * cos d * cos h

cos az = (sin l * cos z - sin d)/(cos l * sin z)

The optical air mass (m) was expressed as 1/cos z. The attenuation of direct solar radiation owing to altitude and azimuth of the sun is approximated by the function P^m (Garnier and Ohmura 1968) for each 30 min interval of movement of the sun during daylight hours. Garnier and Ohmura (1968) found 20 min-intervals to be equivalent to 1 min-intervals in solar computations. In program SUN the function SBEAR = (180 degrees - az) or the solar bearing at various intervals of solar movement. The direction cosines for solar vectors at any interval were calculated as L = sin z * cos(180 degrees + SBEAR); M = sin z * sin(180 degrees + SBEAR); N = cos z (adapted from Taff 1981). The minimum angle (e) between the solar vector and normal vector to the slope facet was calculated by the formula cos e = (sunL * terrL) + (sunM * terrM) + (sunN * terrN) (Garnier and Ohmura 1968). This formula uses the azimuth system in which south = 0 degrees. The daily total insolation on 1 m^2 was determined by summation of radiation for all time intervals during daylight. Solar radiation received in each interval was determined by the equation $I = I_oP^m$ * time. Potential radiation on a horizontal surface is calculated by multiplying daily value of I by cos z. Potential radiation on an inclined surface depends on the minimum angle between solar and normal terrestrial vectors and is calculated by multiplying daily I by cos e (Garnier and Ohmura 1968).

In addition to topographic description by facet, statistical measures of basin topography were derived from the grid of altitudes by vector analysis (Hobson 1967). R1 or vector strength is the length of the resultant normal vector. This ranges from 0 (no preferred orientation) to 1 (all normal vectors of identical orientation) so is a measure of similarity of orientation. The degree dispersion of normal upward-pointing vectors projected on a hemisphere is described by FISHD or Fisher's dispersion index (ESTK in Hobson 1967). The inclination and orientation of the resultant vector were also determined. This indicates the resultant basin slope and aspect.

Potential daily radiation accounting for the effect of topographic shading was determined for each facet. This was done by searching from the center of each facet throughout the grid, on angles to the sun representing the solar position at each 0.5 h interval, to determine whether the solar altitude was above or below watershed topography (Fig. 4). Solar radiation was integrated for each triangular facet for all 0.5 h periods for which sunlight was not intercepted by basin topography.

The effect of topographic shading on the stream network was determined with the program CHANLC (Appendix C) by laying out points at 880 ft intervals on the blue line channel network (Fig. 5). X-Y coordinates of each point on the stream network were recorded with respect to the original grid system. Each point was located on aerial photos and the tree cover density (nearest 10%), riparian canopy height class (1-5, corresponding to 0-3, 4-7, 8-12, 12-15, and >15 m), gap width (meters) in riparian cover

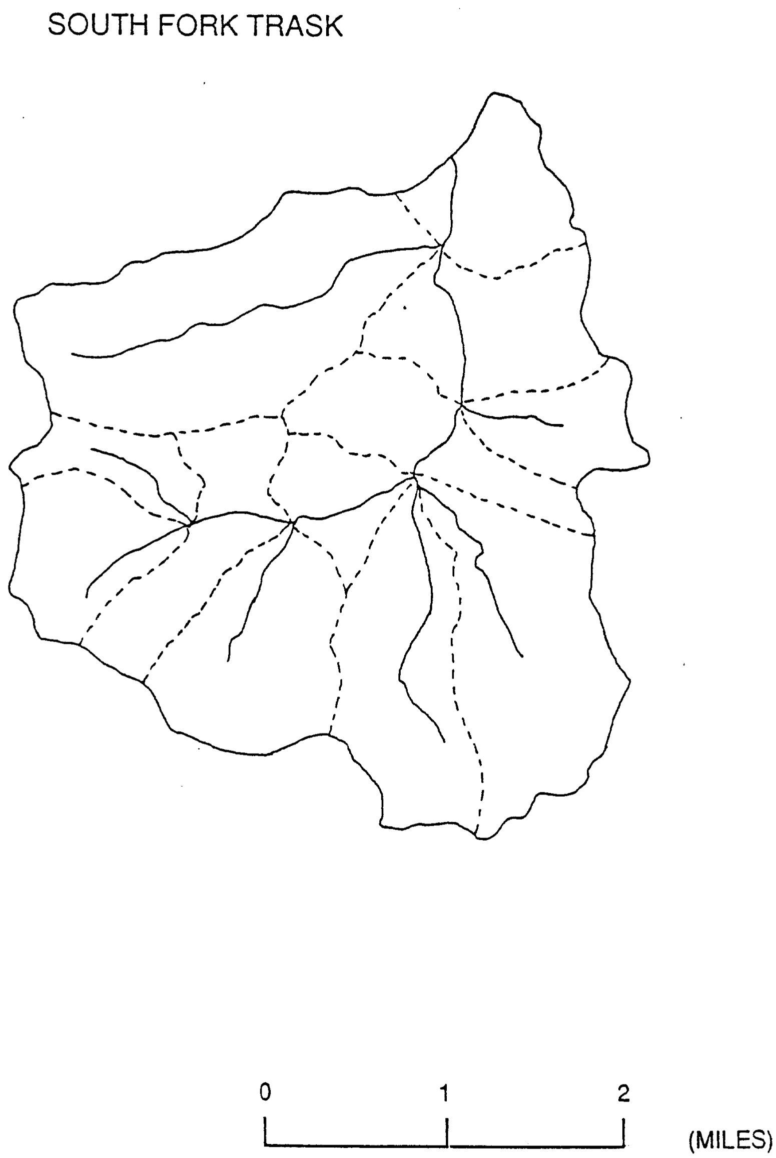


Figure 5. The blue-line drainage network (solid line) and sub-basin boundaries (dotted-line) for the South Fork Trask River. Points at which to initiate integration of daily solar radiation load are spaced at 880 ft intervals along entire blue-line network.

over the channel, and channel compass orientation were estimated for the 880 ft section centered on each point. Direct radiation in $J/m^2/d$ was integrated for each 1/10 of the water surface width by determining for each angle to the sun at 0.5 h intervals whether the tree line or topography intercepted the solar radiation. It was assumed for any direct beam radiation passing the topography but intercepted by the canopy that 5% of the light would pass a 100% cover density. It was further assumed that light penetration through the canopy is inversely related to cover density. Solar radiation load and intensity were determined for each point with and without topographic and canopy shading and also for each blue line channel segment and for the entire network.

Watershed analysis was accomplished by calculating certain primary data for all individual triangular facets from the altitude grid with program ALTXYZ. These primary data were AVSL (maximum slope of a triangular facet in the direction of steepest descent), ORIENT (compass direction of steepest descent on a triangular facet), AVALT (mean altitude of a facet), RAD1 (daily potential radiation on the winter solstice, $J/m^2/d$), RAD2 (daily potential radiation at the equinox, $J/^2/d$). The soil series occurring on each triangular facet was recorded. AVSL and ORIENT were converted to direction cosines (L, M, and N) because orientation data conform to a circular distribution (Watson 1956, Steinmetz 1962, Taff 1981, Zar 1984). That is, a compass direction of 360 degrees (north) is not significantly different from 1 or 359 degrees, so vector representations of orientation must be used. Mathematical formulations of these three direction cosines are sin z cos az, sin z sin az, and cos z, respectively, where z is zenith distance and az is azimuth. Program ALTXYZ also provided variable GAPLA, the ratio of ground surface area to horizontal planar area determined by summing terrain surface area for all triangles and dividing it by the basin area or the area of all triangles projected onto a planar surface. The greater the value of GAPLA, the greater should be the steepness or roughness of terrain. The grid system of altitude points was used to compute other indices of topographic structure (Table 2).

Drainage density (DD) was measured as km/km^2 by digitizing the drainage network, extended by use of map contour-crenulations (Morisawa 1957). The network was extended on topographic maps using the following criteria: (1) extend channels uphill by connecting V-shaped notches in contour intervals, (2) accept as a channel depression any indentation in which the depth of deflection is greater than or equal to 75% of the width between points of inflection from the contour trend line, (3) stop extending a channel upward if a contour is reached not meeting the notch shape criteria unless there are two notches beyond it that meet the criteria, (4) a channel must have at least two notches to be considered a true channel, and (5) connect only notches representing a consistent trend from notch to notch.

An index called MAXDIR (the maximum number of changes in direction of slope for each 100 grid points on N-S, E-W, and both diagonal axes) provided an index of dissection for each basin. A change in slope direction was considered as a downhill to uphill change or vice versa from point to point on the grid. Slope gradients from point to point on all four axes were also determined. The mean slope (SLPTPT) for the four axes of search on the grid system provided an index of internal basin steepness. Since SLPTPT is determined from point to point on the grid and not necessarily in the direction of steepest descent, SLPTPT is less than GMSL (i.e. grand mean of AVSL values for all triangles). Both MAXDIR and SLPTPT were calculated with program PCALT (Appendix D).

Hypsometric integral (Strahler 1952), a popular measure of the distribution of basin area with altitude, was measured by electronic digitizer using every fifth contour (i.e. 400 ft spacing on 15 minute USGS quad sheets). Hypsometric integral (HI) was also

Table 2. A partial list of variables used to describe watershed topographic structure in this work.

Variable	**Measure/Source**
FISHD	Fisher's dispersion index; Hobson (1967)
R1	topographic roughness measure; Hobson (1967)
DD	drainage density (km/km^2)
MAXDIR	maximum number of changes in direction per 100 grid altitude points analyzed on N-S, E-W and diagonals
GMALT	grand mean altitude of all triangles per basin
SD1	standard deviation of AVALT for all triangles (where AVALT is mean altitude of an individual triangle)
GMSL	grand mean slope of all triangles
SDSL	standard deviation of maximum slope of all triangles per basin
HI	hypsometric integral (Strahler 1952)
SLPTPT	mean slope from point to point on altitude grid; taken as largest of 4 means searching grid on N-S, E-W, and diagonals
GAPLA	ground area to planar area ratio on watershed
XALT	mean altitude; taken as mean of all altitude points on grid
KURTALT	kurtosis of all altitude points on grid (Evans 1972)
SKEWALT	skewness of all altitude points on grid (Evans 1972)
CVALT	coefficient of variation of all altitude points on grid
STDALT	standard deviation of all altitude points on grid
KURTSL	kurtosis of maximum slopes of all triangles
SKEWSL	skewness of maximum slopes of all triangles
CVSL	coefficient of variation of maximum slopes of all triangles
RADX	mean radiation intensity of all triangles
RADSD	standard deviation of radiation intensity of all triangles

RADKRT	kurtosis of radiation intensity of all triangles
RADSKW	skewness of radiation intensity of all triangles
RADCV	coefficient of variation of radiation intensity of all triangles

calculated by integrating the area under the hypsographic curve drawn from cumulative frequency analysis of all altitude points on the grid for each basin (Rowe and Brenne 1982, SIPS program, OSU Computer Center). Descriptive statistics (mean, standard deviation, skewness, kurtosis, and coefficient of variation) were calculated from the primary data computed from all triangles for each basin. Using altitude data recorded at all grid points yielded the statistics XALT, STDALT, SKEWALT, KURTALT, and CVALT. Using the mean altitude (AVALT) calculated for each triangular surface, the statistics calculated were GMALT, and SDALT. From the maximum surface slope in each triangle for each basin the statistics GMSL, SDSL, SKEWSL, KURTSL, and CVSL were calculated. Radiation intensities on triangles on the winter solstice (RAD1) represent the effects of topographic shading and consequently spatial relations of basin surfaces. Statistics computed on RAD1 for all triangles for each basin yielded RADX, RADSD, RADSKW, RADKURT, and RADCV.

Multivariate analyses were done on topographic data collected for the set of all triangles per basin and also on indices calculated for the basin as a whole. Discriminant analyses were derived using SPSS (Discriminant). Pearson correlation of variables was calculated by SPSS (Correl). Analyses of variance of soil series groups on variables AVALT, L, N, and RAD1 were determined using (SPSS, Oneway). Factor analysis and cluster analysis were computed by the BMDP (1983) programs FACTOR, K-means clustering (KMEANS), and cluster by cases (BMDP2M). The factor analysis derived principal components from a correlation matrix and rotated axes with a quartimin rotation. The K-means clustering routine is a divisive, non-hierarchical procedure while the cluster by cases routine is hierarchical and agglomerative. Principal components analysis (PCA) and reciprocal averaging (RA) (Gauch 1982) were computed using the program ORDIFLEX. Although RA is generally considered superior to PCA, very similar but slightly more interpretable results were derived from PCA, so results of RA are not reported.

The drainage density of soil polygons was determined by digitizing the channel network on as many major size polygons of a given soil as possible in the 11 study basins. Any blue line channel length in a soil polygon was eliminated from consideration, as it could represent characteristics or position of neighboring soil polygons more than the soil polygon in question. That is, a soil polygon might have a segment of blue line channel running through it and no additional channel network interpreted from contour crenulations.

In addition to manual estimations, drainage density per soil type was also determined by multiple regression with the aid of program REGRESS (Rowe and Brenne 1982, SIPS, OSU Computer Center). Drainage density was calculated for each of the sub-basins represented by links of the blue line system in each of the 11 major basins and having no more than 10% of its area unmapped. Then the percentage of each soil type in each sub-basin was determined on the basis of total area of the sub-basin mapped. Drainage density was the dependent variable and percentages of the various soil types were the dependent variables for each sub-basin. The regression equation allowed estimation of drainage density for soil types singly, given that all others occupied 0% of the sub-basin area.

Spatial structure of the study watersheds was examined by means of a gravity model (Smith 1984). The effect of any soil polygon on the stream reach at the mouth of any size basin could be considered an inverse function of its distance from the mouth and a direct function of its area. All soil polygons were measured individually for area and distance from their centroids down the drainage system to the mouth. A matrix of area of soil of a given type vs. distance was created, areas of soils of a type being combined when they were located in the same distance class. Power of influence (P) of a soil series was calculated as P = A/D where A is area and D is distance. The power of each soil polygon was totaled by soil series type. A relative index of power of influence of a soil series was derived by dividing total power of the soil series by the grand total power of all soil series. Dividing the relative power index by the relative area occupied by the soil series in a watershed indicates the spatial distribution along drainage lines of soil series areas with respect to the downstream stream reach.

IV RESULTS AND INTERPRETATION

A. PRELIMINARY CLASSIFICATION

1. Major regions of the State of Oregon

The Pacific Northwest is characterized by a high diversity of physiographic regions. The major physiographic regions of the Pacific border area run parallel with the coastline through most of Oregon and Washington. These are the Coastal Mountains, central valley, and Cascade Mountains. Oregon's other major regions are the Klamath-Siskiyou Mountains, Deschutes-Umatilla Plateau, Blue Mountains high lava plains, basin and range, and Owyhee Upland. The Coastal Mountains of Oregon are continuous on the north through Washington, bordered on the south by the Klamath Mountains, and on the east by the Willamette Valley. Contact with the Klamath Mountains on the south represents a transition from rocks of predominantly Eocene and Miocene age to the oldest rocks in Oregon. Mean elevation also increases sharply at this boundary. The Coast Range and Willamette Valley shared much of the same depositional, geologic history in the Eocene and Miocene but the Coast Range experienced uplift in the Oligocene (Baldwin 1981).

The geographic distributions of the biota of Oregon emphasize the close correlation between the geographic ranges of biota and the physiographic provinces. Although some species are ubiquitous, the biotic associations of plants and animals are best defined in a physiographic context. The geomorphic history of these regional landforms has led to varying degrees of overlap of species pools in Oregon (Price 1978).

2. Classification of the Oregon Coastal Region

(a) Biota

Biota of the extreme coastal margin is characterized by dominance of Sitka spruce (*Picea sitchensis*) and including western hemlock (*Tsuga heterophylla*), Douglas fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*) and western redcedar (*Thuja plicata*). The coastal zone inland to the divide of the Coast Range is a western hemlock climax association which in many localities is dominated by Douglas fir, western redcedar, red alder and big leaf maple (*Acer macrophyllum*)(Highsmith and Kimerling 1979).

(b) Climate

The climate of the Oregon coastal region is classed under the Trewartha (1943) modification of Koppen's scheme as a temperate oceanic climate, having 4 to 7 months with average temperatures over 10EC and with the coolest month above 0 to 2EC. Weather systems in this region are dominated in the summer by the North Pacific high and in winter by the Aleutian low. Predominant air masses of summertime are marine polar and marine tropical with an occasional continental tropical air mass from the southwestern US deserts penetrating westerly to the coast. The stable air masses of these anticyclonic wind fields are associated with the polar jet migrating northward to about 60 N, and a general subsidence of the air. Winter weather patterns are generated from the interaction of marine polar, marine tropical, and continental polar air masses (Riley and Spolton 1974). The cyclonic air flow is associated with a southerly migration of the polar jet and mean air pressure of ~1002.5 mb. The Aleutian low occurs as a series of migrating low pressure centers, which each yield storms of 3 to 5 d duration. The dominant cloud type is marine stratus. Winter weather occurs in frontal systems that provide fairly homogeneous precipitation along the coast. Orographic and frontal lifting occur as air masses proceed inland.

Mean wind flow direction is from the northwest in summer and west to southwest in winter. The maximum sustained wind speed of 10 yr recurrence for the Oregon coast is ~135 km/h. Resultant wind speeds in fall and spring are lowest owing to rapid changes in direction of flow. Eighty percent of the annual precipitation occurs from October through March with <5% in July and August. Snow is rare except at high altitudes and is of brief duration (Highsmith and Kimerling 1979). Hydrographs of Oregon coastal streams are not influenced greatly by snow melt. Annual precipitation amounts vary from 80 to 90 inches along the coast to an average of 100 to 150 inches inland. Maxima of ~200 inches/y occur in isolated localities. Rainfall intensities in the Tillamook Burn area with 10 year recurrence interval are 1.4 inches/2h (Benoit 1978), 3 to 3.4 inches/6h and 8.0 to 9.0 inches/24h. For the entire Coast Range these values range from 2.8 to 3.8 inches/6h, and 6.0 to 10.0 inches/24h (NOAA 1973). Rainfall increases with elevation but the spatial pattern of mountain peaks also influences rainfall distribution, the highest peak not receiving the greatest rainfall. Along the coastal margin the mean temperature range is 6 to 16C, this increasing inland to 2 to 20 C. For half the year, cloud cover exceeds 80%. Cloud cover of <70% averages 12 to 18 d/mo during summer and 4 to 7 d/mo during winter (Proctor et al. 1980).

(c) Soil

Soils of the Oregon coastal area belong primarily to the Orders Inceptisols and Ultisols. The north and mid-coast basins are dominated by Umbrepts (Inceptisols) and the south coast basins by Humults (Ultisols)(Huddleston 1979, Highsmith and Kimerling 1979). Inceptisols are soils with weakly differentiated horizons that form quickly from parent material. There is no marked accumulation of clay, iron, or aluminum oxides. These soils develop under cool summer conditions. The Umbrepts sub-order has surface horizons darkened by abundant organic matter, crystalline clay minerals, and a high cation exchange capacity. These soils are freely drained, acidic, and develop in areas of high winter precipitation and moderate winter temperatures.

The Ultisols are strongly weathered and leached, well-drained, low in bases, have horizons enriched with silicate clays, and developed under warm, moist conditions (i.e. mean annual temperatures >46 F, and 40 to 120 inches mean annual precipitation) at low altitudes. These soils can develop from a variety of parent materials. The sub-order Humults are dark highly organic, and well-drained (Brady 1974, Highsmith and Kimerling 1979).

(d) Geology

The physiographic provinces, presently known as the Coast Range and Willamette Valley, lay in a large geosyncline in the early Eocene era. The early Eocene was a period of active volcanism. Numerous centers of volcanism west of the present shoreline and in the Cascades east of the Willamette spread submarine volcanic flows, breccia and tuffaceous sediments that converged in the coastal region. After a diminished period of volcanism in the middle Eocene, flows were prevalent again in the late Eocene. Active erosion and deposition of sediments through the Eocene accompanied the wide variations in sea level and inundation of the coastal area. During the Oligocene and Miocene eras, the Coast Range experienced uplift (McKee 1972). The sills and dykes, which were laid down during uplift, produced resistant cap rocks for most peaks in the Coast Range and yielded table lands, knickpoints in streams, and falls amid rather homogeneous sandstone areas.

In the northern half of the Coast Range, the oldest rocks are of early Eocene age. The flows are represented by Siletz River volcanics and Tillamook volcanics. The Siletz Volcanics are submarine flows of 10,000 feet thickness which weather to red and yellow clays. The Tillamook volcanics were laid down from early through late Eocene as sub-marine and sub-aerial flows. Siltstone, sandstone, basaltic tuff, breccia, and pillow lava were interbedded. Columbia River basalts may have traveled down the ancient river system to account for their penetration to the coast and then south to Newport. The primary composition of the remainder of the northern half of the Oregon Coast Range is Flournoy sandstone and siltstone. These beds are 6000 to 7000 ft thick and occur primarily in the southern part of this area. They are heavily penetrated by intrusive volcanics. Other sandstones and siltstones such as King's Valley, Nestucca, Astoria, Alsea, and Yamhill have been described. These formations are basically late Eocene to middle Miocene.

In the Southern half of the Coast Range the predominant rock types are sandstone and volcanics. The Roseburg Formation is comprised by interbedded volcanic and sedimentary rock. The volcanic rock of this formation is the same age and may be continuous with Siletz River Volcanics. The sedimentary component has similarities to the King's Valley Siltstone member of Siletz River Volcanics and exhibits similar stratigraphy. The Flournoy Formation, a thick sandstone formation, is widespread in the southern half of the Coast Range and is of middle Miocene Era. Tyee

Sandstone is of late middle Eocene age and is comprised by rhythmically bedded sandstone grading to siltstone. It is 5000 to 6000 ft thick and was derived from erosion of the Klamath Mountains. Many deposits are known to be continuous throughout the Coast Range or at least similar as indicated by fossil content and mineral composition. The uniform developmental environment of the region since the early Eocene makes these relationships plausible (Baldwin 1981).

(e) Topography

The bulk of the Coast Range has been regionalized by Marston (1980) based on topographic characteristics. These units cut across drainage basins but delineate areas of uniform topographic and geologic character. According to this classification, upland areas are subdivided into coastal fluvial uplands, leeward slope sedimentary uplands, basalt highlands, cuestaform uplands, intrusive tablelands, coastal volcanic uplands and fine textured fluvial lands. These physiographic subsections were putatively linked to stream morphology, gradient, and the character of the basins within these subsections. Mean land surface slopes from sea level to the divide separating the North Coast basins from the Willamette Valley area are 0.013 to 0.020. In the mid-coast area this slope ranges from 0.025 to 0.072. Crests in the north coast are 24 to 29 miles from the ocean and in the mid-coast they are 5 to 9 miles from the ocean. Most distinct peaks throughout the Coast Range vary from 2000 to 3400 ft elevation. Mary's Peak at 4097 is the highest. Many high peaks are in close proximity to the coast line. Low mountains dominate the Coast Range with <20% of the land area comprised by gently sloping land (Proctor et al. 1980).

(f) Culture

The Coast Range of Oregon is characterized by logging and industry related to forest products. Recently, harvest of timber has been heaviest in the southern half of the region. Large tracts of the Coast Range are retained in Federal (Siuslaw Forest) and State (Tillamook Burn) lands. The majority of the high productivity lands are privately owned. Commercial and sport fishing in the ocean and freshwater yield a large local source of income. Hunting is another primary recreational activity in the region. There is no major port or trading center to act as a hub for ocean commerce in the coastal region. Mining, except for sand and gravels, is of limited importance in the region. Commercial retail centers in the Coast Range are of only local influence. The trade routes and centers through the Willamette Valley are of primary importance in maintaining the coastal hinterlands. Lowland areas of the Coast Range are used for sheep and cattle pasture. Even though the climate is favorable with a long growing season, the cool temperatures of the region combined with topographic constraints on farming make the region a poor agricultural area (Highsmith and Kimerling 1979).

3. The Tillamook Burn area of the North Coast of Oregon

(a) <u>Soils</u>

Soils of the Tillamook Burn were mapped from a base map at a scale of 1:126000 by the Soil Conservation Service (SCS) in a study of sedimentation in Tillamook Bay (USDA 1978). The SCS survey, though fairly generalized, is based on 7th approximation (USDA) soil classification standards. Westberg et al. (1978), in a more detailed soil survey, mapped soil series units at 1:43500. They employed a different set of principles and guidelines for classification, this making tentative any conversion from their soil series general descriptions to those used by the SCS.

Soils of the Tillamook Burn can be described as order Inceptisols, sub-order Umbrept, and are generally Haplumbrepts, with Cryumbrepts at higher altitudes. The complete set of differentiating characters used by Westberg et al. to describe soil types are parent rock, depth, texture and structure of topsoil and sub-soil, rock content, and altitude range. Based on the SCS survey, the major soil series for the study watersheds are Kilchis, Klickitat, and Hembre, with contributions from Valsetz, Yellowstone, Trask, and Blachly. The soils are mapped only as associations. By means of Westberg et al.'s system, a total of 15 different soil series were identified in the 11 study watersheds. Ten of these soils comprised >5% of the total area in at least one watershed. The characters most effectively distinguishing soil series in this area are geology, depth to bedrock, coarse rock fragments, and clay content. Except for geology these factors are expected to vary with slope, aspect, and altitude, through control on erosion, soil temperature regime, degree of weathering, and moisture retention. Soil series in this area may be discriminated on as little as one of these main soil characters. For Haplumbrepts or Cryumbrepts, there is the distinction between skeletal/non-skeletal (i.e. percentage rock fragments), coarse-loamy/fine-loamy (texture), typic/lithic (depth to bedrock)(Huddleston 1979). For example, in Westberg et al.'s survey, Rye (RJ) and Neddona (ND) are the lithosolic counterparts to Killam (KM) and Humbug (HC) soils, respectively. The ND/HC association develops on volcanic breccia and basalt, while RJ/KM develops on basalt. The Osweg (OW) series is the lithosolic counterpart to Jewell (JW).

Four of Westberg's mapped soil series (RJ, ND, KM, and HC) are highly correlated with site mapping of the Klickitat-Kilchis association of the SCS system. This implies that Westberg's system is more rigorous in soil series distinctions. When detailed profile descriptions between soil series in the Westberg et al. and the SCS systems are compared, a close relationship occurs only between Rye/Klickitat and Neddona/Kilchis. Other relationships are general ones at the sub-order level. It was hoped that direct conversions could be made between the two systems so that soil hydrologic properties, which are more fully tested in the SCS system, could be transferred to the more detailed mapping of Westberg. The difficulties in establishing these relationships make inferences about hydrologic properties tentative.

(b) Geology

Parent material of the Tillamook Burn study areas is predominantly Eocene basalt of the Tillamook volcanic series (Baldwin 1981). The complex of auxiliary rock types associated in this area is basalt alluvium, Eocene volcanic breccia and siltstone, and Miocene basalt and sandstone (Westberg et al. 1978). Volcanic flows were predominantly sub-marine, but sub-aerial flows also occurred.

(c) Topography

The landforms of the study areas are generally mountainous with moderate (20 to 40%) to steep (40 to 65%) slopes (Westberg et al. 1978). Floodplains are very narrow and tightly confined by rocky valley sidewalls. Potential for meandering is generally low. Stream channels are often bordered by river terraces that are up to 1 to 2 m above normal high water. Ridges are typically very sharp, owing to the presence of resistant basalt. Rock outcrops are common. Topography becomes gentler on a north to south gradient, this being associated with a slight increase in percentage of sandstone/siltstone. Minimum elevations of the 11 study watersheds range from 240 to 840 feet while maximum elevations range from 2640 to 3700 feet.

(d) Water

The main Wilson River near Tillamook has a drainage area of 161 mi^2 and a mean annual discharge of 1171 cfs. The highest monthly mean flows occur in December and average 2723 cfs. The 7-day peak flow with a 10 year recurrence interval is 10,000 cfs. The 7-day low flow of 10 year recurrence interval is 60 cfs. Total runoff comprises roughly 77% of annual precipitation (Benoit 1978). The 2-year and 50 year peak flows for the main Wilson river are 17400 cfs and 33200 cfs, respectively (Orsborn 1980). Using Orsborn's equation based on drainage area, mean annual precipitation, and relief for estimation of 2 year and 50 year peak flows for the South Fork Trask study watershed as an example, values of 1485 and 3893 cfs, respectively were derived.

(e) Culture

The Tillamook Burn area has much the same potential for cultural development as does the remainder of the Oregon Coast Range. However, the succession of fires in 1933, 1939, 1945, and 1951 that burned the forests inland of Tillamook devastated the local timber industry. The first three fires killed an estimated 13 billion board feet of timber (Oregon State Forestry Department 1980). These were the last extensive stands of old growth timber in the Coast Range. Harvesting of second-growth trees in areas of high site class may begin within the next 10 years. Road building and tree removal caused extensive damage during salvage logging after the fires. Landslide scars and logging roads and trails are pervasive.

(f) Vegetation

Red alders are dense in areas not replanted with firs, in heavily disturbed areas, and in sites with severe microclimatic conditions. Alders are predominant along all stream channels and attain diameters of 50 cm DBH. Conifer stands are dominated by Douglas fir with a minor component of western hemlock and western redcedar.

4. Selection and Preliminary Classification of Watersheds

The classification system proposed here is a combination of the systems of Bailey (1976) and Warren (1979). Bailey's classification down to the level of district is used as a starting point. His system utilizes a single variable at a time. The present classification below the district level follows the hierarchy: zone, sub-zone, major drainage, watershed system, network, segment, reach. Not all sub-capacities at each hierarchical level are used as proposed by Warren (1979) because of the lack of data on many variables. Topography and soils are emphasized for classification of the watersheds. This still produces a multi-variable classification but with fewer sub-capacities represented directly.

The present classification scheme is represented conceptually in Figure 6. Bailey's province level identifies broad vegetation regions (e.g. Pacific Forest) with the

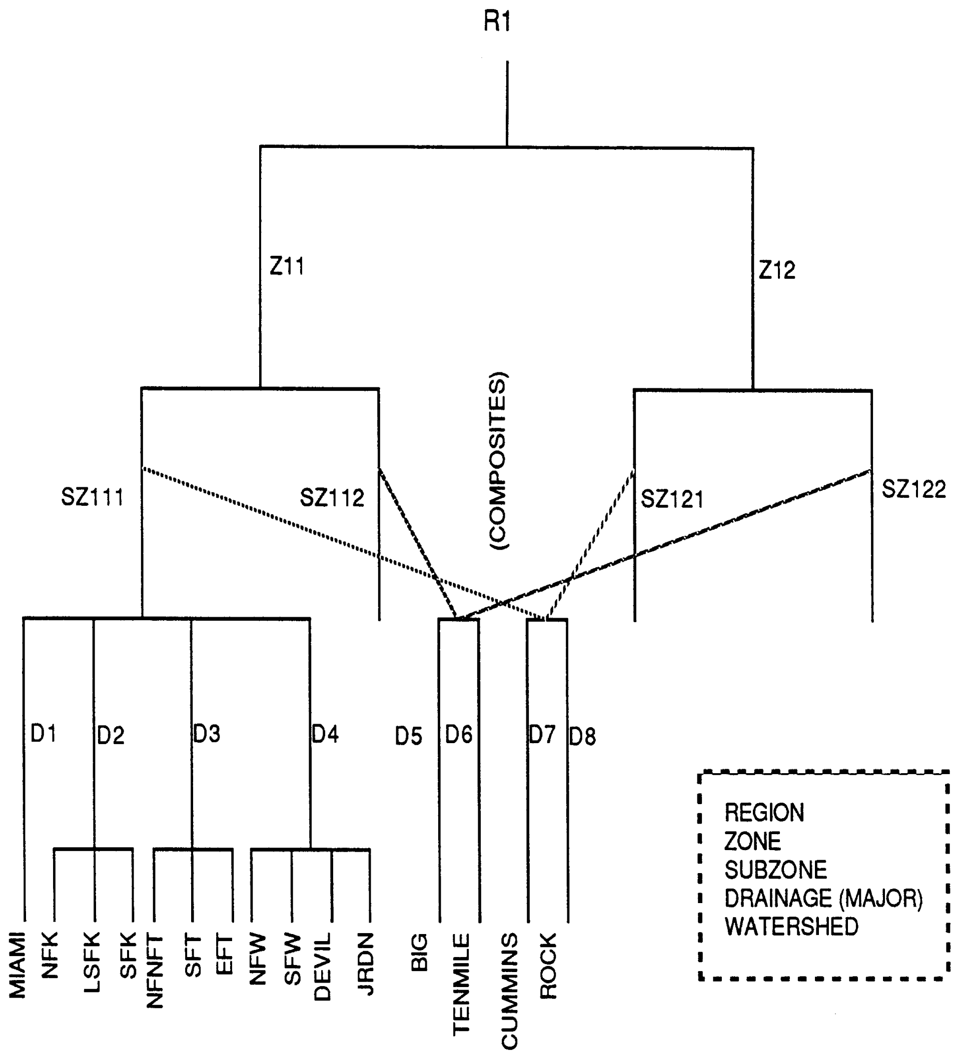


Figure 6. Generalized classification from region to watershed levels as represented by the contrast in streams of the north- and mid-coast areas of Oregon.

Figure 7. Overlays of hypothetical lithologic map, major environmental gradients, and watersheds to illustrate general principals of watershed classification. See Table 3 for hypothetical classification of these sample watersheds by hierarchical level and variables.

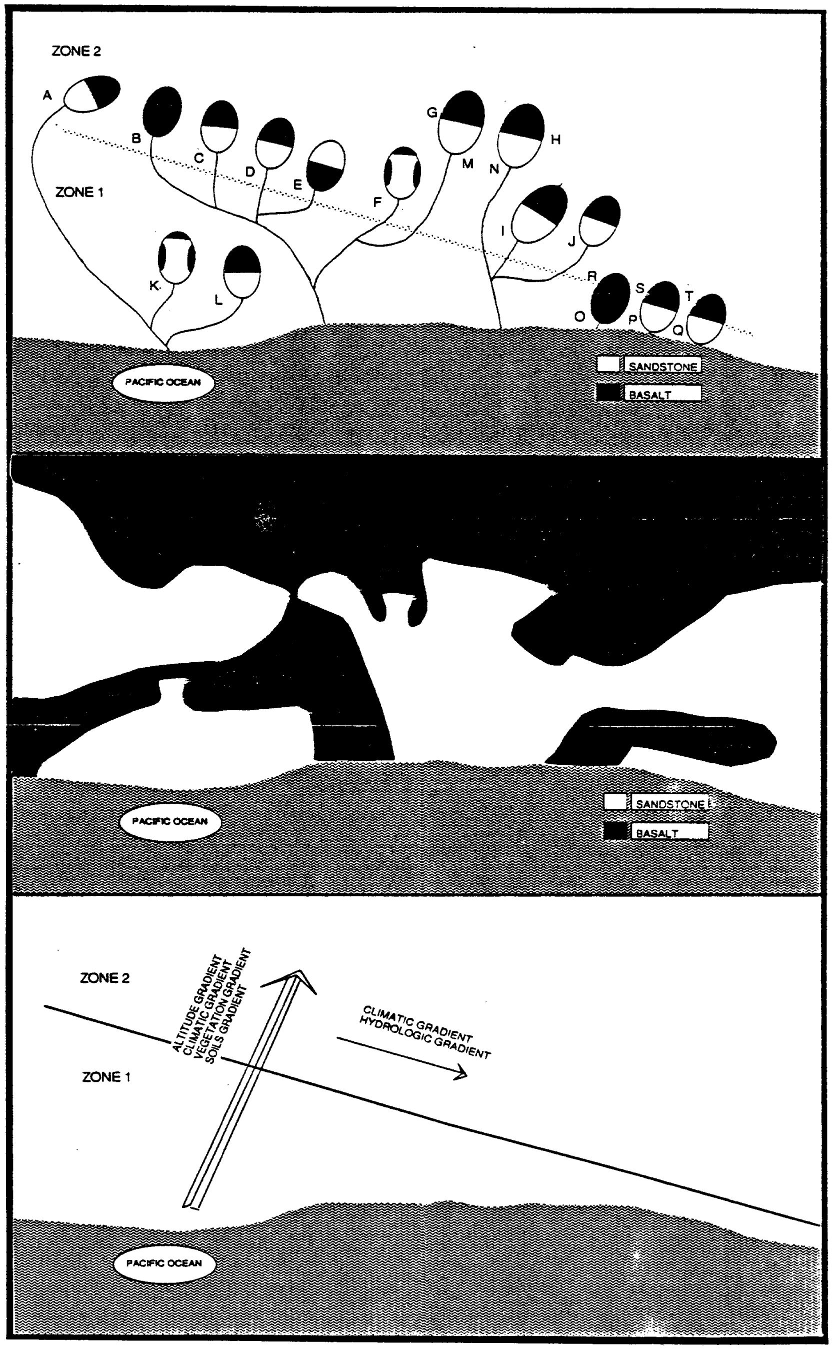

ZONE 2
A
B
C
D
E
F
G
M
N
H
I
J
R
S
T
O
P
Q
ZONE 1
K
L
PACIFIC OCEAN
SANDSTONE
BASALT
PACIFIC OCEAN
SANDSTONE
BASALT
ZONE 2
ALTITUDE GRADIENT
CLIMATIC GRADIENT
VEGETATION GRADIENT
SOILS GRADIENT
CLIMATIC GRADIENT
HYDROLOGIC GRADIENT
ZONE 1
PACIFIC OCEAN

Figure 7

same types of "zonal" soils. His classification system is essentially a monothetic divisive technique. The province level is termed "region" in Figure 6. Bailey's section level (his lowest level) identifies Kuchler's potential vegetation types. In Figure 6, zone 1 (outer coast) is the Sitka spruce-cedar-hemlock forest and zone 2 (inner coast) is the cedar-hemlock-Douglas fir forest typical of the vegetation zonation on the Oregon coast. These zones are closely associated with unique climatic and topographic features. The zones could further be sub-divided on the basis of lithologic units to create sub-zones, where lithology is known and relatively uniform. If lithology is very heterogeneous, areas of different percentage composition could be defined. In Figure 6 SZ111 and SZ 121 are basalt; SZ112 and SZ122 are sandstone. Drainage system is the level below sub-zone. For example, the Wilson, Trask, Miami, and Kilchis drainages are separate systems with no freshwater connections. Each is composed of numerous watersheds of various sizes, the largest being the entire drainage. Drainage area and map slope of the downstream reach can be used in preliminary watershed classification. Further classification of watersheds can then employ various substrate capacity variables.

A generalized version of watershed classification in the Oregon coastal area is given by Figure 7 and Table 3. This classification is based on hierarchical level and on types of watershed substrate variables. Specific characterization of hierarchical levels by capacity components has already been given. Development of more precise substrate variables follows this general treatment.

Watersheds A-T are represented in the Region. There are two zones depicted, these representing the outer and inner coastal mountain zones as in Figure 7. Subzones within these zones might be most simply represented by relatively homogeneous lithologic types, for lack of more site-specific data. Lithologic distribution is not specifically watershed-based so watersheds in a zone might represent composites of

Table 3. Hypothetical watershed similarities at various hierarchical levels and with respect to given variables. Classification by hierarchical level defines regionalization by methods similar to Bailey (1976). Classification at the watershed level is by variable (or type of variable). Hypothetical watersheds classified are those depicted in Figure 7.

Hierarchical Level	Region	Zone	Subzone	Drainage System	Watersheds							Network
					preliminary	*classification*						
Variable					Drainage area	Downstream slope	Altitude	Topo-graphy	Basin slope	Spatial	Orient-ation	Structure
Similar Watersheds	All	(A,B,C, D,E,F, G,H,I,J, M,N)	(A,C,D,E, F,M,N,I, J)	(A,K,L)	(A,B,C,D,E, F,G,H,J,K,L, O,P,Q)	(A,B,C,D,E)	(A,B,C, D,R,F,I, J)	(L)	(M,N,I)	(F,K)	(A)	(O,P,Q)
		(K,L)	(B,G,H)	(B,C,D,E, F,M,G)	(M,N,I)	(F,J)	(G,H)	(I)	(J)	(E)	(others)	(others)
		(O,P,Q)	(K,L)	(H,N,I,J)	(R,S,T)	(K,L,O,P,Q)	(M,N)	(others)	(others)	(B,O)		
		(R,S,T)	(R,S,T)	(O), (P), (Q)		(G,H)	(R,S,T)			(others)		
			(O,P,Q)	(R), (S), (T)		(M,N,I)						
						(R,S,T)						

subzones. Six separate major drainage systems are shown having no surface freshwater connections (Fig.7, Table 3). Within a drainage system, watersheds are given a preliminary classification by means of drainage area and bed slope of the downstream reach. Further classification of watersheds was done with the aid of various types of substrate capacity variables such as basin altitude, topographic structural indices, spatial organization of lithologic units, basin orientation, and network structure. The smallest hypothetical watersheds illustrated in Figure 7 represent the study watersheds in this work.

Even though not all watersheds (basins) may be in the same subzone, their similarities or differences can be revealed through succeeding stages of classification by watershed variables. Basins that are similar at any level of classification or according to any given variable were placed in parentheses in Table 3. In this example, watersheds C and D are similar with respect to all hierarchical levels and variables. Watershed F differs only by one characteristic.

Within the Tillamook Burn area of northwestern Oregon, basins and their downstream reaches were selected according to a preliminary classification based on drainage area and map stream slope. Because it is not possible to get these two features equal for any two watersheds, a balance was sought by increasing or decreasing drainage area from the 10 mi^2 area desired as a study area so that channel slopes in a 0.5 mi reach at the mouth of the basins would be similar. All basins selected were drawn from a zone classified as fairly homogeneous in capacity, according to the 5 components of capacity. Drainage areas of the 11 basins chosen for study ranged from 7.1 to 14.3 mi^2 (mean of 10.4). Channel slopes of the 0.5 mi downstream reaches ranged from 0.009 to 0.035 (Table 4). Aside from the Devil's Lake Fork of the Wilson River, the other watersheds had areas of 7.1 to 13.0 mi^2 and channel slopes of 0.009 to 0.02.

Table 4. List of variables used in preliminary classification of watersheds.

Watershed	Drainage Area	Map Slope	Surveyed Slope (m^2)
MIAMI	2.356 E7	0.016	0.0138
NFK	2.013 E7	0.021	0.0151
LSFK	2.508 E7	0.016	0.0124
SFK	1.834 E7	0.013	0.0090
NFW	2.542 E7	0.023	0.0231
SFW	3.363 E7	0.014	0.0189
DEVIL	3.701 E7	0.031	0.0352
JRDN	3.338 E7	0.021	0.0200
NFNFT	2.470 E7	0.020	0.0162
SFT	2.542 E7	0.016	0.0152
EFT	2.956 E7	0.015	

A summary of the general associations among watersheds is given in Figure 8. These associations were inferred from (1) regionalization using methods similar to Bailey, (2) preliminary watershed classification using drainage area and stream bed slope in the downstream 0.5 mile, (3) watershed analysis using multivariate analysis, (4) watershed characterization by soils data, and (5) measures of drainage network structure. Although only cluster analysis provides a true hierarchical structure, hierarchical associations were subjectively assigned from results of other methods, judging from, for example, spatial proximity of cases or centroids in multivariate space. Figure 8 is intended only to show how the concept of watershed associations emerges with each new method of examining watershed character.

On the basis of the preliminary classification alone, using variables drainage area and slope, the Devil's Lake Fork of the Wilson was different from the remainder of the basins, even though the lithology and mean annual rainfall were similar to the other watersheds. Given a preliminary classification based on drainage area and bed slope of the downstream reach, basins were further classified to establish a basis for evaluation of differences observed in reach capacities and performances. Multivariate analysis of watersheds included (1) discriminant analysis in which group centroids (in which one group is a set of observations on all triangular facets of a watershed) are displayed and variables contributing to the discriminating power are revealed, (2) classification procedures such as cluster analysis in which a hierarchical structure is derived mathematically from the data, and (3) ordination procedures such as factor analysis and principal components analysis. Figure 8 shows associations among watersheds inferred from similarities in certain variables or from the proximity of sets of watersheds in multivariate space.

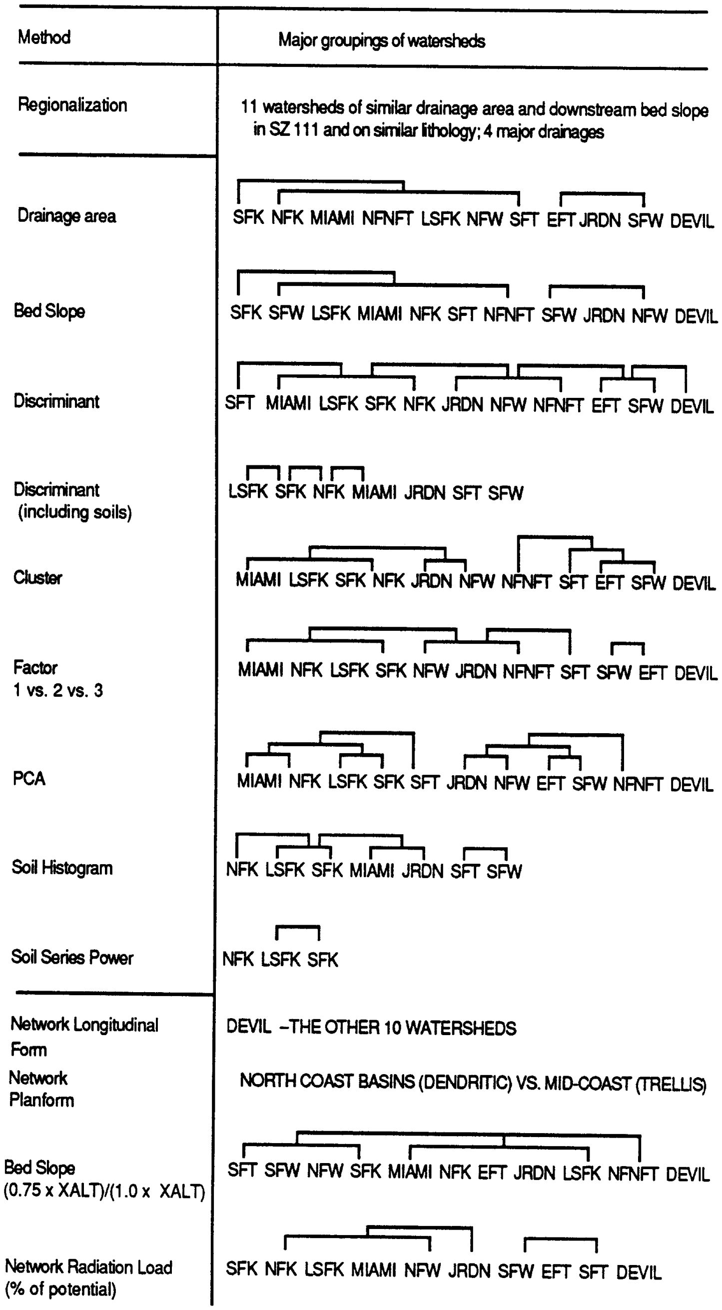


Figure 8. Summary of results of various methods of watershed and stream analysis to be illustrated in Results and Interpretation. (Note: Hierarchical structure has been subjectively inferred from original results, except for cluster analysis.)

The 11 study basins all have combinations of the same geologic materials, i.e. Eocene basalt and sedimentary material derived from the basalt. These basins have at least 90% Eocene basalt except for South Fork Trask which has approximately 60%. The geology of North Fork North Fork Trask, East Fork Trask, North Fork Wilson is not well known but has been crudely mapped. Data on the major watersheds in the Tillamook Burn area from Benoit (1978) are provided in Appendix E.

Given a set of watersheds of a certain drainage area and downstream slope, the problem is how to further classify these. Methods for doing this are developed in this work.

B. CLASSIFICATION AND ANALYSES OF WATERSHEDS

1. Preliminary Discriminant Analysis of Watersheds

After selection of study basins within a region, data were collected on these basins using an altitude grid as a primary source. Computer analysis of the altitude grid yielded measures of slope, aspect, mean altitude, and daily radiation load per m^2 at the winter solstice and the equinox for all smallest triangles produced from the grid. These data plus soil series for each triangle were considered the primary data set.

A discriminant analysis using basins as groups and all triangles per basin as cases was run with variables AVALT (mean altitude of triangular facet), L, M, and N (direction cosines of the normal vector to the triangular facet that are calculated from the slope and aspect of the triangular facet), RAD1 (daily solar radiation load per unit area on winter solstice, i.e. $J/m^2/d$), and RAD2 (daily solar radiation load per unit area on the equinox, i.e. $J/m^2/d$)(Fig. 9). Classification based on discriminant analysis separated the

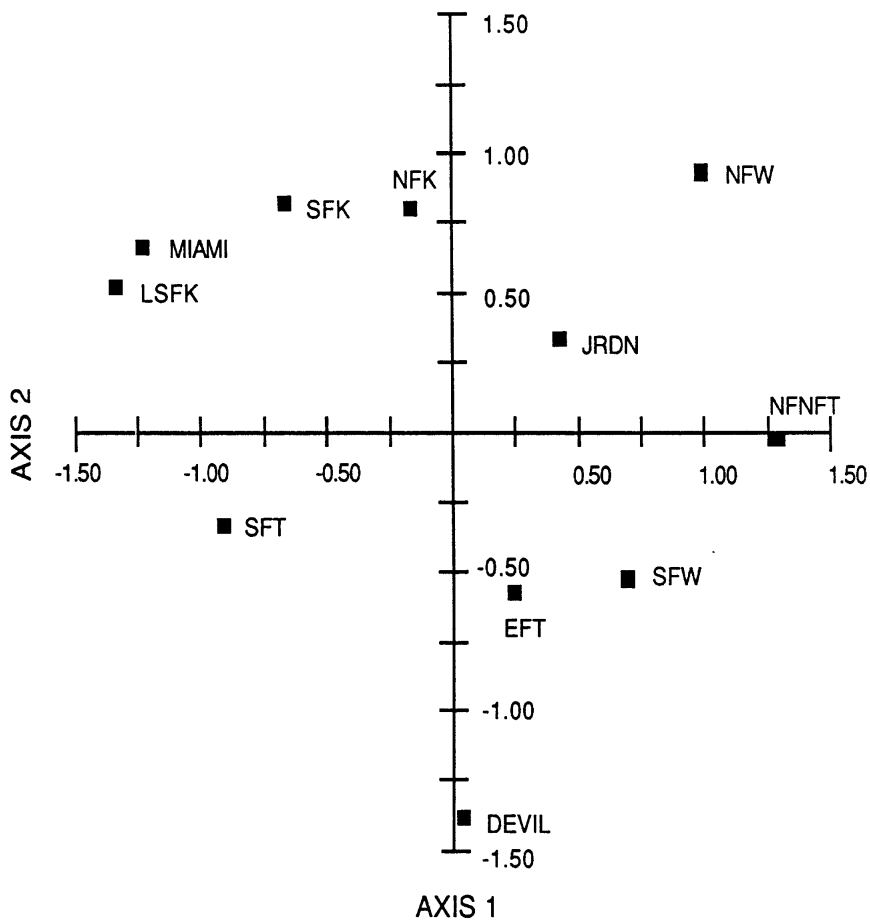


Figure 9. Group centroids of discriminant analysis of 11 watersheds on axes 1 vs. 2 using variables AVALT (mean altitudes of triangular facets), L, M, and N (direction cosines of normal vector to each triangular facet), and RAD1 and RAD2 (daily radiation load in J/m^2/d on winter solstice and the equinoxes for triangular facets).

11 basins primarily on the basis of altitude and slope. The first two discriminant axes captured 96.4% of the among group variance in the canonical variables. This analysis demonstrates the similarity among the Miami and three Kilchis watersheds. North Fork Wilson, East Fork Trask, and Jordan Creek watersheds have higher than average altitudes and slopes so these might be considered to form a group. The North Fork North Fork Trask watershed has the highest mean altitude but intermediate mean slope. The South Fork Trask and South Fork Wilson watersheds have lower than average mean slopes but the South Fork Wilson has a much greater altitude. The Devil's Lake watershed is intermediate in altitude but has a very low mean slope.

The discriminant analysis represents relationships among watersheds as a continuum. Similarity is relative to the axes chosen, implied similarity depending not only on the groups but also on the set of variables chosen to discriminate them. If the variable set adequately subsumes the potentials as well as the states of the systems, then additional variables would not be expected to lead to significant explosion of clusters in discriminant space. The watersheds chosen, being all from the same region, are apt to have a great deal of similarity. Inclusion of basins from sampling a broader spatial scale would probably increase relative differences.

Many aspects of watershed and stream potential were not represented by the six variables used in the initial discriminant analysis. Site physical properties were only topographic and did not include soil or geology. Existing geologic maps for the Tillamook Burn study area are not as detailed as soil series maps so were not used in statistical analyses. Soils series were added to site topographic data for each slope facet in the 7 (of 11) watersheds for which sufficient soil maps existed.

A discriminant analysis of these seven watersheds with the original six variables plus soil series was examined in three dimensions (Fig. 10). The first discriminant axis

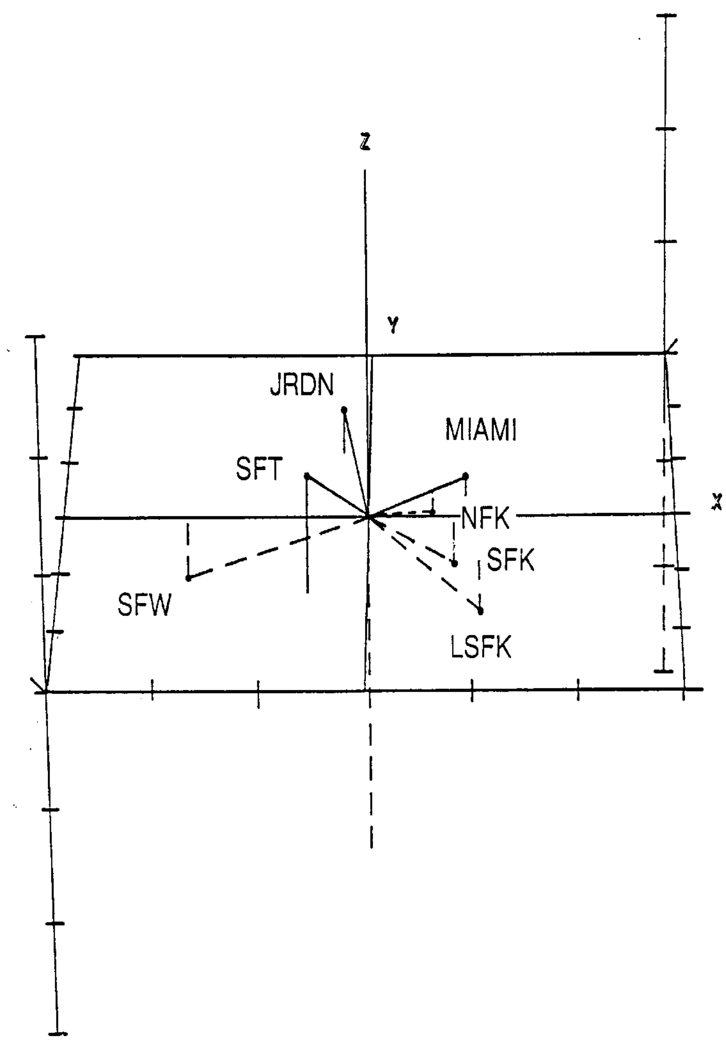


Figure 10. Three dimensional plot of discriminant analysis of 7 watersheds using variables AVALT (mean altitudes of triangular facets), L, M, and N (direction cosines of normal vector to each triangular facet), RAD1 and RAD2 (daily radiation load in $J/m^2/d$ on winter solstice and the equinoxes for triangular facets), and soil series presence.

discriminated basins primarily on the basis of AVALT and N or (sin slope), judging from back correlations with original variables. Axis 2 was most highly correlated with Killam (KM) and Rye (RY) soil series occurrence. Axis 3 was most highly correlated with Jewell (JW), Watseco (WC), and Neddona (ND) soil series occurrence. Axes 1 and 2 account for 78% of the among group variance; adding the third axis accounts for a total of 90% of the variance. The first two axes of this analysis show the Miami and Kilchis watersheds as a distinct group as before. The third axis distinguishes the Miami watershed from the Kilchis watersheds, most obviously by the total lack of ND soils in the Miami. The South Fork Trask watershed is distinctly different from the other basins in having intermediate altitude and slope and the highest KM soil series presence. The Jordan Creek watershed represents the low extreme of KM soil coverage. The South Fork Wilson watershed has KM presence similar to the Kilchis and Miami watersheds but it is much higher in altitude. Axis 3 differentiates Jordan and South Fork Trask watersheds from the South Fork Wilson most obviously on the basis of the relatively higher JW soil presence in the South Fork Wilson. Discriminant analysis, representing basin relationships in continuous multidimensional space, may with a small number of samples make many basin classes appear to exist. The summary of classification results (Fig. 8) shows the fine distinctions among the Miami and three Kilchis watersheds that are primarily based on soils differences. Jordan, South Fork Trask, and South Fork Wilson by contrast are fairly distinct on the basis of two of the three axes.

2. Further Analysis and Definition of Watersheds

(a) Cluster Analysis

Further analysis of the differences among basins was pursued by focusing on a larger set of variables that described each basin as a whole rather than as a collection of facets. Some of these basin variables were statistical measures of dispersion (mean, skewness, kurtosis, variance, coefficient of variation) of data collected by facet (slope, aspect, and altitude). Other variables derived from the grid included Fisher's dispersion index and R1, both statistical evaluations of the dispersion of normal vectors to all plane surfaces of the triangular facets of a basin.

The complete set of 24 variables was employed in a cluster analysis (K-means clustering, BMDP 1983) of the 11 basins. This analysis did not include soils data. Each variable was represented by one value for each watershed, whereas in the discriminant analysis each variable was represented by many values per variable equal to the number of triangular facets per basin. The K-means cluster routine is a non-hierarchical, divisive clustering algorithm. Data were standardized to unit variance and cases were reallocated to clusters at each step in the splitting process.

After the first iteration, two clusters were produced that effectively separated the more rugged basins (Miami, North Fork Kilchis, Little South Fork Kilchis, South Fork Kilchis, North Fork Wilson, and Jordan) from the other basins, which had gentler topography. The three group stage in clustering resulted in (Devil's Lake),(the three Trask watersheds and South Fork Wilson) and (the three Kilchis watersheds, plus Miami, North Fork Wilson and Jordan) as clusters. After division into four clusters, the resulting groups were (Miami, the three Kilchis watersheds, North Fork Wilson, and Jordan), (Devil's Lake Fork of the Wilson), (North Fork North Fork Trask), and (South

Fork Trask, East Fork Trask, and South Fork Wilson). The next division split North Fork Wilson and Jordan from their previous cluster.

At the five group stage of subdivision, the Euclidean distances among groups were greatest between Devil's Lake and all other groups. The greatest of these distances with five groups (13.10) was Devil's Lake vs. Miami and the Kilchis watersheds. The smallest distance (3.89) was between the Miami and Kilchis watersheds vs. North Fork Wilson and Jordan. North Fork Wilson and Jordan are closer to North Fork North Fork Trask than the North Fork North Fork Trask is to South Fork Trask. Based on five clusters, the maximum F-ratio for between vs. within cluster mean squares was found for Fisher's dispersion index (FISHD), the next greatest F-ratio being for kurtosis of altitude points (KURTALT). These F-ratios describe the differences between clusters with respect to individual variables and not overall differences among clusters. Of the 24 variables, the only ones not showing significant ($P<0.05$) F-ratios were DD (drainage density), RADX (mean daily solar radiation intensity for all triangular facets per basin on the day of the winter solstice), XALT (mean of all altitude points for a basin), and GMALT (mean of all mean altitudes of triangles per basin).

The BMDP2M agglomerative clustering program is a hierarchical procedure for combining cases into clusters. Euclidean distances were used to compute the average distance. At each step the two clusters separated by the shortest distance are combined into one cluster. Values of variables in clusters are weighted averages of all cases in the cluster. This clustering routine resulted in similar groupings of watersheds on the basis of the 24 variables (standardized to z-scores) as was reached in K-means clustering, although the affiliations among watersheds are simpler to visualize (Fig. 11) owing to the hierarchical structure. The large amalgamation distance between Devil's Lake Fork

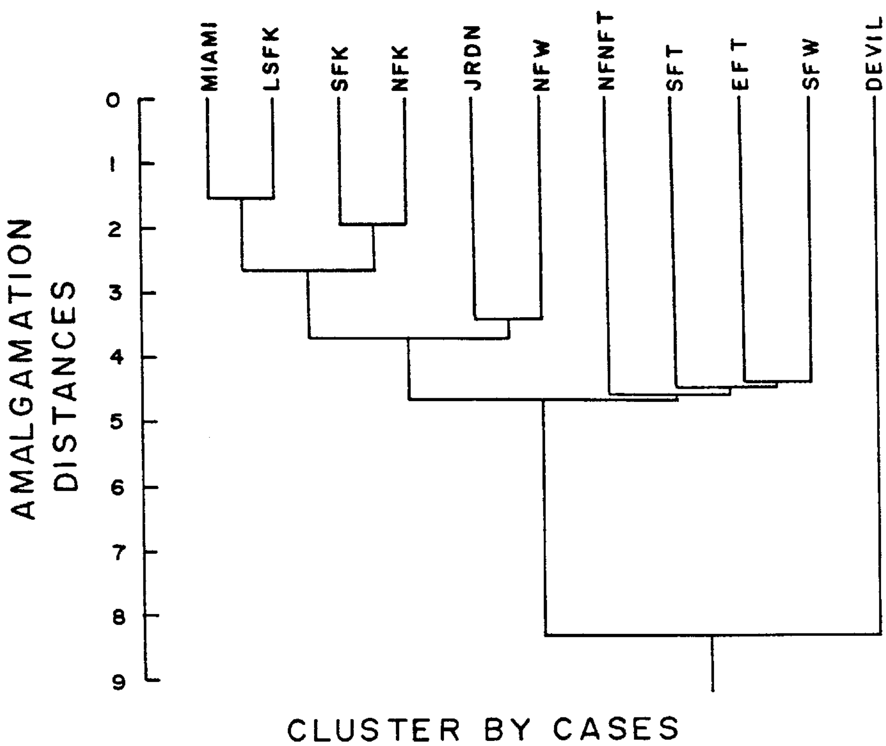


Figure 11. Amalgamation distances (Euclidean) for cluster analysis by cases (BMDP 1983) for 11 watersheds using 24 variables.

of the Wilson and all the other watersheds (8.3) compared with that between the two other major groups (4.6) shows the magnitude of differences among the groups.

(b) Factor Analysis

A factor analysis was then run on 21 of these 24 variables after eliminating the three variables involving coefficient of variation. The factor analysis was performed on standardized data and used a correlation matrix, extracting principal components that were then rotated obliquely (d-quartimin method). Dimensionality was effectively reduced by this procedure, capturing 89.4% of the variability in three factors, 94.6% in four factors. The variables that loaded most heavily on the rotated factors in decreasing order of loading on each factor are: factor 1--GAPLA, SLPTPT, GMSL, RADSD, R1, MAXDIR, SDSL, SKEWSL, DD, RADKRT; factor 2--KURTSL, KURTALT, SD1, STDALT, FISHD; factor 3--XALT, GMALT, HI; factor 4--RADSKW, RADX, SKEWALT. The sorted rotated factor loadings (factor pattern) are given in Table 5. The first four factors seem to be indicators of (1) terrain ruggedness, degree of dissection, and heterogeneity of slope gradient and aspects, (2) relief and slope form, (3) mean altitude, and (4) basin orientation.

The first two factors included the majority of variables. Factors 1 and 2 are not clearly distinguishable. Factor 1 has two pairs of variables that were intended to be replicative, i.e. SLPTPT and GMSL, and MAXDIR and DD. Factor 2 also has a pair of replicative variables, STDALT and SD1. Variables that loaded on factor 1 express the drainage network (e.g. DD and MAXDIR). The greater the mean basin slope (GMSL), the greater the drainage development (DD). It is also easily understood that the greater mean slope (GMSL) and standard deviation of slope (SDSL), the greater the ratio of

Table 5. Sorted rotated (oblique) factor loadings derived from factor analysis (BMDP 1983) of 11 watersheds using 21 variables. Loadings less than 0.250 were replaced by 0.0 for clarity.

Variable	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**
GAPLA	1.056	0.000	0.000	0.000
SLPTPT	0.968	0.000	0.000	0.000
GMSL	0.957	0.000	0.000	0.000
RADSD	0.924	0.000	0.000	0.000
R1	-0.891	0.000	0.000	0.000
MAXDIR	0.864	0.000	0.000	0.000
SDSL	0.826	0.000	0.000	0.000
SKEWSL	-0.816	0.000	0.000	0.000
DD	0.775	0.000	-0.469	0.000
RADKRT	-0.672	0.372	0.000	0.000
KURTSL	0.000	1.003	0.000	0.000
KURTALT	0.000	0.974	0.000	0.000
SD1	0.000	-0.838	0.275	0.000
STDALT	0.328	-0.730	0.000	0.000
FISHD	-0.500	0.604	0.000	0.000
XALT	0.000	0.000	0.918	0.000
GMALT	0.000	0.000	0.904	0.000
HI	0.310	0.000	0.824	-0.339
RADSKW	0.000	0.000	0.000	0.981
RADX	0.000	0.000	0.000	-0.960
SKEWALT	0.000	0.442	-0.412	0.433

ground area to planar area (GAPLA). Factor 2, being associated highly with standard deviation of altitude, (SD1, STDALT), seems to reflect relief. Kurtosis of altitude and slope (KURTALT, KURTSL) probably indicate overall basin form. Because FISHD, a measure of terrain roughness, is in factor 2 and many other variables in factor 1 seem to reflect aspects of roughness (e.g. DD, GMSL, SLPTPT, GAPLA, R1), one can interpret an overlap in factors 1 and 2. It seems that basin roughness varies with slope morphology and that a certain mixture of the two effects is represented in the first two factors.

Factor scores were plotted for the first three factors for each watershed (Fig. 12). Like the cluster analysis, the factor analysis clearly distinguishes Devil's Lake from the remainder of the basins. This separation is made on the basis of factors 1 and 2. The set of four basins including the Miami and the three Kilchis streams is a distinct cluster relative to factors 1, 2, and 3. North Fork Wilson, Jordan, and North Fork North Fork Trask is a fairly distinct cluster on the basis of factors 1, 2, and 3. North Fork Wilson and Jordan were closer to the set of four than was North Fork North Fork Trask, as also shown by cluster analysis. The remaining three basins formed a clear set, this being distinguished from the set of four primarily by factor 1 and internally differentiated by factor 3.

The value of mean altitude and basin orientation in differentiating ecologically or physically important rather than statistically significant differences could be questioned. For example, North Fork Wilson, Jordan, and North Fork North Fork Trask are distinctly separated from the Miami and three Kilchis watersheds with respect to factor 3 (altitude and hypsometric integral). The fact that mean altitude plays an important role in differentiating these basins can be seen in the different soil series found. The summary of classification results (Fig. 8) shows that factor and cluster

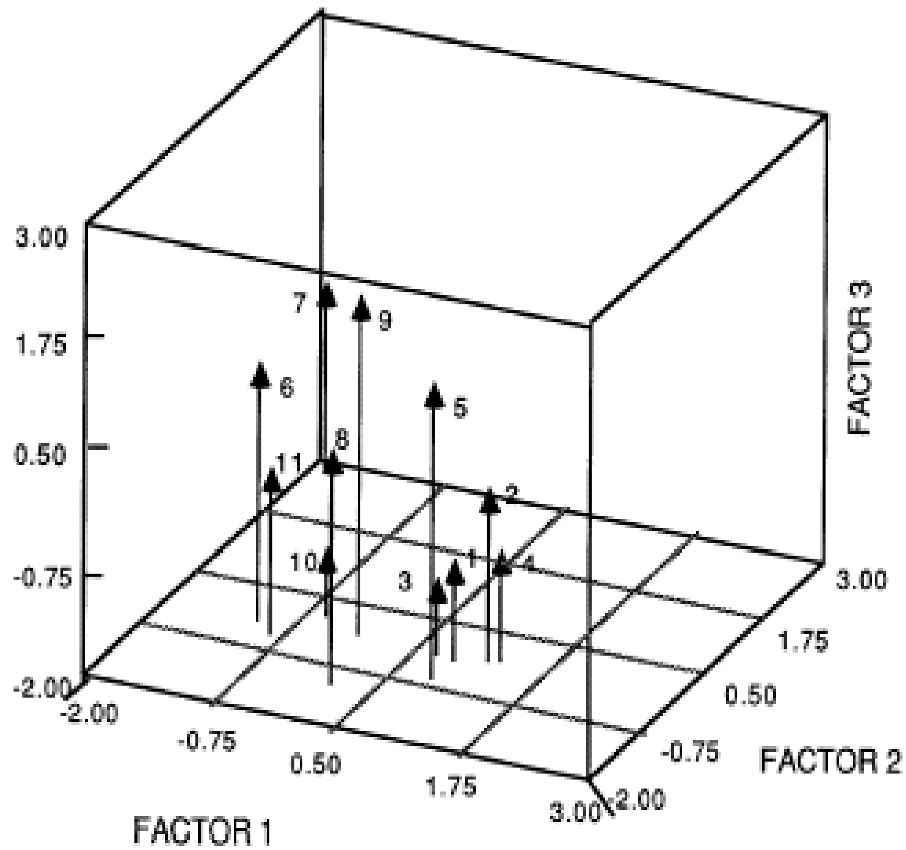


Figure 12. Factor analysis (BMDP 1983) with oblique rotation for 11 watersheds using 21 variables. Three-dimensional plot of first three factor axes.

analyses are very similar in the watershed associations depicted. Factor analysis differed primarily in its representation of the affiliation of North Fork North Fork Trask and South Fork Trask. These two watersheds have some unique characteristics, making unclear their similarity to other basins.

(c) Correlation

Correlations among watershed variables were explored (Table 6). In some cases these comparisons were made between variables determined by standard methods and by methods developed for application to the grid system. The high degree of intercorrelation suggests that (1) simple means often exist for deriving indices that were previously time consuming to measure, (2) the altitude grid is a sufficient data set to express the information content of a set of variables derived without the grid, and (3) physical constraints to geomorphic development result in mutual adjustment of structural variables.

The consistency with which watershed groups were identified despite the variety of classification methods and composition of variables sets indicates a high degree of co-determinacy of system properties and perhaps overall control by a set of relatively universal factors. Part of the value in this effort to classify watersheds is to evaluate a minimal set of variables for its ability to adequately represent system potential and to serve as an index for other variables not included. Even with the reduction of dimensionality achieved, there was still considerable correlation among variables retained. A subset of these basin variables that may be useful for local terrain differentiation cannot be used indiscriminantly (i.e. regardless of scale or place) as a classification tool, because a given mean slope, for example, would act differently

Table 6. Correlation coefficients for intercomparisons among topographic structure variables. (Note: See Table 2 for a detailed description of these variables.)

	FISHD	R1	DD	MAXDIR	GMALT	SD1	GMSL	SDSL	HI	SLPTPT
FISHD		0.783	-0.584	-0.784	0.411	-0.806	0.891	-0.917	-0.236	-0.886
R1			-0.841	-0.742	0.509	-0.326	-0.845	-0.805	-0.106	-0.852
DD				-0.734	-0.743	-0.082	0.695	0.676	-0.304	0.707
MAXDIR					-0.605	0.539	0.925	0.892	0.038	0.925
GMALT						0.028	-0.428	-0.381	0.623	-0.431
SD1							0.653	0.699	0.417	0.642
GMSL								0.965	0.220	0.999
SDSL									0.259	0.962
HI										0.211
SLPTPT										

	GAPLA	XALT	KURTALT	SKEWALT	CVALT	STDALT	KURTSL	SKEWSL	CVSL	RADX	RADSD	RADKRT	RADSKW	RADCV
	0.821	0.114	0.917	0.639	-0.774	-0.880	0.891	0.888	0.856	0.976	-0.887	0.939	0.017	-0.828
	-0.840	0.315	0.564	0.481	-0.628	-0.477	0.498	0.791	0.824	-0.213	-0.857	0.830	0.040	-0.756
	0.695	-0.641	-0.387	-0.050	0.676	0.243	-0.326	-0.587	-0.619	0.020	0.719	-0.624	0.181	0.693
	0.913	-0.443	-0.587	-0.222	0.863	0.660	-0.556	-0.913	-0.846	0.147	0.932	-0.875	0.002	0.840
	-0.384	0.948	0.343	-0.270	-0.832	-0.084	0.235	0.478	0.454	0.141	-0.481	0.407	-0.258	-0.512
	0.578	0.308	-0.857	-0.619	0.498	0.983	-0.878	-0.657	-0.761	0.074	0.638	-0.734	-0.079	0.598
	0.988	-0.209	-0.692	-0.456	0.762	0.774	-0.640	-0.940	-0.945	0.153	0.993	-0.938	0.034	0.898
	0.948	-0.145	-0.750	-0.534	0.722	0.800	-0.744	-0.869	-0.916	0.144	0.945	-0.930	-0.011	0.860
	0.223	0.730	-0.095	-0.782	-0.224	0.372	-0.226	-0.168	-0.209	0.529	0.150	-0.292	-0.567	-0.061
	0.989	-0.214	-0.684	-0.447	0.759	0.766	-0.631	-0.938	-0.942	0.152	0.994	-0.936	0.039	0.900
GAPLA		-0.194	-0.601	-0.411	0.692	0.707	-0.550	-0.918	-0.887	0.169	0.979	-0.900	0.029	0.876
XALT			0.036	-0.516	-0.653	0.202	-0.069	0.261	0.179	-0.262	-0.262	0.148	-0.288	-0.308
KURTALT				0.584	-0.689	-0.882	0.969	0.698	0.850	-0.028	-0.705	0.808	0.007	-0.682
SKEWALT					-0.080	-0.610	0.665	0.401	0.558	-0.508	-0.414	0.614	0.532	-0.211
CVALT						0.593	-0.612	-0.812	-0.813	0.012	0.795	-0.774	0.115	0.756
STDALT							-0.882	-0.766	-0.857	0.080	0.764	-0.828	-0.039	0.717
KURTSL								0.629	0.788	-0.128	-0.640	0.793	0.156	-0.584
SKEWSL									0.932	-0.164	-0.959	0.930	0.034	-0.864
CVSL										-0.115	-0.949	0.956	-0.022	-0.878
RADX											0.154	0.349	0.928	0.277
RADSD												-0.946	0.036	0.905
RADKRT													0.223	-0.778
RADSKW														0.415
RADCV														

Table 6 (cont.)

within different regions and in association with various local physical properties. While the degree of control of certain variables over system performance may change from region to region, it should be adequate to use unweighted variables to classify basin potential in any region provided a complete set of variables is used. Given more understanding of operations of variables at a particular hierarchical level, variables can be weighted to refine a classification.

The number of possible variables to describe natural systems appears limitless. The selection of variables was done using the experience from other published studies regarding most useful indices in models of system behavior. Variables were selected that appear to incorporate dominant aspects of capacity. Variables included measures of topographic roughness, drainage density, slope, aspect, altitude and radiation load, and the statistical distribution of these variables over the entire basin. Determination of which variables are significant is critical in establishing classification criteria. If a set of variables can be found that can substitute (through consistent positive or negative correlations) for a larger set of variables under a wide range of conditions, these variables would be ideal classificatory variables.

A low degree of terrain roughness (FISHD) was associated with slopes and altitudes clustered near the mean (i.e., positive kurtosis) (Table 6). Also low terrain roughness was correlated with a shift in altitude distribution and slope gradient of facets toward the low end (positive skewness). Therefore, the milder the terrain, the lower the percentage of basin area at high elevation and the lower the percentage of slope facets of steep gradient.

Drainage density and MAXDIR (maximum number of changes in slope direction on the grid) were highly correlated as expected. This correlation indicates that MAXDIR is a good substitute for DD, and the ability to calculate it from the grid makes it a useful variable. Other indices were related positively to DD and MAXDIR such as

SDSL (slope variance), GAPLA (ground surface area-planar area ratio), and RADSD (variability in radiation load). Mean slope (GMSL) is also positively correlated with variance in slope. Roughness of topography (FISHD) was greatest when drainage density was high. Also, there is greater terrain dissection with higher mean slopes and greater roughness.

Although spacing of roughness elements (i.e. breadth of peaks) could be large or small leading to low or to high DD, respectively, local relief at a given geographic scale will be greater the larger the mean slope. Conversely, under a fixed local relief a greater number of changes in slope direction occur on a standard length linear transect as mean slope increases. Within the bounds of a given size drainage area in a given climatic region, rock strength properties might dictate the most probable combinations of relief and slope that would lead to a given drainage density. The correlation of roughness (FISHD) and drainage density (DD) then, though not a necessary one, is probably dictated by limits of rock strength.

Since hypsometric integral (HI) expresses the distribution of area with altitude, it was unexpected that no positive correlation would exist between HI and skew and kurtosis of altitude or slope. HI is highly correlated with mean altitude (GMALT). Since correlation with other variables is minimal for HI, it seems that information contained by HI is relatively unique and not well represented by other measures. If high HI indicates relative youth (Strahler 1952), the correlation with GMALT might indicate a trend to more youthful drainages from the coast inland. If inland basins are being uplifted more rapidly, they may be rejuvenated at a faster rate.

Hypsometric integral was calculated by the Strahler (1952) method using topographic maps and also by a new method, integrating the area under the hypsographic curve drawn from data derived from a cumulative frequency analysis of altitudes from the grid. Except for the Miami watershed, HI's derived by the two methods were similar (Table 7). This indicates the adequacy of using the topographic grid system to derive indices which normally require additional time-consuming effort.

Despite the usefulness of hypsometric integral in classification of basin morphology, HI is not necessarily sufficient to differentiate basins. The same HI value can be derived from curves of different form. Also HI is not especially sensitive to upper basin morphologic variations. Consequently, statistical descriptions of the form of the hypsometric curve may be needed to derive the full information content from this methodology (Harlin 1978).

Variability of radiation load (RADSD) is positively correlated with surface roughness (FISHD and R1)(note:high values for these indices reveal low roughness) and drainage density. In a given region, this variation in radiation may be expressed as greater spatial variation in plant communities.

Kurtosis of altitude (KURTALT) is negatively correlated with variability of slope (SDSL) and altitude (STDALT). This indicates that when altitude distributions are clustered near the mean (positive kurtosis), terrain tends to be flatter and less variable. This appears to be an intuitive result, which may simply indicate that kurtosis of altitude adds no additional information. However, variance in an altitude distribution could be high even on a sloping plane surface. There is no obvious reason why as variance of altitude distributions increases, the distributions could not remain normally distributed. Correlations with skewness and kurtosis seem to indicate structural control of basin morphology. Clearly, interaction of drainage density, relative relief, basin area, lithology, and other factors produce the patterns of distribution of altitude variance, skewness, and kurtosis.

Table 7. Comparison of hypsometric integral (HI) derived from digitizing area from contour intervals (Strahler 1952) vs. cumulative frequency analysis of altitudes on grid.

	HI (digitizer)	HI (cumulative frequency)
MIAMI	43.84	47.63
NFK	44.75	44.72
LSFK	43.63	43.32
SFK	42.93	41.88
NFW	50.34	51.65
SFW	45.39	46.78
DEVIL	42.45	40.02
JRDN	47.12	47.82
NFNFT	57.75	56.92
SFT	37.32	39.19
EFT	42.29	41.12

There was a positive correlation between high roughness level (low values of FISHD or R1) and GMSL plus standard deviation of slope (SDSL) and altitude (SD1 and SDALT). A high SDSL is negatively correlated with kurtosis of slope (KURTSL); a high SDALT is negatively correlated with kurtosis of altitude (KURTALT). The high correlation between FISHD and KURTALT (low roughness with clustering near the mean altitude) was not unexpected; R1 was correlated with KURTALT at just under the 95% level.

Kurtosis of slope distribution (KURTSL) was negatively correlated with mean basin slope (GMSL). This implies that when slope gradient distribution becomes clustered nearer the mean, the mean slope decreases. Conversely high mean slopes would be associated with lesser clustering near the mean (i.e. a broadening of the distribution). This relationship may indicate that slope form changes as mean of slope gradients of a basin increases. This may occur as increased rounding of slopes at high and low elevations to promote slope stability.

The high degree of intercorrelation of variables indicates that, at least for these basins, many of the variables are redundant. Some correlations appear to be intuitive, as just described. Other correlations seem not to be necessary ones and might change with different regions. Examination of the correlations reveals that FISHD, DD and/or MAXDIR, HI, XALT, AVSL comprise a small variable set that would adequately represent the contrasts between basins, but not the total information content of the full variable set. A minimum variable set could be FISHD, DD and/or MAXDIR and XALT because HI and XALT are highly correlated as are AVSL and FISHD. HI and AVSL might be included, however, because of the possibility that their information content is not covered by the other variables.

The primary differences between the categories of the minimal set of variables derived from correlation analysis and those derived from factor analysis were that (1) factor analysis reveals that basin orientation is an important factor expressed by several variables, and (2) factor 2 is not readily related to a group of variables defined by correlation analysis, unless it too is primarily an index of basin roughness instead of form.

Kurtosis and skew of altitude are positively correlated as are kurtosis and skew of slope. This indicates that as distributions of altitude and slope become more tightly centered on their means (also associated with lowered roughness), the frequency of observations with low altitude and slope increases. Despite the correlations, only kurtosis of altitude and slope were included in factor 2. Skew of slope was in factor 1 and the skew of altitude was in factor 4. If the primary factors derived from factor analysis are added to those ascertained from correlation analysis, a sufficient set of variables beyond the preliminary ones used to classify watersheds might be FISHD, HI, DD, MAXDIR, XALT, AVSL, mean of RAD1, and kurtosis of altitude and slope (9 variables extracted from 21). All these variables except DD (which is highly correlated with MAXDIR), given the appropriate combination of relief and grid spacing, can be derived using the altitude grid as a primary data source.

(d) <u>Ordination by PCA</u>

Ordinations of the 11 sites vs. 21 variables were done using PCA (principal components analysis). Variables containing any negative numbers had 2.0 added to each value. All data were scaled between 0 and 100 and standardized. In these ordinations variables that seemed not to have a high correspondence with any single group of sites were RADKRT, SKEWSL, RADSKW, and SKEWALT. Variables that were considered to be adequately represented by other variables were SLPTPT, SD1, SDSL, GAPLA, GMALT, and RADSD. After eliminating these variables, another PCA was done with the remaining 11 variables. The new site ordinations were virtually identical to the ordinations with the original 21 variables and the correspondence between sites and the remaining 11 variables was essentially the same as before. This indicates that the same site ordinations can be produced with a limited variable set and that addition of extra variables does not necessarily change the relationship. However, addition of a new variable not highly correlated with existing variables might change the relationships.

Ordinations of variables emphasize the relationship between the variable pairs in which one is a surrogate derived from the altitude grid or else the variable pairs are both determined from the grid by different methods. For example, DD and MAXDIR; SLPTPT and AVSL; SD1 and STDALT; and AVALT and XALT are pairs of replicate variables. For example, MAXDIR was determined as the number of changes in slope direction scanning the grid. It was meant to be a substitute for DD, which requires extensive measurement of stream lengths. MAXDIR is easily determined once the grid data are recorded. Because each pair of variables was very close together in ordination space, it seemed obvious that much redundancy could be eliminated by using only one variable of each pair.

Principal components analysis was used to describe the ordination of the 11 sites vs. 11 variables. In this case PCA captured 80.6% of the eigenvector structure in the first two axes. PCA strongly differentiated Devil's Lake from the other groups (Fig. 13). The Miami and three Kilchis watersheds were a distinct group. The South Fork Trask had affinities with these watersheds relative to the first two axes. The North Fork Wilson and Jordan are tightly grouped on these axes. The South Fork Wilson, East Fork

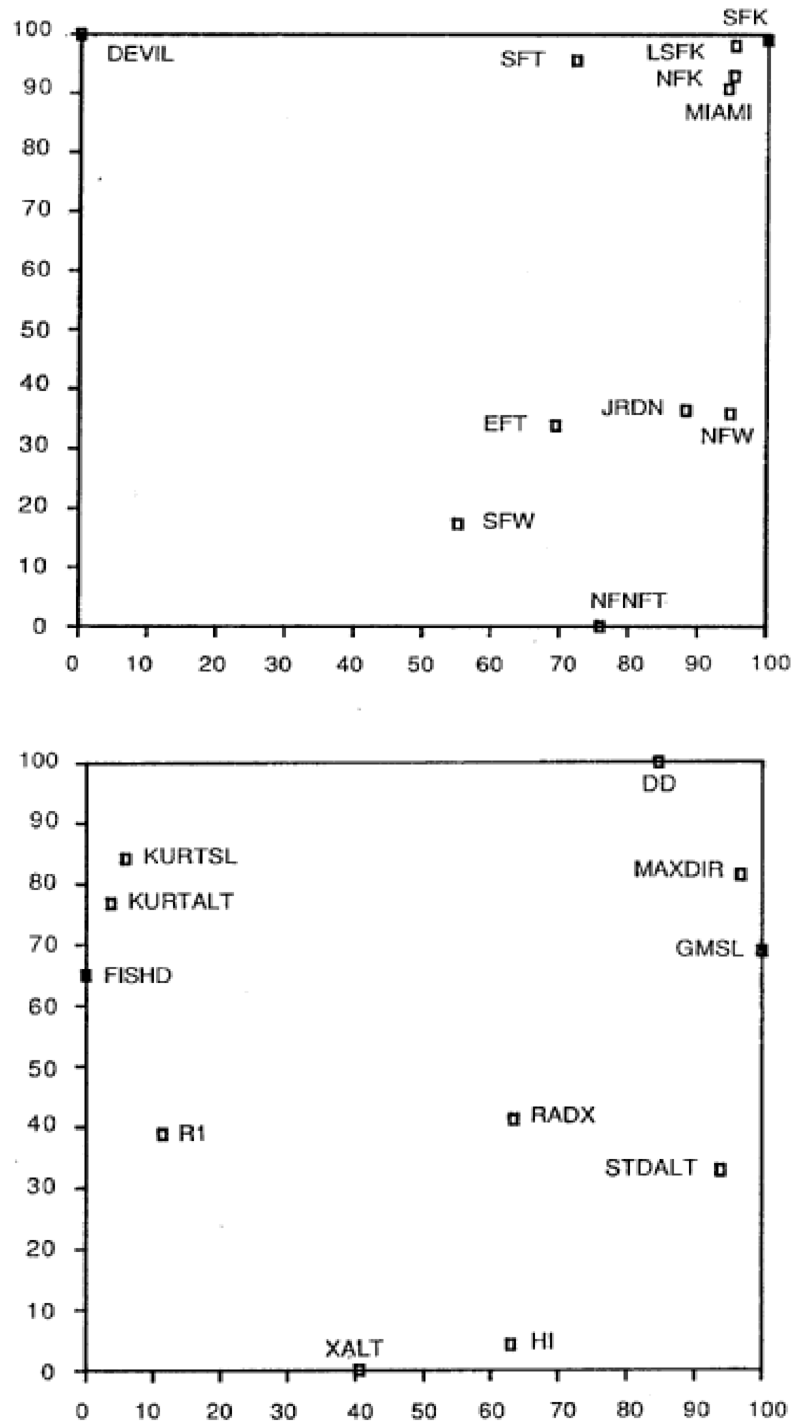


Figure 13. PCA ordination (BMDP 1983) of 11 sites vs. 11 variables. Plot of PCA axis 1 (X axis) vs. axis 2 (Y axis).

Trask and North Fork North Fork Trask comprise another group which is loosely associated.

The grouping of the Miami, the three Kilchis watersheds, and South Fork Trask result from having high drainage density (DD) and high changes in slope direction (MAXDIR). Devil's Lake is in a group of its own and is related in its ordination to the location of kurtosis of slope gradients (KURTSL) and altitude (KURTALT) plus basin roughness (FISHD). This watershed is distinguished by having the broadest valley bottom. North Fork North Fork Trask and South Fork Wilson have the first and third highest mean altitudes, respectively. North Fork North Fork Trask also has the highest hypsometric interval (HI) accounting for its unique position in the ordination. North Fork Wilson and Jordan Creek watersheds are distinguished by having the highest standard deviation of altitudes (STDALT). This variable corresponds well to the ordination of these sites. The position of GMSL (grand mean slope) results from the fact that the Miami and Kilchis watersheds, North Fork Wilson, and Jordan all have high mean slope gradients.

The classification summary (Fig. 8) reveals the same associations among the Miami and three Kilchis watersheds as found in the discriminant analysis with soils data. The uniqueness of North Fork North Fork Trask and South Fork Trask shown by PCA was also revealed by the discriminant analyses, cluster, and factor analyses. Jordan and North Fork Wilson maintain their affiliation in all these methods as do South Fork Wilson and East Fork Trask. Devil is always very distinct from the remainder.

(e) Further Analysis of Soils Data for Watersheds

The importance of differences expressed in the discriminant analysis on the basis of qualitative data such as the soil series names is rather inconclusive without more quantitative data on the soils. Quantitative data are not available by triangular facet but, given a mapping of soil series, mean values of certain quantitative descriptors of soil series can be related to topographic characteristics. Histograms of percentage of the total surveyed area for soils series within a basin were calculated for all basins having >72% coverage by soil surveys (Fig. 14). Seven basins had adequate soils survey information to allow this.

Soil histograms show that only 6 of the 14 soils present in these 7 basins covered greater that 10% of the area surveyed in their basins (Fig. 14). These soils were Rye (RJ), Osweg (OW), Humbug (HC), Neddona (ND), Killam (KM), Jewell (JW), Elsie (ES), and Watseco (WC). On the basis solely of soil histograms, the three Kilchis basins all are similar in having approximately the same soil series and percentages of each type. The Miami lacks the diversity of soil series found in the Kilchis watersheds and looks similar to Jordan in percentages of the major soil series common to each. South Fork Trask has the highest percentage of KM soil and is very similar to East Fork Trask if the low coverage of soil survey for this basin is adequate to characterize it. South Fork Wilson has high percentages of KM and JW soil series and a fairly high percentage of ES. Devil's Lake basin has a high percentage of Grindstone (GZ) soil series, although this is based on an incomplete survey of the basin.

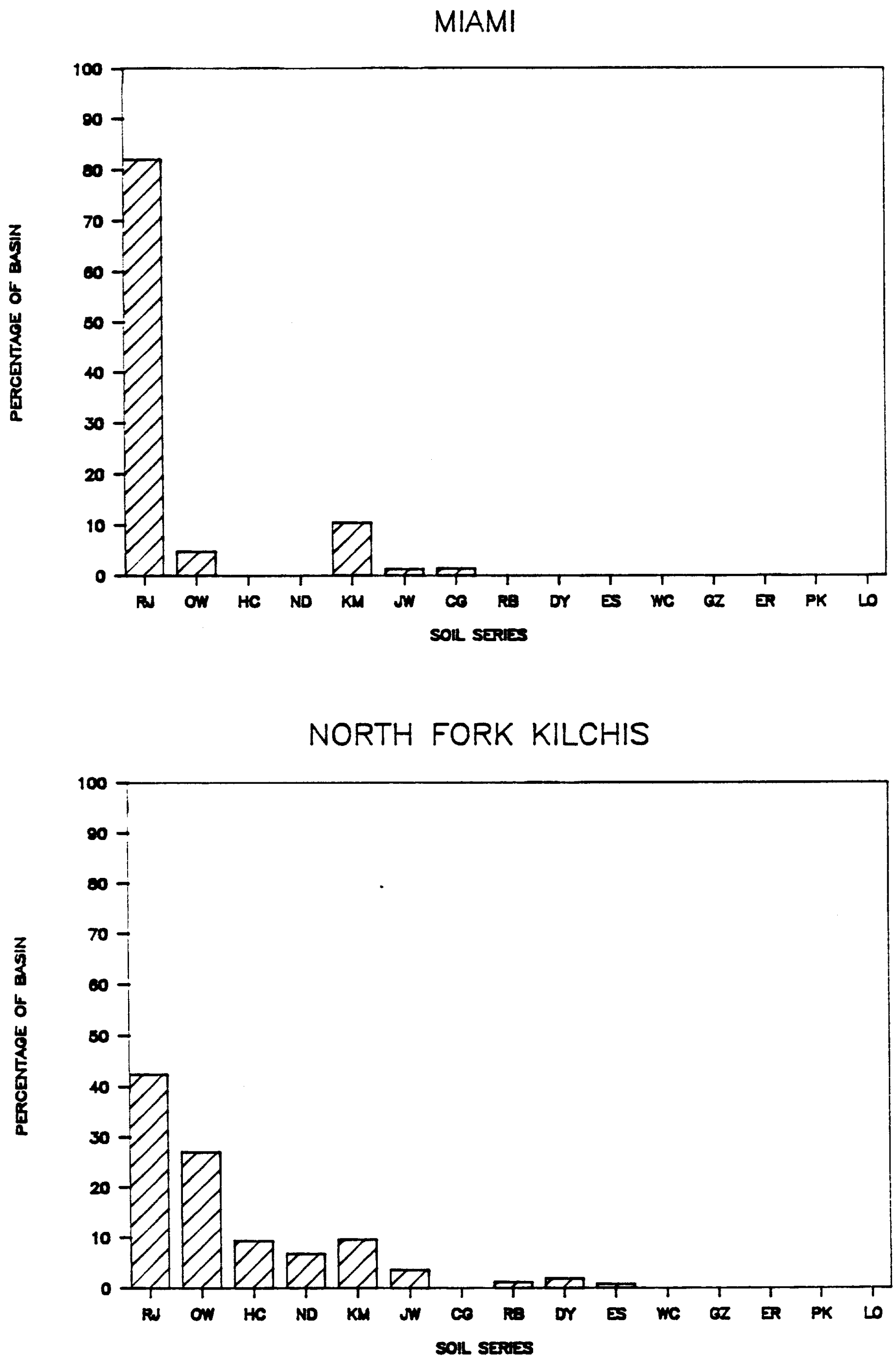
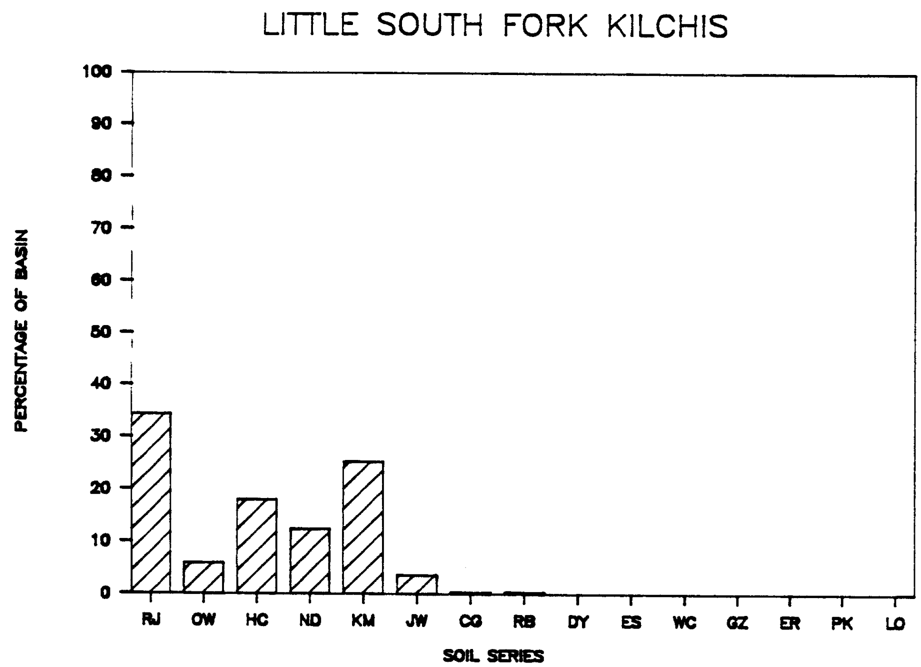


Figure 14. Histograms of percentage of basins comprised by 14 soil series.



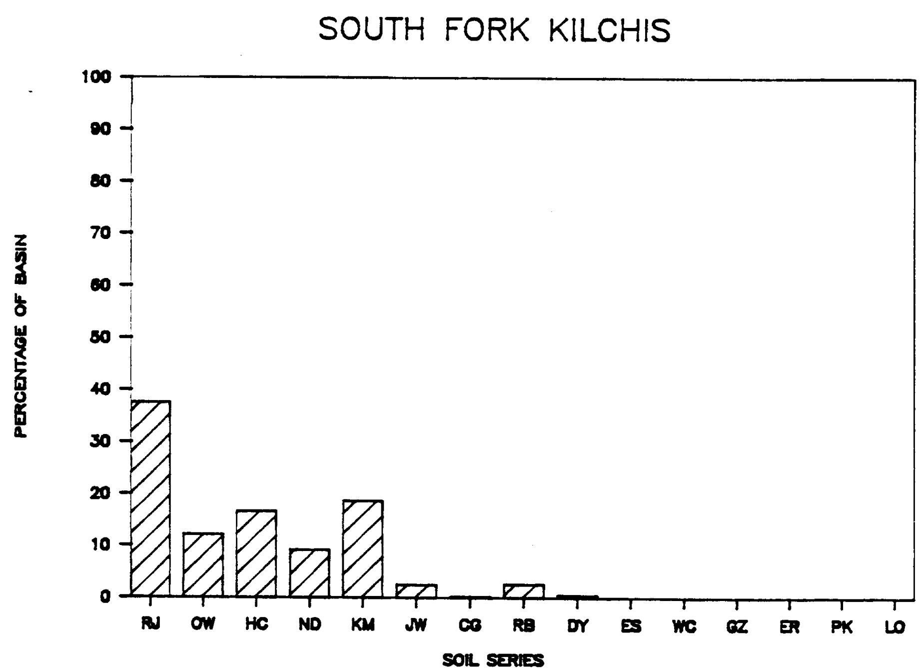
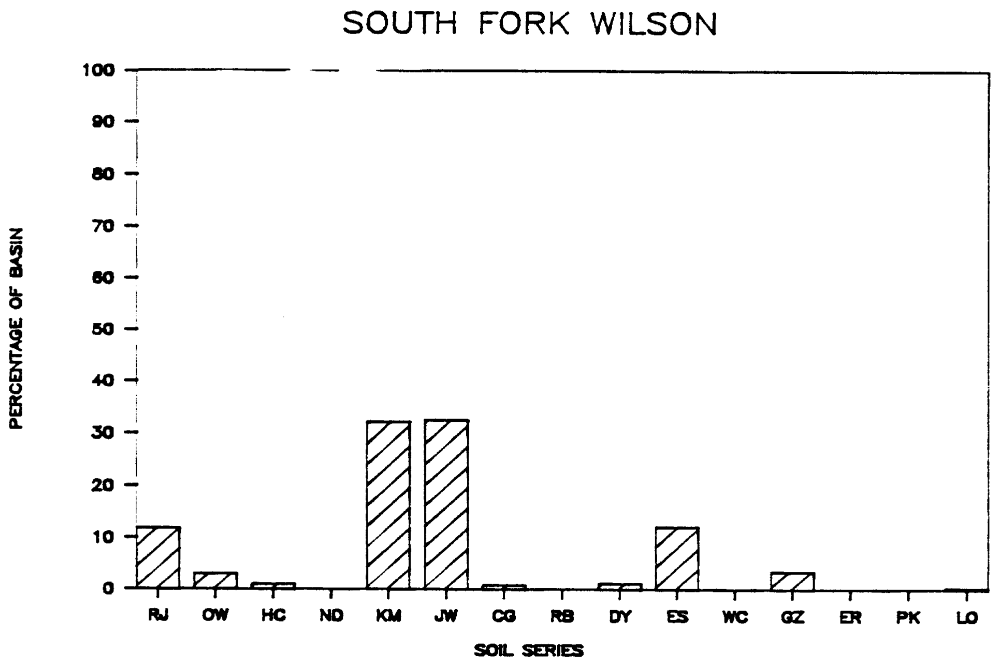


Figure 14 (cont.)



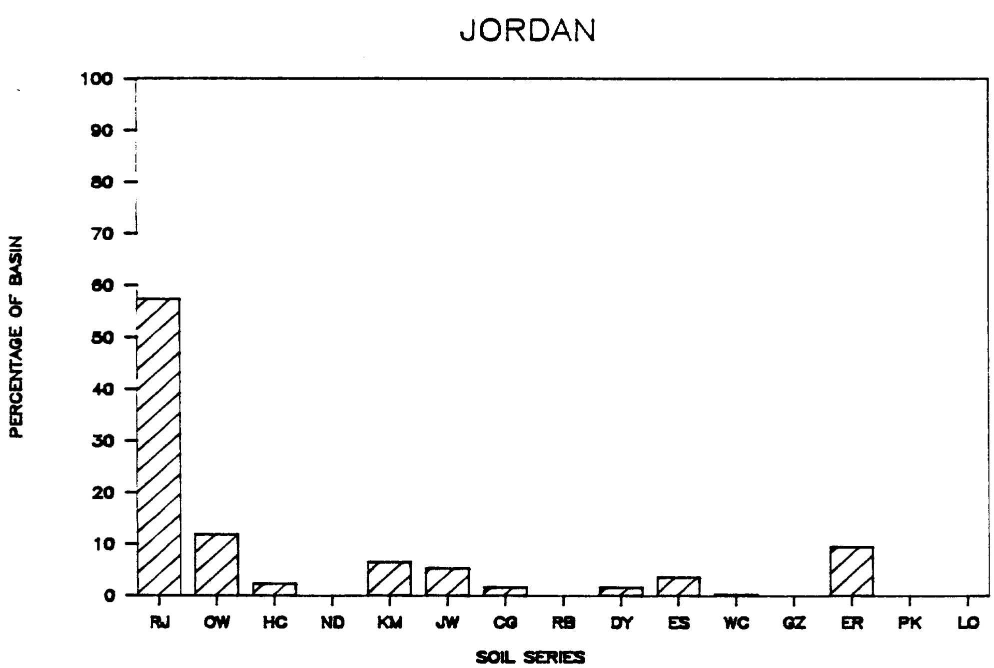


Figure 14 (cont.)

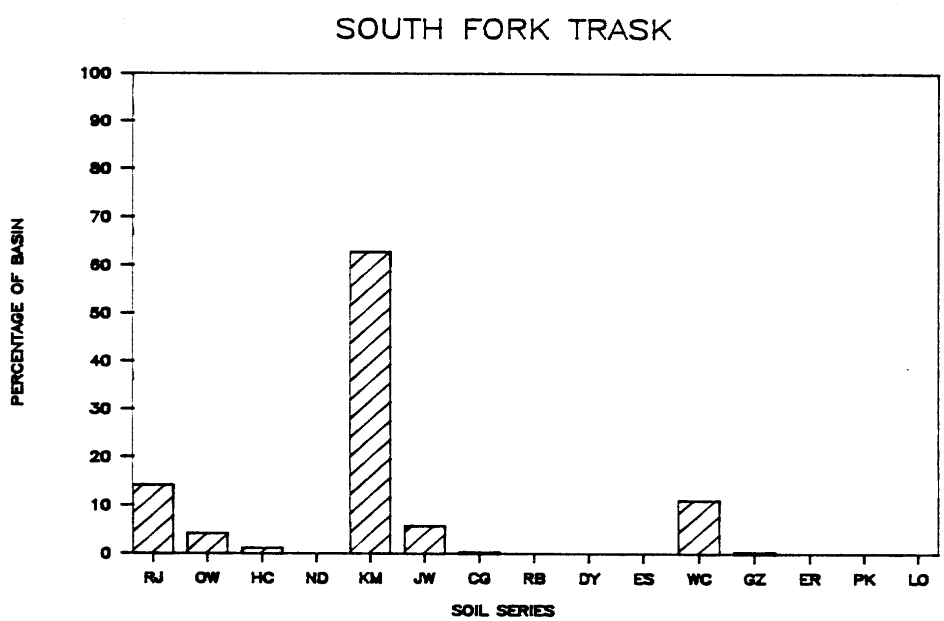


Figure 14 (cont.)

(f) Spatial Structure of the Watershed

Classification to this point has been based on measures of topographic structure and percentage composition of the basin by soils, geology, etc. These measures generally have been free of internal association of parts. Spatial organization of the system is an essential capacity level factor that must be considered in classification. Spatial structure of the basin (i.e. spatial arrangement of parts relative to one another) may serve as a proxy for basin capacity created through interaction of basin units. Since soil series are more accurately mapped than geology in the study area, soil series serve as a good basis for spatial analysis of substrate materials.

(f1) Evaluation of soil series distributions

The spatial relations of the downstream study reach to the soil polygons of the drainage basin can be represented by a gravity model. The influence of components of the environment on the downstream reach can be modeled as proportional to the size of the polygon and inversely proportional to distance from the reach. The distances from the centroids of all soil polygons downstream to the study area were measured following channel network lines. Percentage area of each polygon (relative to total basin area) was divided by distance and the quotient multiplied by 1000. These values were summed for all soil polygons and were then divided by the grand total of these values. The ratio of this strength value to the percentage of total basin area in each soil series indicates whether any soil series has a greater influence on the downstream reach than can be accounted for by percentage area alone.

LITTLE SOUTH FORK KILCHIS

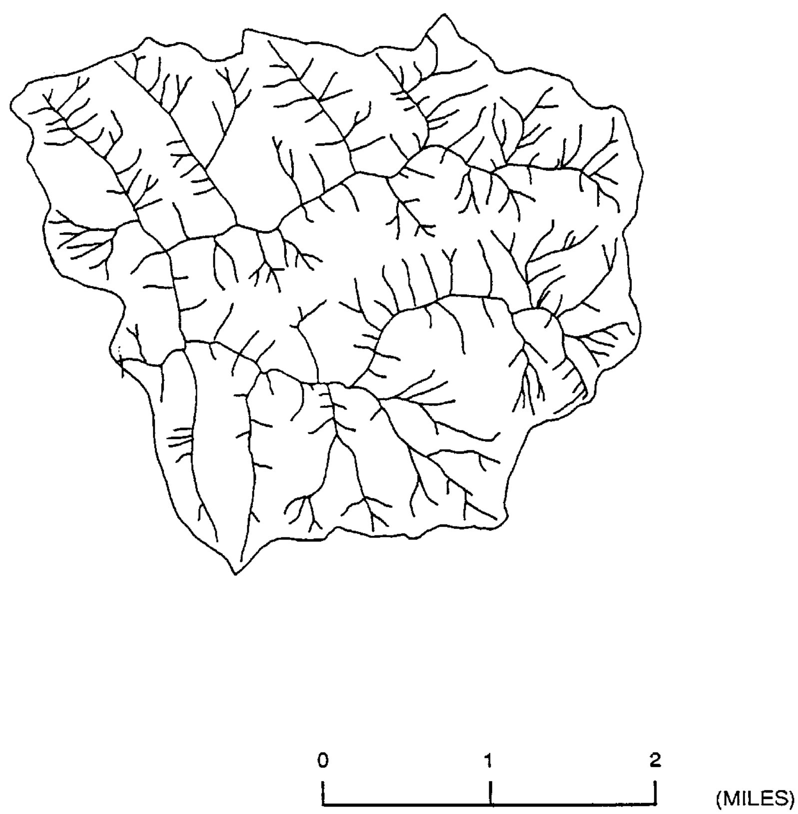


Figure 15. Representative drainage networks (Little South Fork Kilchis, South Fork Trask, and Devil's Lake Fork of the Wilson) extended by the contour crenulation method.

Application of the gravity model revealed for North Fork Kilchis, South Fork Kilchis, and Little South Fork Kilchis that the influence of CG, the alluvial soil, was far greater than one would determine from its percentage area (Table 8) owing to the overriding influence of proximity to the mouth. RJ and KM soils had more influence on the downstream reaches than would be determined by percentage area for these three basins. KM was of greater influence relative to area than was RJ in the South Fork Kilchis but they were nearly equal in the other two basins. The South Fork Kilchis had the greatest variability in influence relative to area for all soil series. The ND soil series had a relative importance of only 0.28. The North Fork Kilchis had the lowest variability in relative influence of soils having relative importance less than unity.

When considering absolute influence of the soil series, JW, CG, RB, DY, and ES make up no more than 2.5% of total influence in any basin. The Little South Fork Kilchis and South Fork Kilchis have similar absolute strength of influence of RJ, KM and HC. For these two basins, OW is stronger in South Fork Kilchis and ND is stronger in Little South Fork Kilchis. The North Fork Kilchis demonstrates a greater influence of RJ and a lower influence of KM than demonstrated in the other two basins. The influence of OW is much greater than in the other two basins. This analysis indicates more affinity between South Fork Kilchis, and Little South Fork Kilchis than between either of these and North Fork Kilchis.

(g) Network-Watershed Interactions in Space

Stream network structure expresses much about the three-dimensional structure of a basin. Classification of a basin should logically proceed in conjunction with classification of the stream network. The basin is the environment of the network as a

Table 8. Power of soil types in the three Kilchis basins.

SOIL TYPES

	RJ	OW	HC	ND	KM	JW	CG	RB	DY	ES	TOTAL
LSFK											
Total power	11.07	1.06	3.15	2.79	7.96	0.55	0.57	0.04			27.19
% of total power(1)	40.70	3.90	11.60	10.20	29.30	2.00	2.10	0.20			
% of total area(2)	34.30	5.90	18.00	12.40	25.20	3.60	0.30	0.30			
(1)/(2)	1.19	0.66	0.64	0.82	1.16	0.56	7.00	0.67			
SFK											
Total power	12.99	3.17	2.85	0.77	8.25	0.43	0.21	0.73	0.06		29.45
% of total power(1)	44.10	10.70	9.70	2.60	28.00	1.50	0.70	2.50	0.20		
% of total area(2)	37.60	12.20	16.70	9.20	18.70	2.50	0.16	2.60	0.45		
(1)/(2)	1.17	0.88	0.58	0.28	1.50	0.60	4.38	0.96	0.44		
NFK											
Total power	14.23	4.50	1.43	0.94	3.29	0.55		0.22	0.28	0.11	25.54
% of total power(1)	55.70	17.60	5.60	3.70	12.90	2.20		0.80	1.10	0.40	
% of total area(2)	42.40	27.10	9.40	6.80	9.60	3.60		1.20	1.90	0.80	
(1)/(2)	1.31	0.65	0.60	0.54	1.34	0.61		0.67	0.58	0.50	

whole, but network structure and basin topography are inseparable.

(g1) Drainage network planform morphology

The network can be evaluated visually after stream extension by means of the contour crenulation method (Fig. 15). The planform network structures of all basins in the study area are dendritic. The degree of trellis or dendritic nature of basins is partially a function of drainage area. Since these study basins are roughly the same area, differences in network structure may express some inherent difference in basin form. North Fork North Fork Trask is more trellis-form than the others (Fig. 15). Little South Fork Kilchis, East Fork Trask, and South Fork Trask are especially dendritic in nature. The contrast between dendritic and trellis-form networks is especially strong when comparing any of the basins in the Tillamook Burn on the North coast with the mid-Coast basins (e.g. Ten Mile, Rock, Cummins Creeks). Basins in both areas have similar geologic materials, potential vegetation, and soils, but the mid-coast basins are very trellis-form.

This continuum of trellis vs. dendritic form is well-expressed in a plot of cumulative length along the mainstem in a downstream direction vs. either cumulative total stream length or cumulative area drained (Fig. 16). Trellis networks would be expected to exhibit a more uniform continuum of conditions along the mainstem than highly dendritic systems, which have a more irregular stairstepped increase in drainage area with distance down the mainstem. In this sense, a continuum of relationships between stream reaches and the watershed for each reach is created with position on a longitudinal gradient, but abrupt changes in environment (watershed) of reaches occur primarily with entry of major tributaries to the system. One drainage network may not

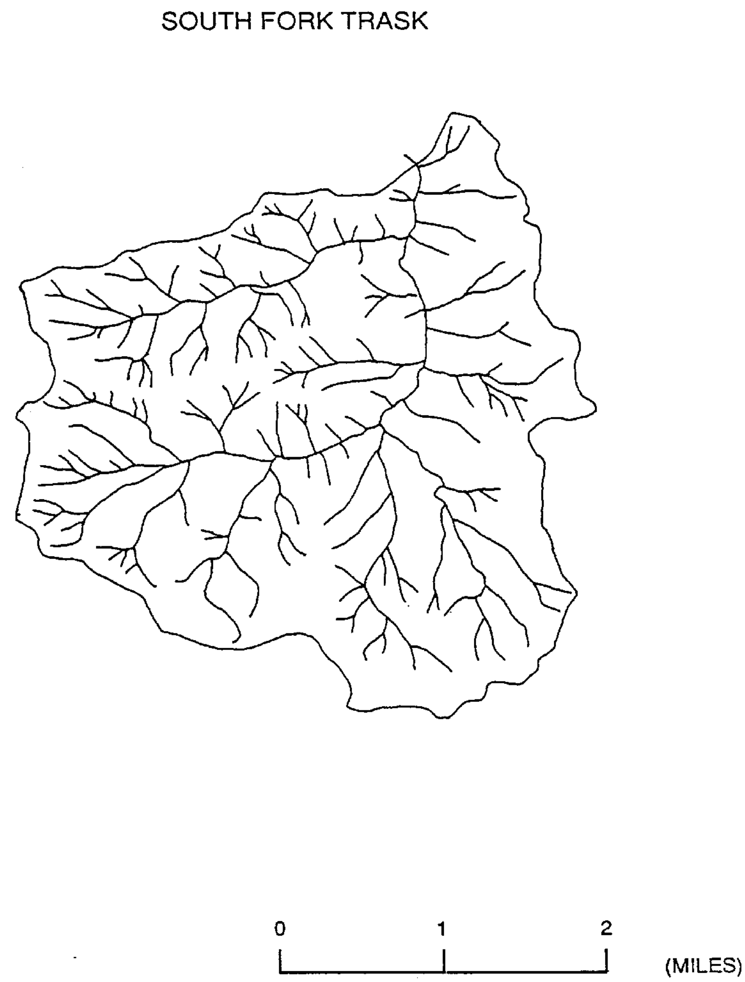


Figure 15 (cont.)

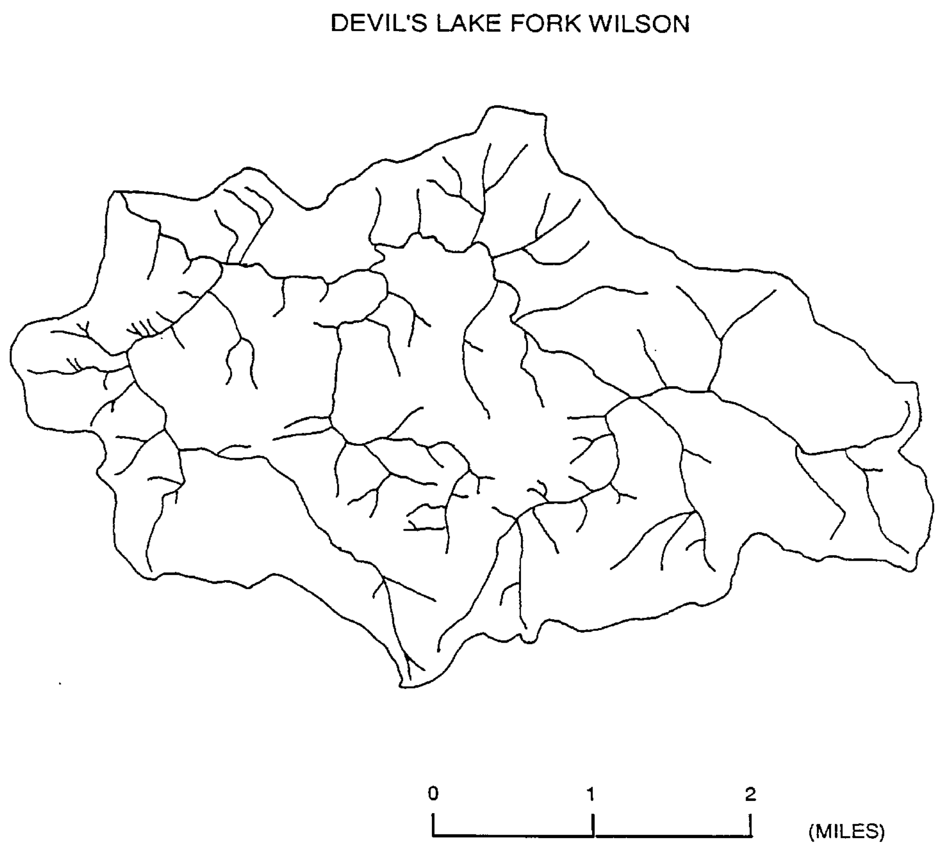


Figure 15 (cont.)

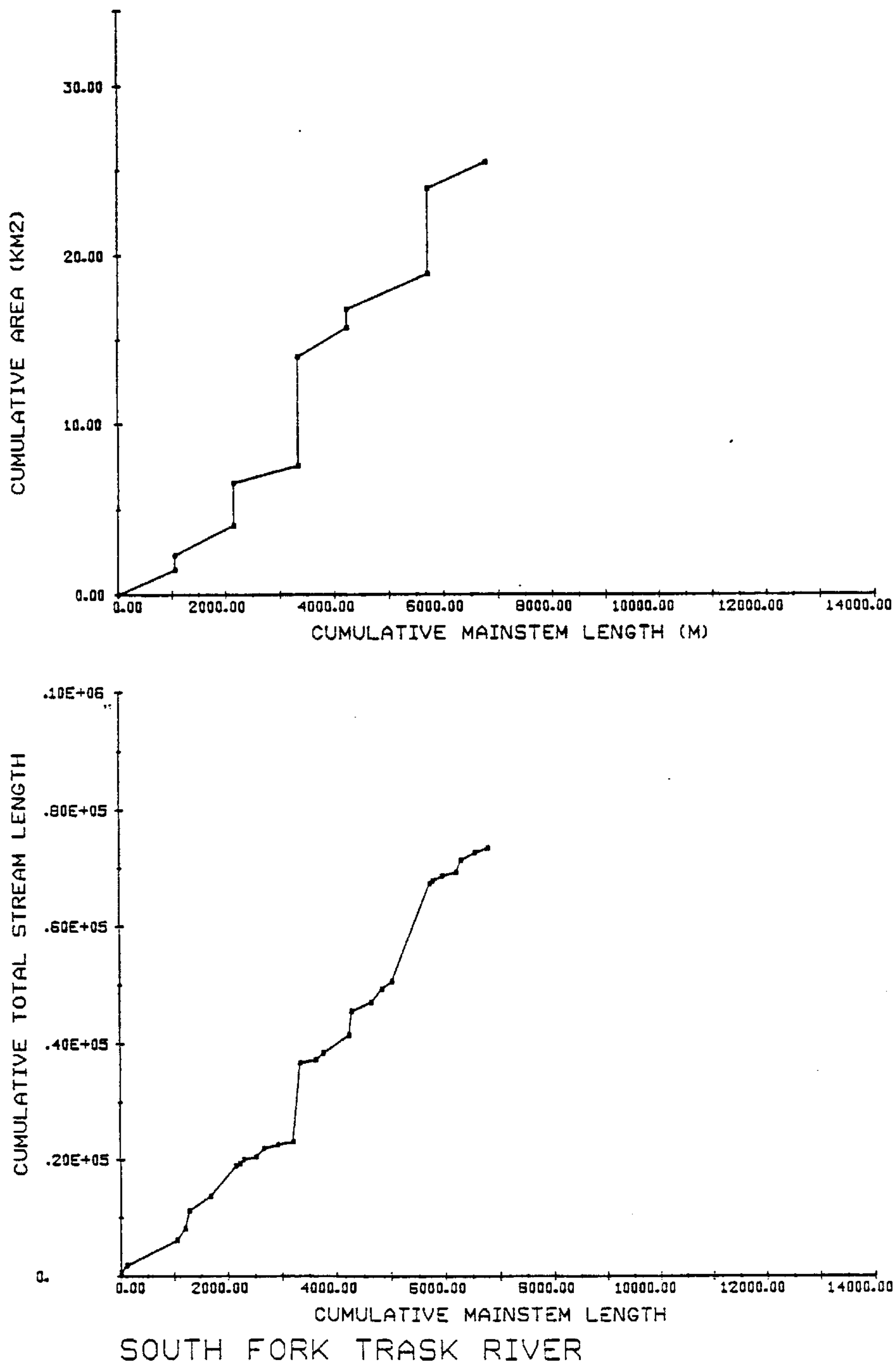


Figure 16. Representative plot (South Fork Trask) of cumulative total stream length vs. cumulative mainstem length and cumulative area vs. cumulative mainstem length proceeding from upstream to downstream on the mainstem.

have a similar continuum to that found in another basin of the same size owing to network structure.

The percentage changes in cumulative drainage area or cumulative stream length with distance down the mainstem are large in basins such as Little South Fork Kilchis compared with a basin such as North Fork North Fork Trask. This analysis could be quantitatively evaluated as a standard deviation in drainage areas of external sub-basins entering the mainstem.

The extended drainage network can be evaluated quantitatively by determining drainage density. Drainage density is one of the most widely used indices of topographic structure. It has been related to numerous basin characteristics such as lithology, soil type, vegetation density, time of geomorphological development, mean annual precipitation, and hydrologic response (Ruhe 1952, Gregory 1976, Schumm 1977). As major controls on drainage density change with physiographic regions, the utility of using drainage density to express differences in basin response diminishes. Between regions, second order drainages may have distinctly different sizes. Within areas of homogeneous vegetation, lithology, climate etc., such as the Tillamook Burn, the differences in drainage density might be thought to express differences in the operation of the basins within the context of a zonal class.

South Fork Wilson and Devil's Lake had the lowest drainage densities (1.89 and 2.23 km/km^2) while South Fork Kilchis had the highest (4.51) (Table 9). The three Kilchis streams had uniformly large drainage densities (4.17 to 4.51). Surprisingly the Miami and North Fork Wilson were somewhat lower at 3.40 and 3.18. South Fork Trask had a fairly high drainage density (3.95) while that in East Fork Trask was low (2.71). Jordan and North Fork North Fork Trask were also fairly low (2.84 and 2.74).

Table 9. The full set of 24 variables used in cluster and factor analysis. See Table 2 for definitions of these variables. Watersheds are (1) Miami (2) North Fork Kilchis (3) Little South Fork Kilchis (4) South Fork Kilchis (5) North Fork Wilson (6) South Fork Wilson (7) Devil's Lake Fork of the Wilson (8) Jordan Creek (9) North Fork of the North Fork Wilson River (10) South Fork Trask (11) East Fork of the South Fork Trask.

WS	FISHD	R1	DD	MAXDIR	GMALT	SD1	GMSL	SDSL	HI	SLPTPT
1	10.76	550.67	3.40	40.60	15.48	5.56	23.33	7.99	43.84	14.4
2	9.93	467.75	4.29	39.70	21.41	5.86	24.27	8.27	44.75	15.3
3	11.30	597.10	4.17	40.10	15.13	5.63	22.61	8.15	43.63	14.1
4	9.46	421.31	4.51	38.00	18.63	5.03	24.48	8.87	42.93	15.3
5	9.10	580.48	3.18	35.70	27.67	6.84	25.33	8.47	50.34	15.8
6	27.36	833.40	1.89	23.10	26.58	5.96	14.40	6.60	45.39	8.7
7	75.23	953.17	2.23	20.50	27.70	2.46	7.79	5.18	42.45	4.6
8	13.39	796.80	2.84	37.30	24.66	7.06	20.57	8.39	47.12	12.6
9	17.24	596.30	2.74	28.00	29.52	5.59	17.95	7.60	57.75	11
10	21.64	635.27	3.95	27.70	17.60	4.59	15.94	7.07	37.32	9.8
11	28.67	747.00	2.71	27.30	23.95	5.68	13.93	6.64	42.29	8.5

WS	GAPLA	XALT	KURTALT	SKEWALT	CVALT	STDALT	KURTSL	SKEWS	CVSL
1	1.11	16.36	-0.60	0.18	39.34	6.44	-0.17	-0.48	36.65
2	1.12	22.21	-0.46	0.20	31.15	6.92	-0.17	-0.34	36.81
3	1.10	15.91	-0.55	0.25	40.33	6.42	-0.36	-0.15	38.68
4	1.13	19.44	-0.64	0.08	30.84	6.00	-0.37	-0.22	39.27
5	1.13	28.54	-0.73	-0.09	27.20	7.76	-0.37	-0.23	36.52
6	1.04	26.95	-0.49	0.19	23.47	6.32	-0.14	0.27	47.41
7	1.01	22.91	1.24	0.69	11.97	2.74	1.45	0.86	67.38
8	1.09	25.21	-0.76	0.14	30.16	7.61	-0.75	0.04	43.33
9	1.07	30.12	-0.32	-0.45	21.29	6.11	-0.32	0.21	44.51
10	1.05	18.27	-0.55	0.27	28.85	5.27	-0.18	0.44	46.39
11	1.04	24.43	-0.68	0.12	25.13	6.14	-0.51	0.21	49.06

WS	RADX	RADSD	RADKRT	RADSKW	RADCV
1	0.338	0.274	-1.253	0.213	81.20
2	0.300	0.284	-1.198	0.495	94.80
3	0.355	0.268	-1.265	0.208	75.45
4	0.324	0.283	-1.257	0.356	87.30
5	0.358	0.286	-1.316	0.261	80.08
6	0.271	0.188	-0.240	0.608	69.13
7	0.325	0.123	0.688	0.304	37.86
8	0.307	0.236	-0.906	0.317	76.99
9	0.383	0.211	-0.932	-0.179	55.03
10	0.291	0.201	-0.379	0.575	68.90
11	0.363	0.195	-0.734	-0.059	53.67

A new method of estimating drainage density was explored based on the altitude grid. The maximum number of changes in slope direction per 100 altitude points (MAXDIR) obtained by traversing the grid along horizontal, vertical, and the two diagonal grid orientations was determined. Changes in slope direction are apt to be indicators of potential channels. Drainage density estimated by this means correlated well with the normal method of digitizing stream lengths. Exceptions were found with the Miami, Jordan, and South Fork Trask (Table 9). MAXDIR, the surrogate for drainage density, indicated that the Miami, the three Kilchis streams, and Jordan and North Fork Wilson all had high drainage densities, while the remainder were low with Devil's Lake being the lowest (Table 9).

(g2) Drainage network longitudinal structure

The longitudinal form of the mainstem of any basin has been generally expressed as mean slope of the mainstem blue line segments between 10 and 85% of the entire length (Fig. 17). However, identification of the upper terminus of the blue line is subject to mapping judgment and anomalies of basin perimeter elevation near the mainstem terminus. A less subjective approach used here is to measure slope of the mainstem from the mouth upstream to the point where the mainstem altitude equals 0.75 x the mean basin altitude (Table 10) determined from the complete set of altitude points (XALT). Slope to this elevation along the mainstem is highest in North Fork North Fork Trask (0.049) and lowest for South Fork Trask (0.026). Other basins with low mainstem slope are Devil's Lake, South Fork Wilson, Miami, and East Fork Trask (0.027 to 0.030). The remaining basins vary from 0.032 to 0.036 slope.

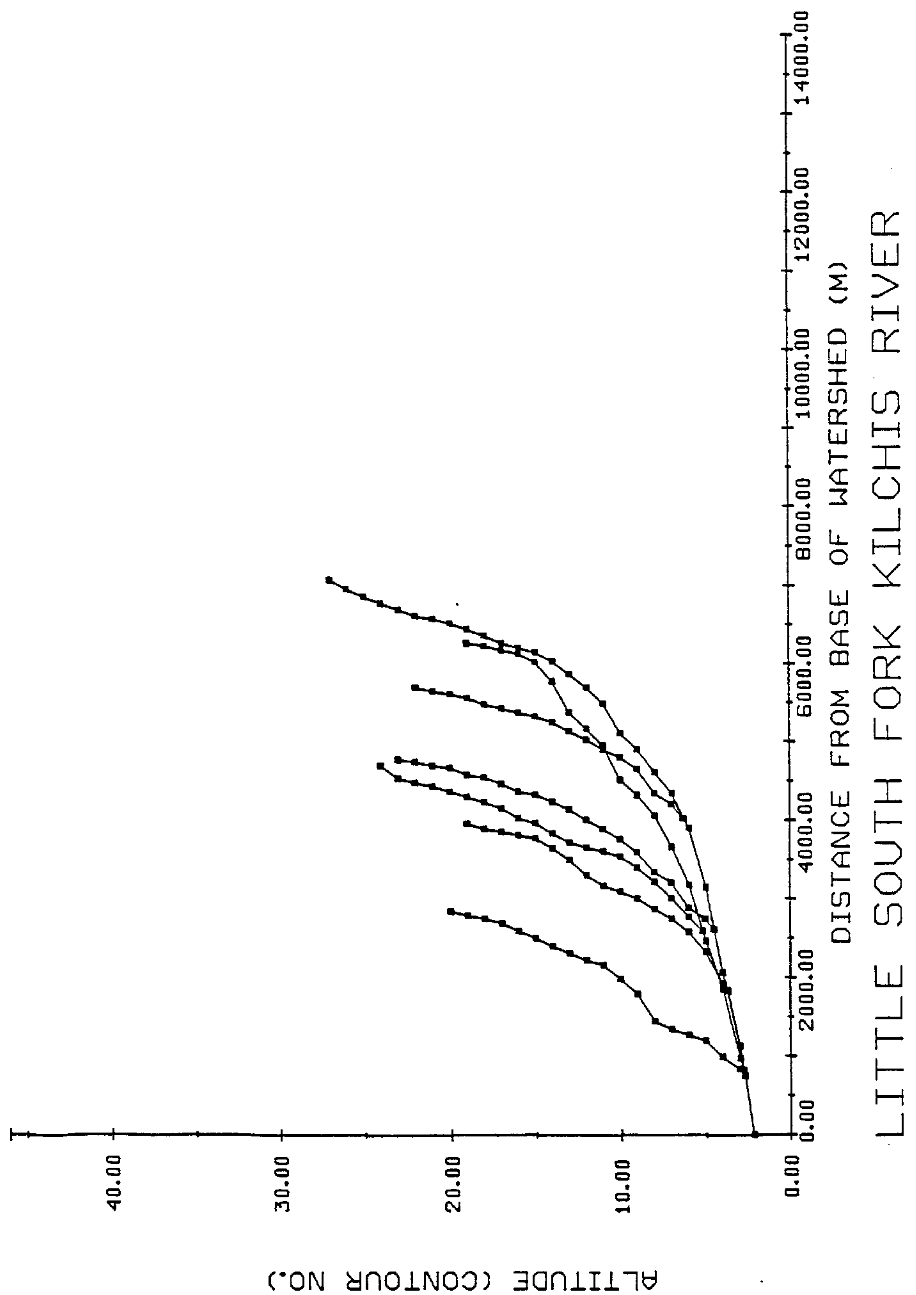


Figure 17. Representative longitudinal structures of mainstem and blue-line tributaries of selected drainage networks (Little South Fork Kilchis, South Fork Trask, and Devil's Lake Fork of the Wilson).

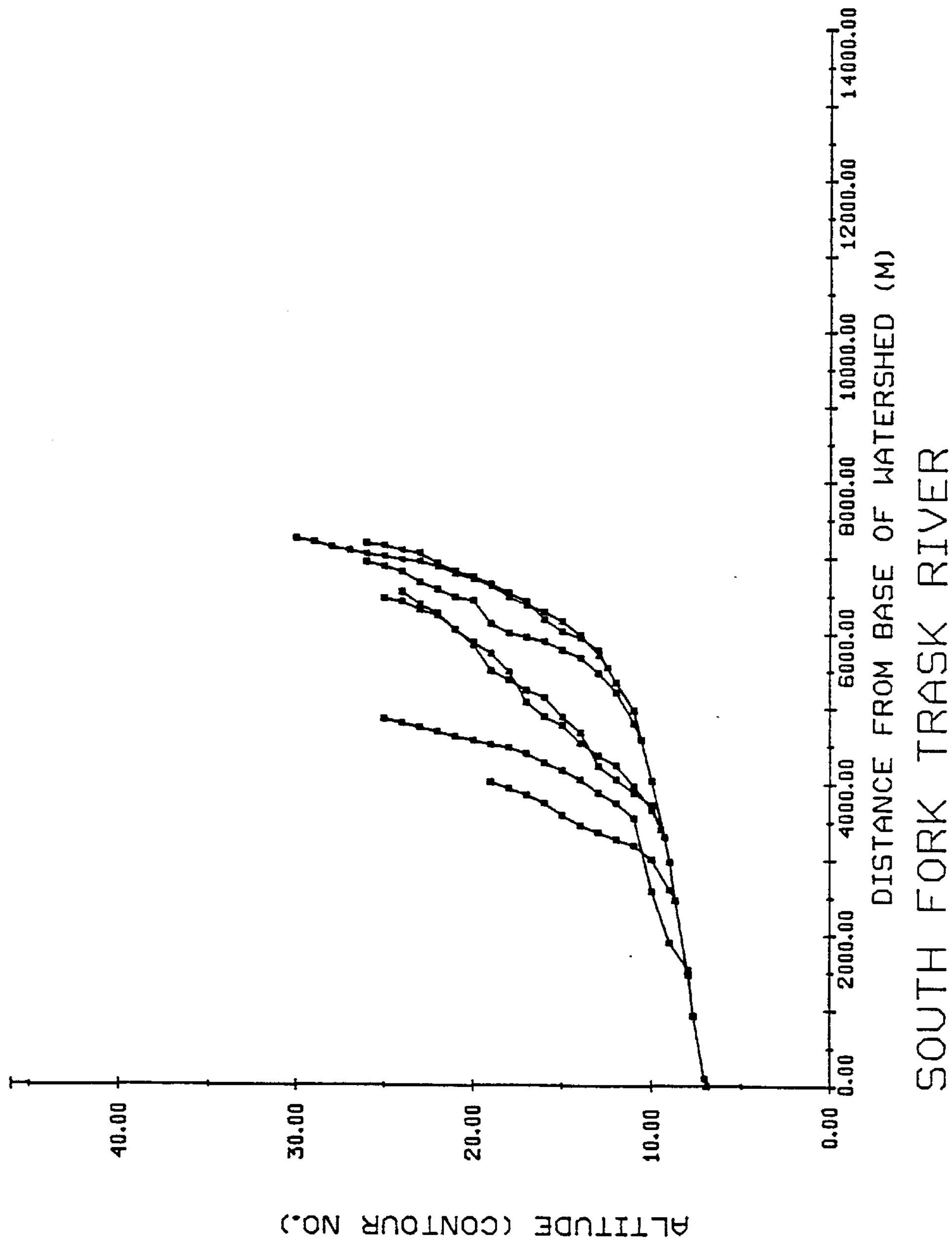


Figure 17 (cont.)

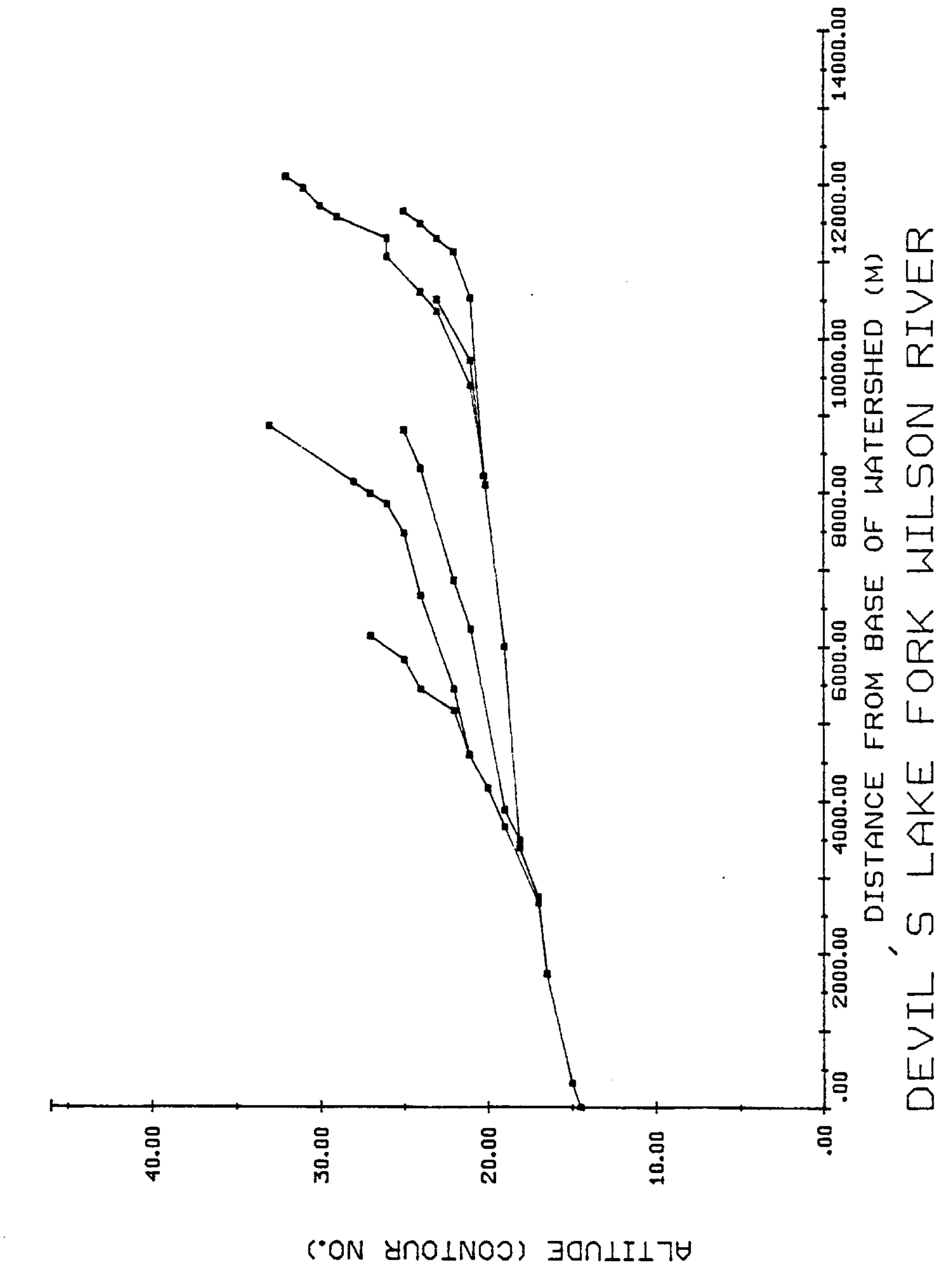


Figure 17 (cont.)

Table 10. Determination of instream bed slope from mouth of watershed to points on mainstream at 0.75 and 1.0 times XALT.

	XALT (x 80 ft)	(1) Slope to 0.75*(XALT)	(2) Slope to 1.0*(XALT)	(1)/(2)
MIAMI	16.36	0.0293	0.0392	0.747
NFK	22.21	0.0346	0.0457	0.757
LSFK	15.91	0.0338	0.0443	0.763
SFK	19.44	0.0318	0.0450	0.707
NFW	28.54	0.0322	0.0464	0.694
SFW	26.95	0.0286	0.0426	0.671
DEVIL	22.91	0.0268	0.0183	1.464
JRDN	25.21	0.0360	0.0473	0.761
NFNFT	30.12	0.0487	0.0552	0.882
SFT	18.27	0.0258	0.0386	0.668
EFT	24.43	0.0302	0.0397	0.760

The same interpretation, except for two basins, is generated by calculating slope to 1.0 x the mean basin elevation. Devil's Lake basin is unusual in having a lower slope to 1.0 x the mean altitude than 0.75 x the mean altitude, this indicating high altitude flattening. In the South Fork Wilson, the mainstem increases in slope between 0.75 x and 1.0 x mean altitude enough to place it among the majority of basins in slope to 1.0 x mean altitude (0.42 to 0.47).

(g3) Drainage network orientation effects

The relative importance of variables in multivariate analysis is difficult to establish. Consequently, all variables were equally weighted as there was no determination of relative importance. Variables in all multivariate analyses here were standardized to mean of 0 and variance of 1. This counteracts differences in magnitude of values for different variables, but ecological or physical effects of changes in variables by one standard deviation unit may not be comparable.

Compass orientation of the basin's network or basin resultant vector are variables that have not been properly evaluated in the past. Differences among basin networks related to orientation are most likely due to solar radiation distribution. Two basins with identical topography, network structure, and mean altitude may flow in different directions. Arbitrary direction classes may be established but it must be decided whether flow to the east is comparable to flow to the west. This question was explored using a single basin of constant morphology and mathematically rotating it to different flow directions.

A series of points located at X-Y coordinates in relation to the basin altitude grid were spaced at 880 ft intervals on the blue line network of South Fork Trask, a basin of moderate ruggedness in the Tillamook system. Daily solar radiation accumulation on the winter solstice was calculated at each point, while accounting for topographic and canopy cover. The network was then rotated counterclockwise by 45 degree increments to 180 degrees. The effect of this rotation on mean radiation/m^2 as a percentage of the potential without shading was calculated for each segment and for the entire network with topographic shading and with topographic plus canopy shading.

For the network as a whole, total network radiation load with topographic shading varied from 74% to 86% of potential radiation as the South Fork Trask basin was rotated counterclockwise 180 degrees (Table 11). Including canopy shading produced a variation in the total network radiation load from 45 to 52% of potential as the basin orientation was experimentally changed. Canopy cover on South Fork Trask appears to reduce variability of radiation load under rotation. This effect could change in character with variations in longitudinal distribution or density of vegetation cover. The effect of topographic shading would be less with lengthening days and greater with increased ruggedness as found in North Fork Wilson.

The topographic shading effect on individual segments owing to basin rotation is much greater than for the entire network (Table 12). Blue line segment 3 varied from 45 to 85% of potential daily radiation on the winter solstice through 180 degrees of rotation. Segment 14 varied from 62 to 93%, while segment 15 varied only from 54 to 69%, and segment 10 from 92 to 99%. Adding canopy shading effects caused a variation in segment 3 from 16 to 44% of potential, and in segment 14, 39 to 59%. Segment 13 varied from 7 to 11%, and segment 15 from 27 to 45% of potential sunlight received on the segment.

While it appears that whole networks may be able to dampen any effects of variation in orientation, orientation may play an important role in determining the

Table 11. Total network radiation load on South Fork Trask calculated at 45 degree increments of rotation (counterclockwise) with topographic and topographic plus canopy shading. Ratios were converted to percentages and are interpreted as percent of potential direct solar radiation. Computations are made at -23.44 degrees solar declination.

Rotation (degrees)	(1) Network radiation w/topog.	(2) Network radiation w/o topog. or canopy	(1)/(2)	(3) Network radiation w/topog. plus canopy	(3)/(2)
0	0.1328 E12	0.1544 E12	86.03	0.7440 E11	48.19
45	0.1265 E12	0.1544 E12	81.94	0.8015 E11	51.91
90	0.1150 E12	0.1544 E12	74.48	0.7051 E11	45.67
180	0.1261 E12	0.1544 E12	81.67	0.6897 E11	44.67

Table 12. Ratios of total segment radiation loads with vs. without effect of topography and with vs. without effect of topography plus canopy at 45 degree increments of basin rotation (counter clockwise). Ratios were converted to percentages and are interpreted as percent of potential direct solar radiation. Computations are made at -23.44 degrees solar declination.

(Segment radiation intensity w/topog.)/(w/o topog.)

Segment number	Basin rotation (degrees)			
	0	45	90	180
3	84.61	63.12	45.41	77.98
4	94.41	92.33	86.35	85.79
5	97.41	94.41	88.48	95.16
6	92.71	91.02	89.89	79.09
7	94.41	88.38	86.22	74.56
8	70.16	43.42	26.68	94.28
9	82.15	95.34	99.64	85.72
10	98.94	96.67	92.15	96.67
11	94.41	94.31	97.77	97.68
12	89.13	87.66	89.9	99.22
13	79.6	68.84	59.47	98.11
14	93.03	74.13	62.15	65.53
15	57.8	69.47	58.32	53.98

Table 12 (cont.)

(Segment radiation intensity w/topog.)/(w/o topog.)

Segment number	Basin rotation (degrees)			
3	44.18	41.85	16.46	42.32
4	64.04	70.13	67.21	60.05
5	54.26	65.58	63.91	52
6	68.7	63.59	63.27	55.07
7	57.91	61.27	54.91	50.76
8	11.98	7.182	2.41	15.36
9	16.78	19.82	20.96	17.87
10	33.14	32.39	30.87	32.39
11	28.11	28.11	29.02	29.28
12	43.09	42.39	43.3	48.55
13	8.72	7.04	6.79	10.58
14	59.11	55.25	39.12	48.23
15	33.78	45.44	42.13	27.35

radiation balance to a given stream segment. That is, stream segments of comparable width, riparian vegetation type, height, canopy density, and canopy gap width over the channel may vary greatly in the percentage of potential radiation reaching the segment, as mediated by orientation. Immediate effects of differences in light load would be differences in primary production and subsequent secondary production, heat load resulting in elevated mean water temperature, and diel temperature amplitude of variation. Though effects on the experimentally rotated network appear to be fairly small, the effect may be different with different network structure (e.g. more trellis-form) and may vary with greater topographic control and with less uniform distributions of riparian vegetation throughout the network.

The effect of topographic shading on the network varied among the 11 basins studied when each basin was evaluated in its actual orientation (Table 13). Effects of topographic shading were in general correlated with degree of basin roughness. Devil's Lake Fork of the Wilson had the greatest network radiation load (97%) as a percentage of potential on the winter solstice. East Fork and South Fork Trask networks had similar percentages (85 and 86%) of potential network loads. The Kilchis streams, though very similar by all other indicators, appear to diverge on the basis of network radiation load as a percentage of potential without topographic shading. Though the gravity analysis of soil polygon distributions and factor analysis based on 21 topographic variables indicated a closer relationship between South Fork and Little South Fork Kilchis, than between either of these basins and North Fork Kilchis, the percentage of potential radiation received on the networks under actual basin orientation showed greater affinity between Little South Fork and North Fork Kilchis (42% and 51% of potential, respectively, owing to topographic shading).

Table 13. Ratio of total network radiation load with vs. without topographic shading effect on basins in actual orientation (-23.44 degrees declination). Ratios were converted to percentages and are interpreted as percent of potential direct solar radiation. Computations are made at -23.44 degrees declination.

(Network radiation w/topog.)/(w/o topog.)

	(%)
MIAMI	51.32
NFK	41.62
LSFK	50.97
SFK	26.87
NFW	53.68
SFW	81.24
DEVIL	97.09
JRDN	60.47
NFNFT	
SFT	86.03
EFT	85.44

It is possible that under different basin orientations more comparable radiations loads could be established for the networks. Network radiation loads and spatial organization of soil polygons are network classification criteria, which at a fine scale resolution could be important in differentiating Kilchis streams, for example. At coarser scales these two factors would not appear to give conflicting impressions of basin associations because the Kilchis networks would fall into the same class of percentage of potential radiation load on the network and soil polygon organization.

Considering the fact that classification could be continued by adding new variables until all basins are unique, one must determine which variables are essential, and, if variables are not all of equal importance, how they can be ranked. For example, is soil polygon organization more important than network radiation loads? With respect to stream ecology both may be of equal importance, but when discussing sediment routing, the soil polygon organization may be of greater importance. When more variables are used in the classification, more variables with weak correlations to specific processes of interest (e.g. sediment routing) will be included. Given a set of primary variables describing a set of watersheds, certain variables could be considered to be of general importance regardless of the objectives of study. This was exemplified through the series of methods for watershed classification. Beyond this, a limited set of auxiliary variables could be weighted to facilitate classification of basins for more specific types of studies.

As just shown, North Fork Kilchis and Little South Fork Kilchis might be matched for certain objectives and South Fork and Little South Fork could be matched for others. With respect to preservation and management of systems of a given type, the Kilchis set of streams would be considered as a unit. Considering the size of these basins and the diversity of basins in the region, there is probably little to gain from a timber management perspective from finer resolution classification than the basic classification. However, for a full appreciation of the fish production in downstream reaches of these basins, a fuller classification might be essential.

3. Summary Comparison of Preliminary Classification with Different Levels of Further Classification

Classification has been shown to be a process originating in a theory of natural systems allowing organization of experience, prediction, and self-refinement through study of the relations between morphology and process of tentative classes. The initial classification and its refinements require identification of variables for representing classes and for gathering data. The present classification system represents the initial stages of this recursive process--that of deriving tentative classes and exploring utility of variables to define system potential. The class concept implies concrete objects. However, the series of methods used in classification emphasizes the dual nature of classes. Affinities among watersheds can be continuous as well as discrete.

The watersheds classified here were selected from a subzone of the North coast of Oregon. Regional and zonal characteristics were developed from classifications of Bailey (1976) and Omernik and Gallant (1986). The preliminary classification identified watersheds of a comparable size and bed slope in the downstream mainstem. If watersheds had widely differing drainages or downstream bed slopes or came from different regions, other characteristics would be trivial by comparison. Sorting the 11 watersheds by drainage area produced three major groups with South Fork Kilchis as the smallest and Devil's Lake Fork of the Wilson as the largest (Fig. 8). These two watersheds also had the lowest and highest bed slopes, respectively, in the downstream 0.5 mi. Although bed slope typically decreases as drainage area increases, not all basins of a given drainage area have the same bed slope. It is also not always possible to find identical drainage areas on the mainstem because of the irregular increases in cumulative area downstream, so the preliminary classification was an attempt to find optimum matches of area and bed slope. Whatever inherent inabilities there are to match these attributes appear, from further analysis, to be related to overriding basin differences.

A preliminary discriminant analysis based on six topographic variables identified five major watershed groups. The Miami and Kilchis watersheds are a distinct group. South Fork Trask has some affinities to this group but has a lower mean slope. Devil is in a group by itself. A further exploration of classes commenced by adding soils data for seven basins. The affinities among Miami and the Kilchis watersheds still existed. South Fork Trask and Jordan were differentiated from these by a high proportion of KM soils.

Cluster analysis on 24 variables statistically describing basin topographic structure continued to show the Miami and three Kilchis watersheds as a group. This group was linked to the group Jordan and North Fork Wilson as had been done by the preliminary discriminant analysis. Devil was, as always, a group by itself. The remaining four watersheds were linked. The fairly strong link between South Fork Wilson and East Fork Trask was also expressed by the preliminary discriminant analysis.

Factor analysis by its first three axes shows a strong tendency for Miami and the three Kilchis watersheds to form a group. North Fork Wilson and Jordan are tightly grouped in these three dimensions and are quite similar to the Miami and Kilchis watersheds. North Fork North Fork Trask seems to be intermediate in its affinity for the previous six watersheds and the remaining ones, except for Devil. South Fork Wilson and East Fork Trask are tightly grouped in these three dimensions. Devil strongly separated from the remaining watersheds in the first two dimensions but is intermediate in the third.

Principal components analysis also shows the Miami and Kilchis watersheds to be a group. The affinity of South Fork Trask for this group appears again. Factor analysis shows it to be set apart primarily by factor 1. Preliminary discriminant analysis showed this to be primarily a mean slope difference although addition of soils to discriminant analysis includes a major distinction by soil type. Jordan and North Fork Wilson are again grouped as are East Fork Trask and South Fork Wilson. North Fork North Fork Trask is again set apart somewhat from the previous group of four basins. Devil remains a unique basin.

Visual observation of soil histograms indicates a tight link between Little South Fork Kilchis and South Fork Kilchis. North Fork Kilchis is closely related to this pair. South Fork Trask and South Fork Wilson have similarities in soils that are also expressed by cluster analysis and discriminant analysis with soils data.

The gravity model for soil series power of influence at the basin mouth links Little South Fork Kilchis and South Fork Kilchis as did the histograms. Histograms revealed percentages of total basin area covered by soil series types. The gravity model expressed their spatial distribution.

Network classification is a hierarchical level below watershed but is intimately connected with watershed structure. Longitudinal form of drainage networks separates Devil from the remaining networks. Planform differences in network form show North Fork North Fork Trask to be the most trellis-form but all 11 basins are principally dendritic. By contrast, mid-coast basins are strongly trellis-form. This reinforces subzonal differences.

Bed slope ratios of slope from mouth to 0.75 x mean altitude/slope from mouth to 1.0 x mean altitude show Devil to be highly different from the other mainstems.

C. PARTIAL VALIDATION OF THE SYSTEM OF CLASSIFICATION THROUGH USE OF SOIL SERIES

Any system of classification is not apt to be simply validated but finds validity in its utility and in the extent that it makes clearer the relationships among the hierarchical systems classified (e.g. topographic vs. soil components of a system; biological community vs. habitat; watershed vs. stream). A partial indication of the utility and internal consistency in the methodology can be obtained by examining the relation of soil series to their topographic site characteristics. Qualitative indices of site differences in soils (i.e. soil series names) may be misleading when used in classification. Functional relationships among various soil series may vary considerably and they may exhibit different degrees of overlap in site character. Soil development over time is expected to be a function partially of the site characteristics. Therefore, the degree of differentiation in physical, chemical, or hydrologic properties of soils may be largely expressed by site physical descriptions.

1. Quantitative Description of Soil Series in Study Basins

The importance of differences in percentages of soil series is difficult to assess without knowledge of quantitative characters of the soils. Taxonomic relationships between soil series may involve only a few basic characteristics or may extend to a broad range of factors involved in producing very similar soil behavior properties.

The soils identified by Westberg et al. (1978) in the 11 study basins were Haplumbrepts except for the LO soil series which was a Humaquept. Fourteen soil series were identified plus one category termed rock outcrop (RB). These soil series were found in three primary altitudinal zones yielding distinct soil temperature regimes.

In the Tillamook area the mesic, frigid, and cryic soil limits were found at approximately 0-2000, 2000-2800, and>2800 feet. Within each temperature zone soil series were distinguished (1) by rock content as skeletal or non-skeletal, (2) by depth as shallow, moderately deep, deep, and (3) by texture into the five classes sandy loam, sandy clay loam, loam, clay loam or silt loam, and clay or silty clay.

The break point for the skeletal/non-skeletal distinction is at 35% rock as a weighted average for the soil at a depth of 10 to 40 inches or 10 inches to bedrock, whichever is shallowest. Soil depths are termed shallow if less than 20 inches to bedrock, moderately deep if 20 to 40 inches and deep if greater than 40 inches. These soils are effectively arrayed in terms of temperature regime, rock content, texture, and depth (Fig. 18). In the mesic temperature zone occur 10 of the 14 soil series. These soils contain 0 to 73% rock fragments and are moderately deep to deep. About half the soils are skeletal and half are non-skeletal. Texture assumes the full range of values defined.

On the basis of percentage rock fragments and depth there are three general clusters of mesic soils. The RJ and ND soils have high rock fragment content but RJ can have greater depth to bedrock and is a fine textured soil, whereas ND is coarse. The second group (ER, CG, KM, WC and HC) has 28 to 50% rock fragments and is moderately deep to deep. HC is shallowest and coarsest of this cluster. ER, CG, and KM have 28 to 35% rock fragments and are all deep soils but ER is fine-textured, CG is coarser, and KM fairly coarse. The WC soil has 50% rock fragments, is deep and

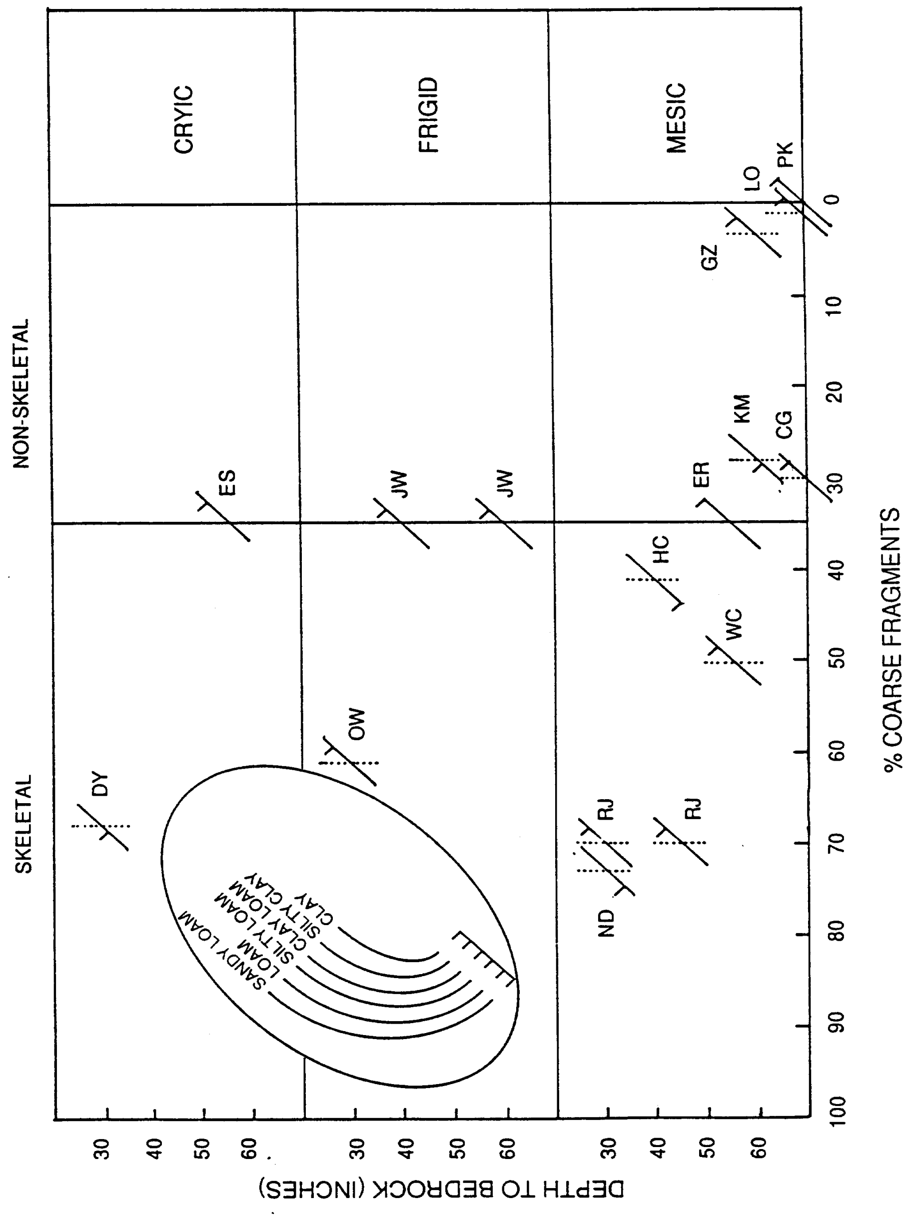


Figure 18. Relationship among soil series with respect to depth to bedrock (inches), percentage coarse rock fragments, soil texture, and climatic environment for soil development. Dotted lines through centers of texture ranking bar show position on percentage coarse rock fragment axis.

moderately fine-textured. The third group consists of GZ, LO, and PK, all soils that are low (0 to 3%) in rock fragments and are deep (>60 inches). GZ and LO have similar texture but LO is a Humaquept and GZ a Haplumbrept. LO and GZ soils have discontinuities and LO, PK, and GZ all have A-B-C horizonation. PK has siltstone, LO siltstone plus igneous, and GZ igneous parent material. PK soils are finer textured than GZ and LO.

In the frigid temperature range are OW and JW soils. OW has a much higher rock fragment content and is shallower than JW. Both soils have the same texture. JW has A-AC horizonation, while OW has A-AC-C.

In the cryic temperature range are DY and ES. DY has coarser texture, is shallower, and has a much higher rock fragment content than ES. ES has A-B-C horizonation and DY has A-AC-C, similar to OW.

Certain continua in soil series exist across temperature regime boundaries. ES-JW represents a cryic to frigid transition. Both soils have similar texture, rock content, and depth, although JW includes some shallower components. The main differences are that the A horizon of JW is 20 inches thick and that of ES is 10 inches. ES has an A-B-C horizonation, while JW has an A-AC.

DY to OW represents a cryic to frigid transition. DY and OW have similar depths and percentage rock content and both have A-AC-C horizons. The main difference, other than temperature is that DY has a finer texture and a shallower A horizon.

The OW-RJ transition is from frigid to mesic. Rock content, depth, and texture are similar and both have A-AC-C horizons. OW has a 20 inch A horizon and RJ has a 10 inch horizon. The A horizon of JW, the other frigid soil was also 20 inches.

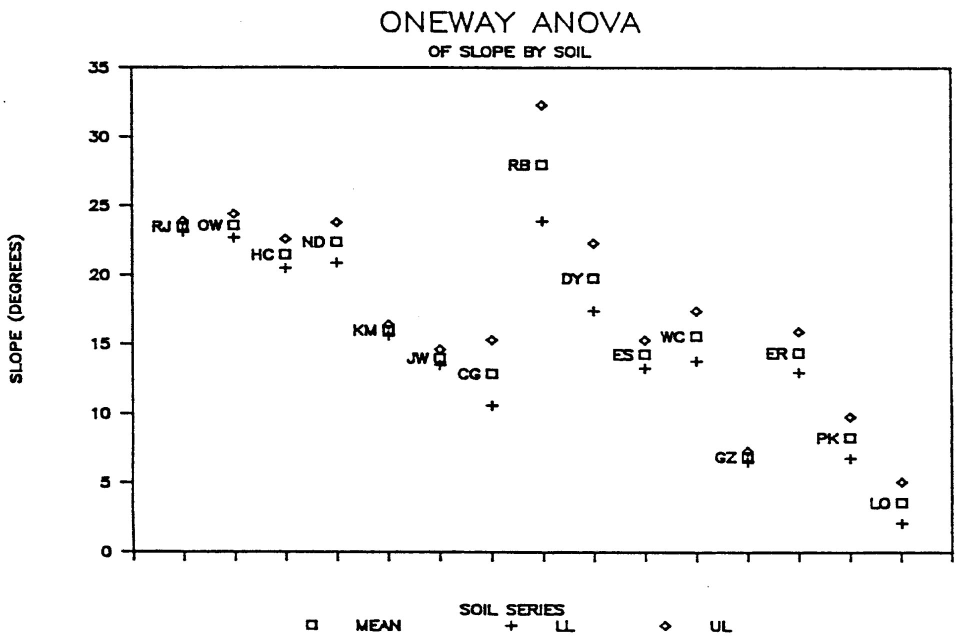
JW to ER represents another frigid to mesic transition. Both soils have similar rock fragment content and depth to bedrock but ER has somewhat finer texture, A-B-C horizonation, and sedimentary parent material.

2. Soil Quantitative Character Related to Topographic Expression

A oneway analysis of variance (SPSS 1975) was done on all triangular facets for which soil data were available in the 11 study basins. Means and 95% confidence limits of these soils for variables AVALT, L, N, RAD1 were determined (Fig. 19). Significant differences were evaluated by a Duncan test of means. The clearest distinction of differences in topographic character by soil series type occurred with altitude. Clear breaks are observed among soil series in the mesic, frigid, and cryic groups. In the frigid group, however, the OW soils were significantly lower in altitude than the JW soils.

For the mesic soils, CG and WC soils assumed the lowest altitude position in the basins. The RJ, HC, ND, and KM soils formed a group at approximately the same altitude range. These soils had 28 to 73% rock fragments. All but KM averaged no deeper than 45 inches to bedrock. The second group of mesic soils (LO, PK, ER, GZ) were found in a distinctly higher altitudinal range. These soils were greater than or equal to 60 inches deep and were fine textured. ER had 35% rock fragments, while the others had extremely low rock content.

Fairly similar patterns were found with these soils when the oneway analysis on slope was done using these soil series. The cryic soils were distinguished by DY occupying significantly steeper slopes than ES. In the frigid range OW is significantly steeper than JW.



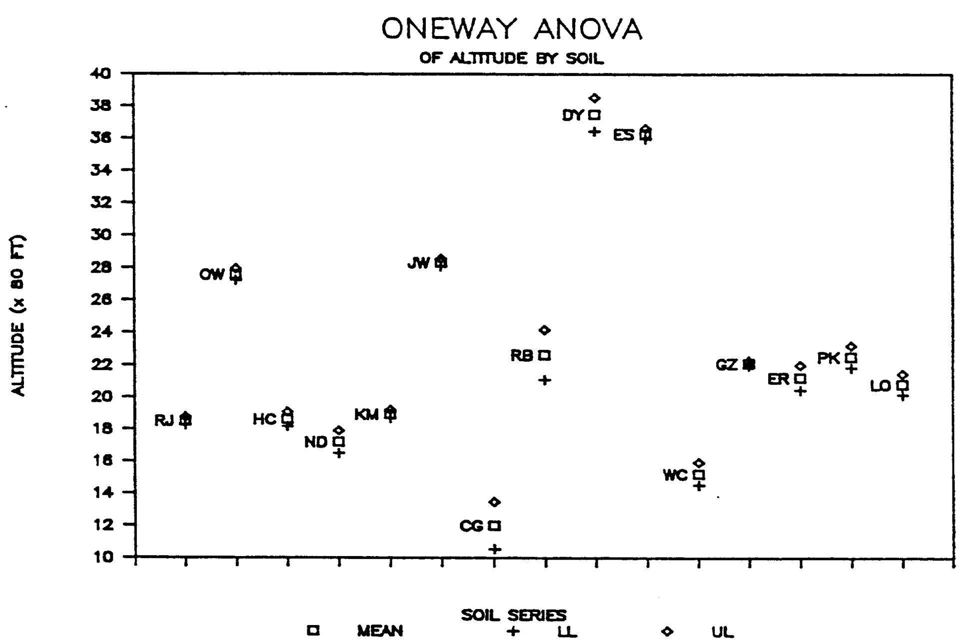


Figure 19. Oneway analyses of variance (SPSS) of altitude, slope, and RAD1 (daily solar radiation in $J/m^2/d$ on winter solstice) by soil series. Mean, lower limit, and upper limit for each soil series was computed by Duncan's Multiple Range Test.

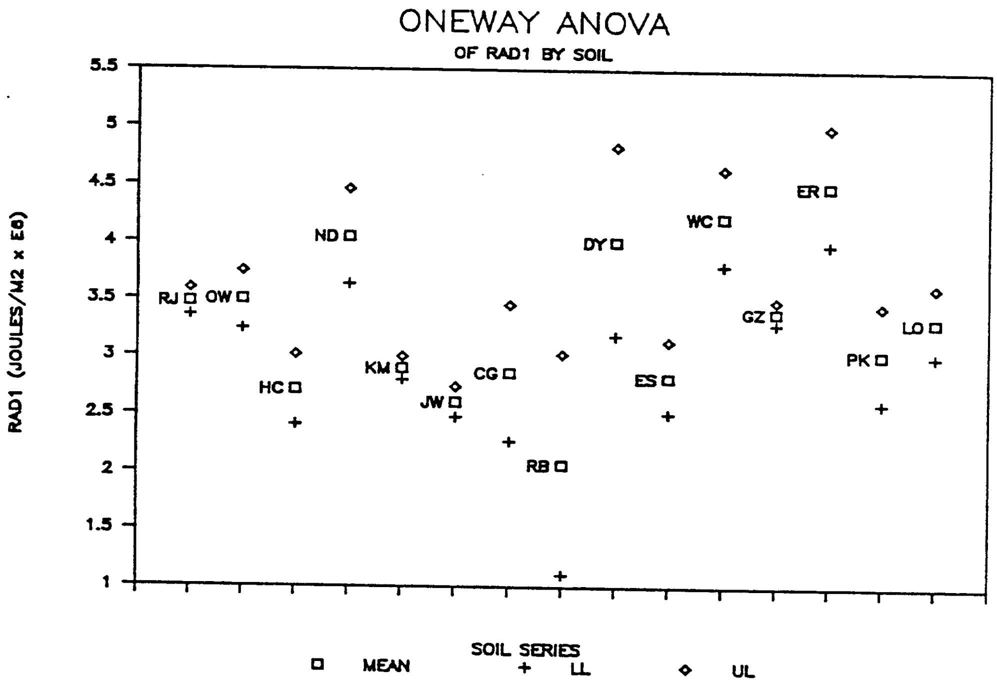


Figure 19 (cont.)

The mesic soils have a cluster (RJ, HC, and ND) with approximately the same mean slope of all triangles per soil type. The KM soil, having the same mean altitude as these soils, has a much lower mean slope. The WC and CG soils formed a cluster at the lowest altitude range for the 11 basins, with WC being slightly higher elevation. Likewise WC and CG have a slightly higher mean slope.

The deepest mesic soils (LO, PK, and GZ) were found on the lowest mean slopes. LO, having a fluventic origin, has the lowest mean slope of all soils. These soils are found at mean altitudes greater than the CG-WC and RJ-ND-HC-KM groups. They actually are located in the low relative elevation areas of basins with a higher than average mean altitude. The ER soil, found in the same altitude ranges as LO, PK, and GZ, had a significantly greater mean slope. The RB (rock outcrop) areas were found on the steepest of all slopes.

The relationship among soil series derived from calculation of RAD1 for triangles is very similar in means and confidence limits to that expressed by calculation of L (the first direction cosine). The DY soil series has a higher mean daily radiation on the winter solstice than ES. The same relationship is found for OW vs. JW, and RJ-ND vs. KM. The lowest mean radiation was found on rock outcrops. For the most part, the same relationships among soil series are maintained when daily solar calculations are made for the equinox for all triangles, i.e. RAD2.

Oneway analyses of variance took into account differences in means of soil types based on single variables (AVALT, L, M, N, RAD1, and RAD2). When these variables were used in a discriminant analysis with soil types as groups, the first discriminant function selected was most highly correlated with AVALT and the second with N (slope)(Fig. 19). Relatively tight clusters were formed by the mesic soils (RJ-ND-HC-KM), (CG-WS) and (LO-PK-GZ). The cryic groups (DY-ES) and frigid groups (OW-JW) are primarily separated by mean altitude. The differences in slope were previously reported in Oneway tests.

The weighted percentage of coarse rock fragments in the sub-soil was calculated from profile descriptions. Linear regression of percentage rock fragments on mean slope for the soil type yields an R^2 of 0.85 (n=14, P<0.001) with equation Y=-19.04 + 3.67X. This equation predicts 100% rock fragments at a mean slope of 32.44%. The triangles identified as rock outcrops (RB) had mean slope of 28.0% (95% C.I. 23.9 to 32.3 degrees). In addition, mean slope is negatively correlated with mean depth to bedrock (R^2=0.65, n=14, P<0.001).

Drainage density was determined for the major soil types by digitizing stream lengths and calculating areas of individual soil polygons of a given type. Polygons chosen for any soil represented the largest few polygons of that soil type in each study basin. In addition, areas of all soil polygons were determined by digitizer for all sub-basins in the study watersheds. Percentage of sub-basin area (interior and exterior basins) was determined for each soil type. A multiple regression of sub-basin drainage density (not including length of blue line segments) was run vs. percentage of sub-basin area in all soil types. Only sub-basins with <10% of their total area unsurveyed for soil were included. Soil types PK, LO, ER, CG, and DY, which comprised a small percentage of the total area of study basins, were eliminated from the regression to avoid areas summing to 100%. Many of these could not be considered anyway because sub-basins in which they were found were often not completely surveyed. Multiple regression with backstep variable selection provided an optimum R^2 (0.3010) with six soil variables in the regression (RB, HC, RJ, KM, OW, and ND in descending importance). The forward stepwise selection yielded a smaller R^2. The full regression model with ten soil variables had R^2=0.330. Using this equation to estimate mean drainage densities for each soil type when all others were set to 0% area yielded values similar to those measured manually. The correlation of drainage densities for nine soil types (excluding RB) determined by the two methods (direct measurement and multiple regression) has R^2=0.550 (n=9, p=0.02).

3. Conclusions

Addition of soil series data to the classification process has been shown to provide greater discriminatory ability among watersheds. Although soil characteristics are known to be a function of topographic properties, soils distribution cannot be perfectly determined from knowledge of topography. For example, RJ and ND soils and HC and KM soils, respectively, have similar topographic properties but have different soil properties. Soil distributions are mapped by a combination of soil analysis on the ground and extrapolation from topography. To the extent that mapped soils polygons reflect topographic character, the grid method used in classification is validated by the consistency with which it separated soil series according to written descriptions of the soils. The correlation between general soils physical data and average physical character of the sites (e.g. soil depth, percentage rock fragments, soil temperature regime) provides additional support to the use of topographic data derived from grid methods in inferring capacities of individual site classes. The ability to predict drainage density of individual soil series from knowledge of overall subbasin drainage density and the percentage of the subbasin comprised by different soils shows highly independent expression of site capacity. That is, subbasin drainage density seems to a great degree to be a weighted average of the drainage densities of the individual soils. Interaction with upslope soils may not be highly important in production of subbasin drainage density.

V DISCUSSION

A. FOUNDATION OF CLASSIFICATION IN THEORY, OBJECTIVES, AND OBJECTS

Development of a classification system such as proposed here arises from a background of theory of landform evolution, statistical analysis, and relation of form to process for predictive purposes. Given the organismic general systems theory of Warren, Allen, and Haefner (1979), and a set of objectives for classification, variables were chosen to represent the system. Conceptual representation of system organization and selection of variables bring into consideration the relation of the system to its environment, basin spatial interconnectedness, landform sensitivity and response thresholds, and the temporal and spatial scale on which to relate system form and process with that of its environment.

The general systems theory of Warren et al. (1979) represents a natural land system as a nested hierarchy of systems, each having its subsystems and environment. The immediate environment is the next higher incorporating system in the hierarchy. A system at any level has a capacity described in theoretical terms by the capacity components climate, biota, substrate, culture, and water. These capacity components are described empirically by proxies or system characteristics that are relatively time invariant to the time frame considered in the objectives of classification.

Objectives in watershed classification vary considerably in modern watershed management. Many types of classification systems exist for specific management goals. These single purpose systems are designed to predict soil erosion, timber yield, water yield, biotic associations, etc. There are several problems with most existing classification systems. Most such systems segregate objects on the basis of relatively time variant characteristics. For example, riparian zone classifications often employ only present riparian vegetation to segregate objects. The fact that this vegetation changes through succession means that classes continually change. In addition, similarities in vegetation class hide many other features of the riparian zone which form its capacity, or its ability over the long term to interact with its environment and produce all the performances of which it is capable.

Modern forest management mandates long-term multiple-use planning and consequently requires system classification based on a full set of capacity components in which the capacity is defined on at least a vegetative successional time frame. Most effective management depends on new insights from research. In order for the research and management communities to most effectively communicate they must be using the same system of classification. Experience gained in managing watersheds returns information to research, which helps refine the classification. Classification systems structured on a theoretical framework raise in relief relationships among systems and do so with respect to certain spatio-temporal frames of reference not otherwise possible. It is a way of ordering facts and experience. Classification acts as a hypothesis generation mechanism in research and a blueprint for staggering management efforts of all kinds and their intensities on similar watersheds.

The most convenient objects for classification of land systems are watersheds. Ecosystems can be defined on many spatial scales and at some scale could cut through a watershed boundary. Watersheds also can be of any size, and at large sizes may include several ecosystems, climatic types, lithologies, soil orders, etc. The present classification employs Bailey's regionalization to his section level (roughly corresponding to region in the present terminology). Within this level, study watersheds were selected by a preclassification. Within the region level, watersheds of a given drainage area and of a similar class would not necessarily be contiguous.

Classification of natural systems requires identification of objects and their boundaries. More or less definite boundaries of ecosystems, and the idea that similar communities or systems can be recognized in different locations within a macroclimatic region, are tenets of the polyclimax theory of plant succession. In addition, climax community variation occurs as a result of topographic and edaphic factors (see Mueller-Dombois and Ellenberg 1974). Diffuse boundaries and species assemblages changing continuously along environmental gradients are logical consequences of the individualistic or continuum theory of plant communities. Classification necessitates recognition of discrete objects. The system proposed here attempts to determine classes of watersheds, but multivariate techniques of analysis emphasize the gradients of similarity among them and the primacy of certain variables given the set of study watersheds.

Watershed boundaries are typically unambiguous discriminators of landscape objects, although exceptions to the utility of watershed boundaries exist (Hughes and Omernik 1981). Ecosystems, regions, terrain units, climatic systems, soil systems, etc. are not so clearly distinguishable. They can be identified at various scales of spatial resolution but can be described only partially by any set of classificatory variables. Assuming that an object is not readily discernible at a given scale in one of these systems, one could collect data from uniformly distributed points in terrain relative to these variables. Pattern in spatially continuous data can be revealed by statistical techniques such as trend surface or spectral analysis (Harvey 1968) that would fix the scale of transition between recognizable objects. In watershed classification the object is fixed by drainage boundaries but object identification becomes determination of meaningful classes of objects by statistical classification. Quadrat sampling and other mathematical representations of pattern presuppose that a scale has been identified at which data are non-random (Harvey 1968). This emphasizes the need for theory and experience with an area before classifying. Clustering techniques can resolve progressively smaller groups of related watersheds of a given size (possibly discontinuous spatially), and it is the prerogative of the observer to specify a meaningful group size and scale of the individual datum.

Vegetation ecologists often use the concepts of alpha and beta diversity (Whittaker 1970). Alpha diversity is community diversity within a habitat unit resulting from niche diversification; beta diversity is community diversity found along complex gradients resulting from habitat diversification. One would expect that at any chosen scale for examining communities, there exists greater diversity by proceeding to the next higher scale, or along gradients of maximum change which exist at right angles to boundaries of units, than among patches of a community type in a given environment. Even within a patch of any scale, diversity can be autogenically induced during succession or evolution (induced by diversity of vegetation physiognomy) or externally controlled by topographic complexity. Selection of scales for regionalization of communities and their corresponding complex environmental gradients highlights the roles of theory and objectives in classification and the interdependence of habitat and community concepts.

B. FEATURES OF THIS CLASSIFICATION

The theory of natural system capacity developed by Warren, Allen, and Haefner (1979) was employed by Warren (1979) in watershed/stream system classification. The Warren classification system, which allows theoretical integration of systems from large regional scales down through successive hierarchical levels to stream network, segment, reach, or lower levels if necessary, was employed in the present system with aspects of Bailey's and Omernik and Gallant's (1986) systems of land classification. In developing the present empirical classification, Bailey's system was used primarily for larger scale regionalization, and although he used less comprehensive classificatory variables, his system is similar in character to the one presented here. Omernik and Gallant's system takes Bailey's ecoregion system as a framework, refines Bailey's section boundary lines (his smallest mapped units), and defines finer scale homogeneous zones within them primarily by use of maps of land use, land surface form, potential natural vegetation, and soils. These variables are all considered together rather than by using one variable per level in the hierarchy. The Tillamook Burn study areas fit principally within what Omernik and Gallant call the most typical type areas of the Coast Range.

The primary features of the present classification are (1) the hierarchical structure, (2) a set of variables representing total system capacity or a major subset of system capacities, (3) implicit classification of performances of a system which would be observed over a long period of time, by means of performances which are relatively invariable with time, (4) incorporation of the spatial interconnectedness of system parts, and (5) a theory to explain the connection between a system and its environment. In other words, system class is determined by its capacity and the capacity of its environment.

Total system capacity is an integration of interacting capacity components, substrate, climate, biota, culture, and water. Each component is represented by unique spatio-temporal distributions (e.g. vegetative distribution) but the interactive nature of the five components is most usefully dealt with for scientific and management purposes according to watershed boundaries. Each system is composed of subsystems. Geographical subsystems have a unique spatial organization which partially defines system capacity. The system, likewise, is spatially linked to surrounding systems.

The structure of the environment and of the system itself must be understood in order to derive an adequate classification. Models of the structure of the environment could take many forms. Systems in the environment of a study system can be modeled as isotropically linked. That is, linkages to the study system are equally strong in all compass directions and only decrease by distance. Also the environment can be linked to the system in a directed way. Such a model might link systems to the west of the study system (orientation with respect to upwind terrain). Directed linkages along gravitational lines would represent a drainage basin approach. A gravity model was used in this paper to link systems to updrainage systems. The strength of the linkage is a function of the size of the system and its distance updrainage from the study reach. Structure is partially written onto systems by the established drainage patterns.

Bailey's system of regionalization relies heavily on the correlation of distribution of climate, physiography, soils, and vegetation. Bailey's section level (ranking fourth in his ecosystem hierarchy) was a segregation of land systems on the basis of potential natural vegetation, or vegetation representing the climatic climax. His district level, below the section, is defined with respect to uniformity of geomorphology. The next lower level, the landtype association, is defined on the basis of landform, lithology, soils, and vegetation associations. Bailey's section level corresponds to region in the present work. Watersheds within a region in the present work can be composites of two or more zones or subzones, depending on watershed size. The watersheds, themselves, were preclassified by drainage area and downstream slope, and then by extensive topographic and soils analysis. The variables used in classification are essentially those categories Bailey identifies for the two levels below his section level. However, the present classification scheme is a taxonomic one (Bailey 1976) as opposed to his regionalization. Regionalization, or successive subdivision of land units, might be thought to be a more holistic process, but it suffers from lack of relation to watershed boundaries. Multivariate classification of watersheds within a region would be likely to differentiate watersheds with respect to subzonal affiliations, but extensive subzone units would be difficult to assemble by this technique. This is because watersheds of any one chosen size are not necessarily contiguous and subzones are land units comprising integrated watershed systems. Nevertheless, watershed structure reflects its developmental environment and its function so there is good reason to use these two means of classification.

Warren's system of classification is a powerful theoretical medium for uniting the disciplines of land classification and landscape evolution. The system provides the hierarchical framework for organizing the variables of classification at the proper scales of space and time. It also provides a theory for adjusting the time frame for examination of landscape morphology and process. The temporal sequence of potential capacity, realized capacity, and performance is compatible with Schumm's (1977) scales of dependent/independent variables controlling system behavior on different scales of time. The ability to define system potential by a set of variables that are relatively stable in time arises from the presumed tendency of geomorphic systems to move from one meta-stable state to another when internal or external thresholds are exceeded. Classification of any system and its environment requires identification of magnitudes and frequencies of characteristic processes and requires determination of the sensitivity of landscape components to change as well as the tendency to recover to an equilibrium form (Brunsden and Thornes 1979). Climatic or hydrologic regions can be expressed statistically. The drainage network appears to be a landscape unit of special sensitivity to watershed change.

The integrated classification provides a heuristically powerful means of representing system structure. It incorporates the breadth of bio-physical theory by basing the classification theoretically on the full capacities of the systems. It is based on a theory of natural systems which lends itself well to models, logical synthesis of historical data on systems, and re-evaluation of the adequacy of capacity proxies in an interactive process of classification, examination of system behavior, and possible modification of the classification.

Empirical methods of watershed classification were centered on a simple format, a grid. Triangles formed from the grid represented land facets for which a statistical description of their attributes (capacity proxies) were made for the entire watershed. Relationships among watersheds were examined by multivariate analysis of all attributes of all facets for watersheds. The classification involves reductionism by decomposing a system to facets, each of which has sets of attributes, and also involves synthesis through spatial analysis within a basin and elimination of variables used in classification. Spatial analysis took the form of (1) calculating solar radiation distribution by facet and in the drainage network, accounting for topographic and canopy shading and (2) estimating the magnitude of influence of soil units by use of a gravity model, which involved grouping facets of similar soils and determining downstream distance to the study reach and size of the soil unit.

A basic theoretical assumption entailed in the classification is the interrelationship of physical and biological components of natural systems. The present classification of natural systems is based essentially on physical capacity without accounting for the use of the physical system by all biota. It is a matter of definition that a species or community can only maintain itself in places where the physical system provides its needs (its habitat). Habitat for a species can be broadly defined (for generalists) or narrowly defined (for specialists). Habitat for a stream community type can be well specified by the physical regime of a segment or reach class. A segment provides a physical system having a relatively fixed drainage area, channel cross-sectional form, channel slope, and a capacity for spatio-temporal distribution of subhabitat units. The gradient view to ecology might deny the reality of community types, but the abrupt transitions between stream segments make natural boundaries in conceptualizing interacting species assemblages through time in relation to channel development and terrestrial vegetative succession. Spatial and temporal variability of any physical system class assure that habitat will be provided for many species with similar resource needs. This physical diversity is assumed to lead to habitat diversity, which leads to biological diversity at whatever scale of physical system identified.

The use of topography and soils as primary components of classification at the watershed level in place of the full component set was a necessary compromise of the theoretical ideals of Warren et al. (1979). These data types provided the most complete and differentiating coverage of the watersheds available. Climatic data were not available at this spatial scale, and cultural effects among these watersheds do not seem to be differentiated locally from the overall regional character. Vegetation community data are not available at the watershed level, except as generalizations based on altitude and aspect from regional experience. Vegetative performance (age, density, type) at the triangular facet level is available, but these data do not clearly reveal differences in capacity of the facets so well as topography and soils do. Rather, vegetation at the facet level could be interpreted as operating within the framework of the potential natural vegetation of the area and influenced by the physical capacity of the facets, partially expressed by topography and soils.

The focus on topography and soils data can be empirically justified on the basis that basin morphology and drainage network structure are intimately linked to long term climate and lithologic control. Soils formation is a result of long-term interaction of climate, vegetation, lithology, and topographic structure through time of geomorphic development. Basin morphology and drainage network structure, in turn, control watershed hydrologic character or its water yield and sediment yield characteristics. The influence of the variable source areas in modifying the shape of hydrograph peaks illustrates the importance of network capacity as a distinct hierarchical level.

Consideration must be given to variable sensitivities and recovery rates of land systems after disturbance (Chorley, Schumm, and Sugden 1984).

C. IMPLICATIONS OF THIS CLASSIFICATION SYSTEM FOR WATERSHED AND STREAM SCIENCE AND MANAGEMENT

The present classification system serves a dual function. It forms the framework for observing and understanding the "facts" of watershed science and also makes this information useful for management. Land managers extrapolate from experience on watersheds of a given class to other watersheds of that class. This experience allows prediction of potential future states on the basis of past states or realized capacities. This extrapolation can be made on the basis of regional affiliation for some problems. More specific problems require classification of watersheds of a given drainage area within a region, or even classification of stream networks, segments, reaches, and habitats. Comparisons among stream habitats in a region should always be made with respect to the environment of the habitat. For example, a riffle of a certain gradient can be found in many stream segment classes that can occur in different watershed classes. Comparison out of environmental context does not allow consideration of the full range of capacities of the systems. The principal management implication of this type of classification is its emphasis on recognition and protection of the capacities of systems, or their potentials to exhibit their full set of performances.

The empirical methods presented here illustrate a particular interpretation of the Warren theory of natural systems. It makes use of coarse level resolution of ecological regions, such as done by Bailey (1976) and Omernik and Gallant (1986). It then provides techniques for classification of watersheds and streams within defined regions. Although topography and soils were the primary components used in classification and a rationale has been given for the probable sufficiency of these indices of capacity, the grid methods given can also be used to classify watersheds on the basis of lithology, vegetation, climate, culture, etc., if variables representing these components are obtained at the same scale as for previous data. In addition, such data collected at a coarser scale of resolution for the region can be used to classify much larger drainage systems. Trend surface methods would allow subdivision of ecoregions using coarse scale climatic or other data.

There are several kinds conclusions drawn from the experience of classifying the watersheds and streams in the Tillamook Burn:

(1) Soil series were well segregated by topographic variables slope, aspect, and altitude. This means that soil depth, horizonation, percentage coarse rock fragments, soil texture, and soil temperature regimes varied according to topography. Although some soil series were closely related, topography can act as a good predictor of soil and many other types of capacities.

(2) Basin orientation is an important variable affecting network solar radiation accumulation and distribution through topographic shading.

(3) Classification must be done at a scale appropriate to the objects being managed or studied scientifically. Preliminary classification of watersheds within a region and zone by drainage area and downstream slope is appropriate for many objectives. More refined distinctions can be made by inclusion of watershed topographic and soils variables. The gravity model of spatial interconnectedness of basin sub-units illustrates a methodology for integrating upstream basin processes. The ability to progressively refine a classification reveals the continuum from discrete classes to positions along multidimensional gradients.

(4) The empirical methodology was constructed from the basis of a natural-cultural systems theory (Warren, Allen, and Haefner 1979). Empirical methods and models reflect the theory of system capacity including capacity components, geographic hierarchy, structure, and spatial organization. These methods can be applied at any scale within the geographical hierarchy. Regular grids are commonly used in geographical applications, but usually for single purposes. A grid is used here as a basis for integration of all resource data for analysis by multivariate statistical methods. In addition, grid topographic data facilitated calculation of an index of drainage density and hypsometric integral, which are widely used and time-consuming to derive. The grid enabled other calculations of topographic structure and correlation of resource attributes at grid sites.

(5) The use of multivariate methods for handling numerous resource attributes at each land facet permitted more faithful representation of all components of capacity considered than might be possible intuitively. These methods highlight assumptions about weighting all variables in classification equally. As scientific experience continues to be examined within the framework of a good classification system, the ecological hypotheses generated by assumptions of weighting factors and completeness of representation of system capacity can lead to development of more meaningful classifications.

Regionalization of environmental data in flat terrain is a relatively easy problem compared with that in rugged terrain. A transect in flat terrain produces a comparable set of environmental data regardless of scale. But in rugged terrain the homogeneity of environmental data expressed on a regional scale exists in repeatable patterns of diversity at a scale corresponding to the roughness units. Landform roughness sets the scale of environmental diversity and consequently the capacity for maintenance of the regional species pool. Capacity for local distribution of species and communities is set by the spatial distribution of land units of the correct class.

This linkage between physical and biologic systems forms the basis of biogeographic theory. Biologic systems co-evolved under environments of given capacities. Changes in environment through time force the co-evolving biologic systems to geographically follow shifts in the "centroids" of the environments to which they are best adapted. Because environment is more than climate, biota actually tend to track the entire spectrum of capacities of the physical system. Creation of remnant populations occurs when bridges are severed between provinces of preferred environment. This process results in discontinuous patches of similar communities such as mountaintop communities in a desert. Groups of these mountaintop communities might be placed into the same class but not necessarily linked to more extensive mountain communities elsewhere that are embedded in a different environment. Spatial discontinuities in system classes are natural. For example, all terrestrial units of a given slope, aspect, and altitude in a region are not connected. Extensive management units that are maintained for long periods of time in altered successional states can effectively create remnant populations unable to persist or disperse to similar sites.

Management and conservation of natural units such as mountaintop communities requires an understanding of system diversity and the linkages of the system to its environment as well as linkages to other similar systems in the region. This principle is reflected in modern park management. The co-adaptation of adjoining systems provides the linkages that help maintain system integrity. System boundaries are less rigid in this conceptualization and the interdependencies with nearby systems form a higher level system with management requirements of its own.

The proper focus of resource management is at the levels of communities and systems of communities and not solely in saving the most vulnerable threatened and endangered species. System-environment management must allow expression of the sequences of physical performances through time characteristic of the system's recent development so that habitats will be available for all species of the community. Management then amounts to protection of the capacity of the system and its environment and not just maintenance of a single performance (e.g. providing a constant yearly flow instead of the seasonal cycle; reducing riparian ecosystems to riparian management units consisting of alder stands rather than diverse conifers, hardwoods, and shrubs). Management of a community as a capacity rather than a performance would mean management of the entire sere and not just a single favored seral stage. A community then is not simply the assemblage of populations found at a single time and in a given community habitat but is all associations of species found at that location through time. This kind of shift in management philosophy coupled with adoption of a classification system like the one here presented would facilitate maintenance of entire species pools rather than single species or single seral stages of communities.

Development of communities as seres is illustrated in Figure 20. A stream community as an entire sere derives its biological capacity from its species pool. A community is coupled to its community habitat, just as any single species is coupled to its habitat. A particular stream community habitat could be described as a stream segment embedded in higher level watershed systems. Stream communities are also a function of the terrestrial vegetative communities, which may be described as a polyclimax system of subcommunities, each representing biological responses to complex patterns of physical and chemical gradients. Species preferences could be represented as seasonally changing multivariate surfaces of physical-chemical gradients for which corresponding geographic areas hold the greatest probability for an individual to compete successfully for space.

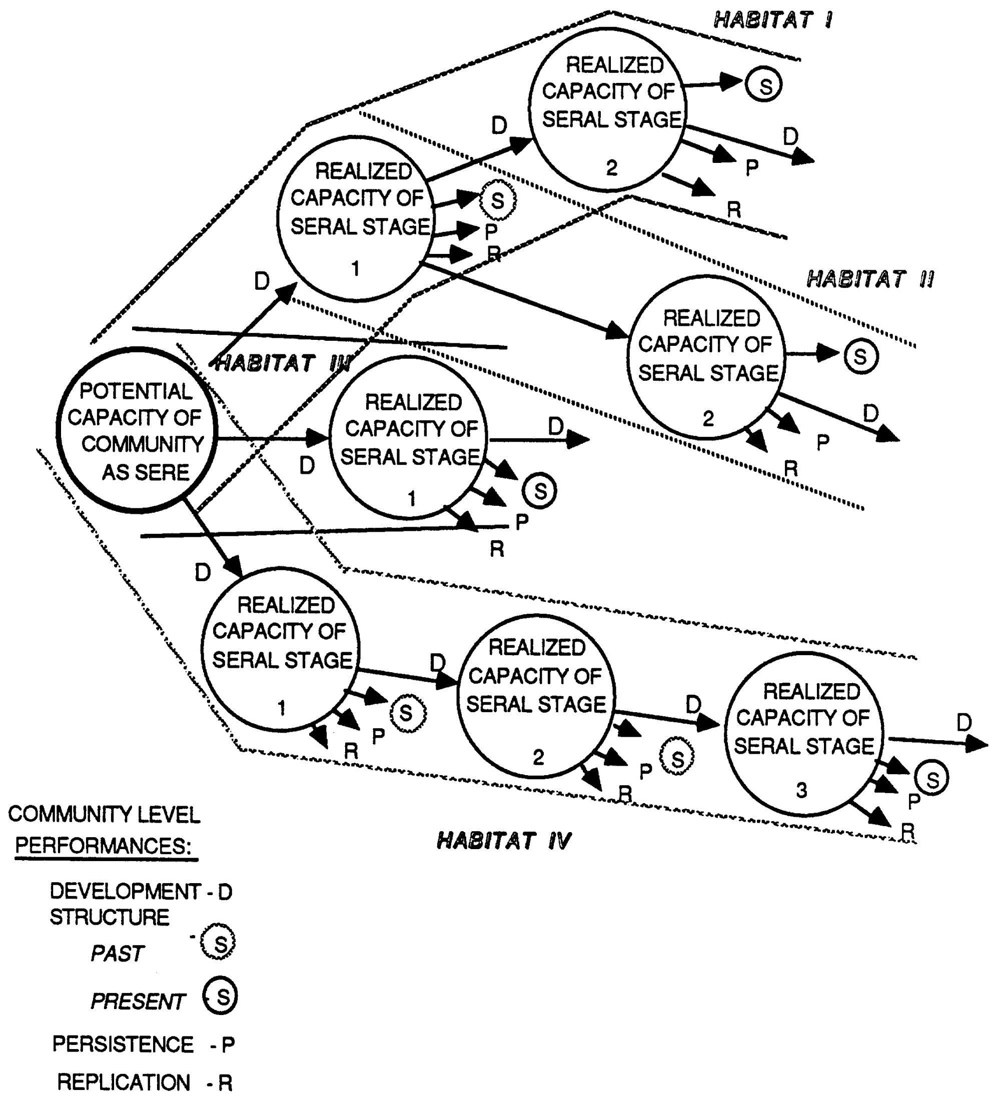


Figure 20. Polyclimax view of community development through time. Topographic and edaphic differences in the landscape unit determine developmental trajectories of subsystems of the landscape. After Warren (1979).

The polyclimax view of a community can be depicted as a set of geographic locations (topographically or edaphically defined) in a watershed. Sixteen such locations are shown in Figure 21. The sequence of biological developmental states at any location represents a sere. All seres in a watershed of a defined size could be considered a polyclimax, extending the standard polyclimax concept in time frame the way the community concept has been. Each location is presently either suitable occupied or suitable unoccupied habitat for any given species of the sere. The class of the site determines its probability of becoming suitable habitat during various time periods throughout its development. Tracking each location through developmental time shows the watershed to be comprised of a mosaic of suitable and unsuitable habitats. Suitability is diagrammed for only one representative species or community. Unsuitable habitats

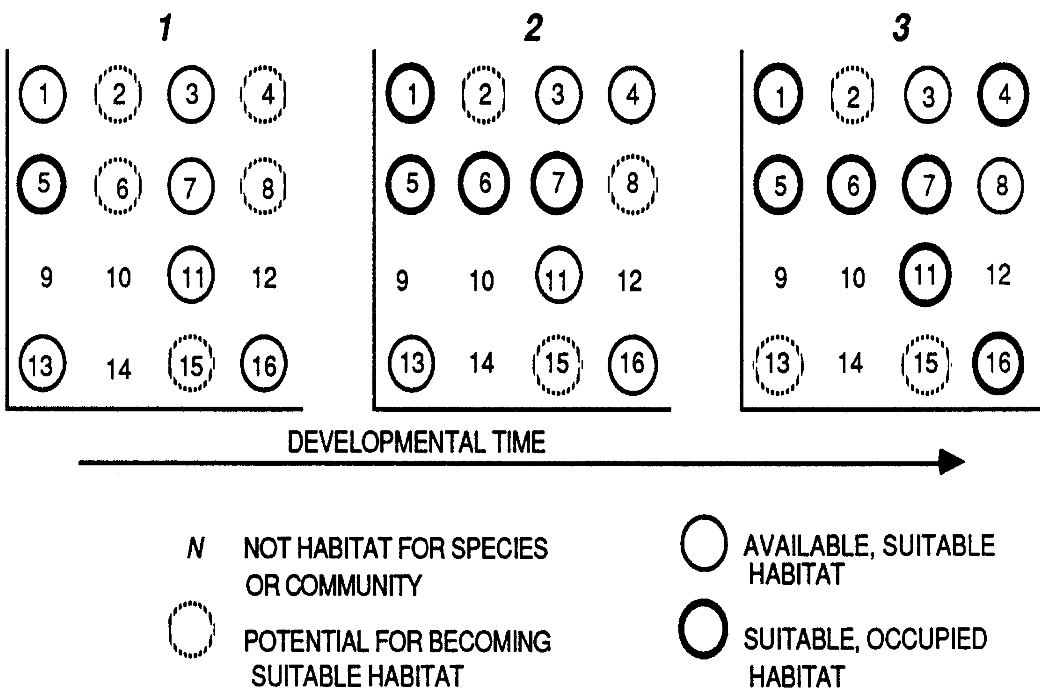


Figure 21. Concept of development of 16 contiguous land facets through time. At each point in time each facet either does not have the capacity to be habitat for a particular species or has the capacity to develop into suitable habitat, is available habitat, or is suitable, occupied habitat. After Warren (MS).

in Figure 21 are suitable for other species in the community or other communities in the polyclimax.

Proper management of the watershed involves maintenance of the capacities of its subsystems (sites in this example) to develop and persist. It also means not purposely altering all subsystems of a given class and performance at the same time. The pace of management (i.e. disturbance of habitats of a given class) must not exceed the rate of habitat performance types of the class coming into existence, assuming the present polyclimax is to be maintained in its present relative proportions. Changes in spatial organization, frequency, and duration of expression of habitat performance types (including vegetative performance) determine the probability of extinction of all species comprising the community.

Systems to be classified may be stationary (e.g. watersheds, stream networks, segments, watershed climate) or mobile (e.g. weather systems, some stream habitats). Classifiable physical structures in a stream such as riffles and pools can change positions in time. If the organism is an obligate riffle dweller in all its life stages, it must move with its habitat which is identified with the riffle physical structure within the context of a stream segment class. If the organism is stationary (as a tree), it must be adapted to all temporal variations of its habitat at a site. The topographic structure at the site of a tree may or may not change with time, but if the tree is adapted to its site class, the sequence of seasonal changes in the physical conditions at a site must be called its habitat. Physical structures or regimes at a site may demonstrate spatial or temporal variation.

If a stream segment is the physical unit considered, its class would define the seasonal and annual changes in habitat proportions and mobility. Habitat is defined with respect to the species or communities adapted to it. Many fish species utilize several physical structures (e.g. riffles, pools, backwaters) daily, so their habitat is defined as an assemblage of physical structures linked geographically to one another and hierarchically to higher and lower level systems, which define the capacity of the habitat.

Knowledge of habitat requirements of fish remains inadequate despite the decades of work in this field. The ability of many species to move from tributaries to mainstem and back during various portions of their life cycle means that essential habitat can involve several stream classes. Management of stream habitat exposed to logging, road building, grazing, and mining requires preservation of the physical performances of the essential stream classes corresponding to their normal range of variability under unperturbed conditions. After a stream has been heavily disturbed through management, the prospect of continued future management of the watershed and stream becomes certain. Habitat restoration after destruction is complicated by the fact that the characteristics of naturally occurring stream habitats are seldom known. They can be inferred from similar stream classes but this extrapolation necessitates a classification.

Stream restoration often focuses on increasing the abundance of the limiting habitat type. A factor typically thought to limit fish production is availability of overwintering habitat. If 99% of the fish are found in 1% of what was identified as overwintering habitat, it could be said that the 99% of the habitat which is of poor quality is basically not overwintering habitat at all. Non-use of an area by fish is not always an indication that it is not habitat. Competition can exclude fish from preferred habitat. Therefore, the species pool for any stream segment along with segment class is apt to control productivity of the system for any given species. Non-use can indicate poor seeding of the area, but it may also indicate that concepts of what constitutes habitat need to be refined. The present classification system is formed on hierarchical levels with capacities that must be associated at the proper scale with the biological systems. Habitat for an aquatic insect, a fish, and a tree require different scales of recognition of land systems and conceptual organization of units. Optimum stream productivity for any given fish species is dependent on an optimum ratio and spatio-temporal organization of habitat units. Ability to recognize and manage such units is still primitive.

Fishery management should involve maintenance of the capacities of the stream and watershed systems so that proper spatial assembly of the structures comprising habitat for managed species is provided. If the fish require a unique temporal sequence of physical structures or regimes, the capacity for this sequence must be maintained. The importance of these ecological principles in classification rests on the need to consider not only the frequency distribution of individual physical structures but also their spatial interrelationships. Larger scale physical structures formed from aggregates of individual structures may comprise the habitat of a mobile species, while another species may be confined to a single site with its temporal variation. A mental pre-classification is imposed on nature in the selection of scale of the smallest physical unit that is a building block of habitat, by applying our past experience with types of physical units to which organisms appear to respond.

Presently, all National Forests in the United States are planning management strategies for their lands for the next 10 to 15 years. Plans for timber harvest require consideration of cumulative effects on fisheries. Given the necessity of preventing adverse cumulative effects, it would seem that the theories or models for predicting fish resource condition would be well documented. Models of soil stability allow rough classification of soils into low, medium, and high erosion sensitivity classes. Each class is assigned its own equivalent clearcut percentage. A forest management model for prevention of resource damage is the timber harvest dispersion constraint. This assures that not over a certain percentage of a watershed is cut and that logical cutting units separate clearcuts. This constraint is modeled in FORPLAN and required by the National Forest Management Act (Section 219.27). It spreads out the environmental disturbance in an effort to prevent localized severe damage. There is an implicit assumption that cumulative effects will be non-significant provided that disturbances are dispersed, thresholds are not exceeded, and each activity is done according to best management practices (BMPs).

There are sediment models to calculate sediment yield to stream channels from timber harvest and road building. These models are used to predict a level of erosion-producing management activity that would not result in more than a fixed level of stream degradation. However, without knowledge of stream-specific usage by species and the physical nature of the stream and its watershed, the impacts on fish communities, the ability of sediment to be transported or stored, and the recovery rate of channel structure to equilibrium forms cannot be estimated. The other major empirical difficulty is, given accurate prediction of sediment yield to streams, how to convert a level of accelerated sedimentation or channel change to a projected change in habitat capacity to produce salmonid smolts.

Usually only 10 to 20 streams, at best, on a forest have been surveyed for biological, chemical, or physical data. Extrapolation of these data is not feasible without a classification, and channel slope is an insufficient tool. Meeting the necessity of managing all resources simultaneously requires an integrated classification. Dispersion of cutting units must satisfy not only fishery needs but also wildlife, soil resource, and forest vegetative community needs. Management of all resources requires a watershed classification that can integrate aquatic and terrestrial resources.

Such a classification at the stream level could be used to infer species distribution, smolt production potential, sediment production potential, acid rain effects, aquatic primary production potential, etc. An integrated classification could be used to evaluate which watersheds would provide the largest return on investment in stream habitat enhancement. By identification of capacity of watershed systems, streams could be identified with high potential for producing various species of fish or achieving successful supplementation with hatchery fish in different life history stages.

The classification also acts as a model for cumulative effects analysis. For example, potentials for cumulative effects of sedimentation on a given stream reach can be evaluated after classification of its watershed class and its present performance. The gravity model of spatial relations of watershed sub-units plus classification of certain upstream subwatersheds could aid in estimation of severity of threat to a study reach. If the study reach is a critical spawning or rearing area, a focus on the reach plus its environment is justified. Classification should be done, for example, to facilitate planning of timber harvest and management in certain terrain units with respect to critical downstream reaches. This requires modeling of the spatial and capacity relationships of the site to its environment. In this sense, classification is problem-oriented and is not done simply for the sake of identifying similarities.

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VII APPENDICES

A. APPENDIX A

1. Computer Program ALTXYZ Used to Compute Slope, Aspect, and Altitude of Triangular Facets of Terrain.

```
      PROGRAM ALTXYZ
C     PROGRAM MODIFIED APRIL 25,1982;ADDED VECTOR
CALCULATIONS
C     ON JUNE 22,1982;MODIFY ORIGINAL PROG JUNE 28,1982;
C     MAJOR CHANGES JULY 1,1982;DEC.15.1982 CORRECT ERROR(IF
SUBNO=
C     2)ACi=0.  TO BE USED WITH A 40 BY 30 ALT MATRIX
      LOGICAL NAME(11),LF,CR,NOM(11)
      DIMENSION NTOTSL(12),TOTSL(23),AVSL(23),PCBR(12),PCSL(12)
      INTEGER ALTBR(23,12),ALTSL(23,12),NTOTBR(12),ALT(40,30),
     cTOTNO(23),SUBNO,SLOPBR(12,12)
      DATA TOTSL/23*0./,NTOTSL/12*0/,ALTBR/276*0/,NTOTBR/12*0/
      DATA ALTSL/276*0/,TOTNO/23*0/,SLOPBR/144*0/,PCBR/12*0./
      DATA PCSL/12*0./,AVSL/23*0./
C     SET ALT MATRIX DIMENSIONS
      IMAT=40
      JMAT=30
C     SET DIMENSION OF ALT (23 INTERVALS)
      NX1A=23
      TOTA=0.
      TOTB=0.
      TOTC=0.
      COUNT=0.
      TSLOPE=0.0
C     SET CLASS INTERVALS FOR SLOPE,ALT,BEARING FREQ.DISTRIB.
      CLASSS=5.001
      CLASSA=2.001
      CLASSB=30.001
      NKOUNT=0
      SUMALT=0.
      LF=10
      CR=13
  220 FORMAT(' ENTER 11 CHARACTER FILENAME')
      WRITE(3,220)
  221 FORMAT(80A1)
  222 FORMAT(1X,79A1)
      WRITE(3,221)CR,LF
      READ(3,221)(NAME(I),I=1,11)
```

```
      WRITE(2,222)(NAME(I),I=1,11)
      CALL OPEN(6,NAME,2)
C
  250 FORMAT(' ENTER 11 CHARACTER FILENAME FOR DATA STORAGE')
      WRITE(3,250)
      WRITE(3,221)CR,LF
      READ(3,221)(NOM(I),I=1,11)
      CALL OPEN(7,NOM,2)
C
  230 FORMAT(' WRITE CODE, 1=PRINT OUT AVALT,BEAR,SLOPE;2=NO
PRINT')
  231 FORMAT(I1)
      WRITE(3,230)
      WRITE(3,221)CR,LF
      READ(3,231)NCODE
C
  232 FORMAT(' WRITE CODE, 1=STORE AVALT,BEAR,SLOPE;2=NO
STORAGE')
      WRITE(3,232)
      WRITE(3,221)CR,LF
      READ(3,231)MCODE
C
C     READ DATA-- ALTITUDE MATRIX ARRANGED ON I,J COORDINATES
    1 FORMAT(40(I2,1X))
C
      DO 10 JJ=1,JMAT
      J=JMAT+1-JJ
      READ(6,1,END=416)(ALT(I,J),I=1,IMAT)
   10 CONTINUE
C
C     FIND SETS OF 3 POINTS TO CALCULATE
AVALT,SLOPE,ORIENTATION
C     WRITE AVERAGE ALTITUDE,SLOPE, AND BEARING FOR EACH
TRIANGLE
C     WRITE OUT AVALT,SLOPE,BEAR, TO DISC IF MCODE=1
  415 FORMAT('0I  J  NN  AVALT  SLOPE  BEAR',/)
  416 WRITE(2,415)
  413 FORMAT(10X,3(I2,1X),3(F5.1,2X))
  418 FORMAT(3(I2,1X),3(F5.1,2X),A1)
C
   11 DO 20 JJ=1,JMAT
      J=JMAT+1-JJ
      DO 20 I=1,IMAT
```

```
      IF(ALT(I,J).EQ.99)GOTO 20
      L=I+1
      IF(L.GT.IMAT)GOTO 20
      IF(ALT(L,J).EQ.99)GOTO 20
      IF(J.EQ.1)GOTO 3
      K=J-1
      IF(ALT(L,K).EQ.99)GOTO 3
      SUBNO=1
      CALL SUB(ALT(I,J),ALT(L,J),ALT(L,K),AVALT,BEAR,
     cSLOPE,TOTA,TOTB,TOTC,COUNT,SUBNO)
      IF(NCODE.EQ.1)WRITE(2,413)I,J,SUBNO,AVALT,SLOPE,BEAR
      IF(MCODE.EQ.1)WRITE(7,418)I,J,SUBNO,AVALT,SLOPE,BEAR,LF
      CALL ALSLBR(AVALT,SLOPE,BEAR,ALTSL,TOTSL,ALTBR,SLOPBR,
     cTSLOPE,SUMALT,NKOUNT,CLASSA,CLASSS,CLASSB)
    3 N=J+1
      IF(N.GT.JMAT)GOTO 20
      IF(ALT(I,N).EQ.99)GOTO 20
      SUBNO=2
      CALL SUB(ALT(I,J),ALT(L,J),ALT(I,N),AVALT,BEAR,
     cSLOPE,TOTA,TOTB,TOTC,COUNT,SUBNO)
      IF(NCODE.EQ.1)WRITE(2,413)I,J,SUBNO,AVALT,SLOPE,BEAR
      IF(MCODE.EQ.1)WRITE(7,418)I,J,SUBNO,AVALT,SLOPE,BEAR,LF
      CALL ALSLBR(AVALT,SLOPE,BEAR,ALTSL,TOTSL,ALTBR,SLOPBR,
     cTSLOPE,SUMALT,NKOUNT,CLASSA,CLASSS,CLASSB)
   20 CONTINUE
C
C    ---------------------------------------------------------
C
C    CALCULATE TOTAL NO.IN EACH ALT CLASS (ROW TOTALS)
      DO 225 NX1=1,NX1A
      DO 225 NX2=1,12
      TOTNO(NX1)=TOTNO(NX1)+ALTSL(NX1,NX2)
  225 CONTINUE
C
C    CALCULATE AVSLOPE FOR EACH ALT CLASS
      DO 600 NX1=1,NX1A
      IF(TOTNO(NX1).GT.0)GOTO 601
      AVSL(NX1)=0.0
      GOTO 600
  601 AVSL(NX1)=TOTSL(NX1)/FLOAT(TOTNO(NX1))
  600 CONTINUE
C
C    WRITE ALTITUDE SLOPE FREQ.TABLE
```

```
  46 FORMAT(1H1,79A1)
     IF(NCODE.EQ.1)WRITE(2,46)NAME
  43 FORMAT('0         ALTITUDE-SLOPE FREQUENCY DISTRIBUTION
   c            TOTNO AVSL  ')
  44 FORMAT(' ALT/   1    2    3    4    5    6    7    8    9   10
   c 11   12',/,' CLASS')
  65 FORMAT('0       0    5   10   15   20   25   30   35   40   45
   c  50   55')
  70 FORMAT('        5   10   15   20   25   30   35   40   45   50
   c   55   60',/)
     WRITE(2,43)
     WRITE(2,44)
     WRITE(2,65)
     WRITE(2,70)
  45 FORMAT(1X,I2,'-',I2,1X,12(I2,3X),I3,2X,F4.1)
     NN=0
     NM=2
     DO 300 NX1=1,NX1A

WRITE(2,45)NN,NM,(ALTSL(NX1,NX2),NX2=1,12),TOTNO(NX1),AVSL(NX1)
     NN=NN+2
     NM=NM+2
 300 CONTINUE
C
C    CALCULATE TOTAL NUMBER IN EACH SLOPE CATEGORY(COLUMN
TOTALS)
     DO 360 NX2=1,12
     DO 360 NX1=1,NX1A
     NTOTSL(NX2)=NTOTSL(NX2)+ALTSL(NX1,NX2)
 360 CONTINUE
 365 FORMAT(' TOTAL',12(I3,2X))
     WRITE(2,365)(NTOTSL(NX2),NX2=1,12)
C
C    CALCULATE % OF TOTAL NO. OF TRIANGLES IN EACH CATEGORY
 366 FORMAT(' %     ',12(F4.1,1X),/)
     DO 377 N=1,12
     PCSL(N)=(FLOAT(NTOTSL(N))/COUNT)*100.
 377 CONTINUE
     WRITE(2,366)(PCSL(N),N=1,12)
C
C    WRITE ALTITUDE-BEARING FREQ. TABLE INCLUDING % OF
TRIANGLES
C    IN EACH ALTITUDE CLASS; APPEND COLUMN TOTALS AT BOTTOM
```

```
  54 FORMAT('0ALT/      ALTITUDE-BEARING FREQUENCY
DISTRIBUTION')
  75 FORMAT('0CLASS  0   30   60   90  120  150  180  210  240
    c 270  300  330')
  80 FORMAT('       30   60   90  120  150  180  210  240  270
    c  300  330  360  %'/)
     WRITE(2,54)
     WRITE(2,75)
     WRITE(2,80)
  55 FORMAT(1X,I2,'-',I2,1X,12(I2,3X),F4.1)
     NN=0
     NM=2
     DO 510 NX1=1,NX1A
     PCALT=(FLOAT(TOTNO(NX1))/COUNT)*100.
     WRITE(2,55)NN,NM,(ALTBR(NX1,NX2),NX2=1,12),PCALT
     NN=NN+2
     NM=NM+2
 510 CONTINUE
C
C     CALCULATE TOTAL NUMBER IN EACH BEARING CATEGORY
(COLUMN TOT.)
     DO 380 NX2=1,12
     DO 380 NX1=1,NX1A
     NTOTBR(NX2)=NTOTBR(NX2)+ALTBR(NX1,NX2)
 380 CONTINUE
     WRITE(2,365)(NTOTBR(NX2),NX2=1,12)
C
C     CALCULATE % OF TOTAL NO. OF TRIANGLES IN BEARING
CATEGORIES
 382 FORMAT(' %     ',12(F4.1,1X))
     DO 381 NX2=1,12
     PCBR(NX2)=(FLOAT(NTOTBR(NX2))/COUNT)*100.
 381 CONTINUE
     WRITE(2,382)(PCBR(NX2),NX2=1,12)
C
 561 FORMAT('1     SLOPE-BEARING FREQUENCY DISTRIBUTION',/,
    c'0BEAR/  0   30   60   90  120  150  180  210  240
    c 270  300  330',/,
    c' SLOPE 30   60   90  120  150  180  210  240  270
    c  300  330  360'/)
     WRITE(2,561)
 563 FORMAT(1X,I2,'-',I2,1X,12(I2,3X))
     NN=O
```

```
      NM=5
      DO 562 NX1=1,12
      WRITE(2,563)NN,NM,(SLOPBR(NX1,NX2),NX2=1,12)
      NN=NN+5
      NM=NM+5
  562 CONTINUE
C
C     CALCULATION OF AVERAGE ALTITUDE
      TOTALT=0.0
      NCOUNT=0
      DO 150 J=1,JMAT
      DO 150 I=1,IMAT
      IF(ALT(I,J).EQ.99)GOTO 150
      TOTALT=FLOAT(ALT(I,J))+TOTALT
      NCOUNT=NCOUNT+1
  150 CONTINUE
C
C     CALCULATE AVERAGE SLOPE OF ALL TRIANGLES
      AVSLOP=TSLOPE/COUNT
   83 FORMAT('0       AVERAGE SLOPE=',F4.1,'   TOTAL NO. POINTS=',I3)
      WRITE(2,83)AVSLOP,NCOUNT
C
   84 FORMAT('0       AVERAGE OF ALL ALTITUDE POINTS=',F4.1,/,
     c'        AVERAGE OF AVALT TRIANGLES=',F4.1)
      XALT=TOTALT/FLOAT(NCOUNT)
      GAVALT=SUMALT/FLOAT(NKOUNT)
      WRITE(2,84)XALT,GAVALT
C
C     CALCULATE VECTOR STRENGTH (LENGTH OF VECTOR RESULTANT
OF ALL
C     VECTOR OBSERVATIONS) AND VECTOR STRENGTH (R) IN UNIT
VECTOR
      R1=SQRT(TOTA**2.0+TOTB**2.0+TOTC**2.0)
      R=R1/(COUNT-1.)
C
C     CALCULATE L,M,N FOR MEAN VECTOR (BEST EST. OF TRUE
DIRECTION COS)
      XL=TOTA/R1
      XM=TOTB/R1
      XN=TOTC/R1
C
  853 FORMAT('0     DIRECTION COSINES OF MEAN VECTOR',/,
     c'   L= ',E12.4,' M= ',E12.4,' N= ',E12.4)
```

```
      WRITE(2,853)XL,XM,XN
  854 FORMAT('0     TOTAL OF DIRECTION COSINES OF PLANES',/,
     c'     TOTA=',E12.5,'  TOTB=',E12.5,'  TOTC=',E12.5)
      WRITE(2,854)TOTA,TOTB,TOTC
C
C     CALCULATE GRADIENT VECTOR IN I,J COORDINATES
C     SIGN DETERMINES QUADRANT IN UPHILL DIRECTION
      GVi=-TOTA/TOTC
      GVj=-TOTB/TOTC
C
C     CALCULATE SLOPE AND ORIENTATION FOR MEAN VECTOR
      IF(ABS(GVi).EQ.0.0.AND.ABS(GVj).EQ.0.0)GOTO 650
      IF(ABS(TOTA).NE.0.0)GOTO 651
      ORENTN=90.0
      GOTO 652
  650 BEARN=180.0
      SLOPEN=0.0
      GOTO 653
  651 ORENTN=(ATAN(ABS(TOTB/TOTA)))*57.2958
  652 SLOPEN=(SQRT(TOTA**2.+TOTB**2.))/ABS(TOTC)
      SLOPEN=ATAN(SLOPEN)*57.2958
      IF(GVi.GE.0.0.AND.GVj.GE.0.0)BEARN=270.-ORENTN
      IF(GVi.GE.0.0.AND.GVj.LE.0.0)BEARN=270.+ORENTN
      IF(GVi.LE.0.0.AND.GVj.GE.0.0)BEARN=90.+ORENTN
      IF(GVi.LE.0.0.AND.GVj.LE.0.0)BEARN=90.-ORENTN
C
  850 FORMAT('0     SLOPE OF MEAN VECTOR=',F5.1,' BEARING OF MEAN
VECTO
     cR=',F6.1,/,'      R1 FOR MEAN VECTOR=',E12.5,'  R=',E12.5)
  653 WRITE(2,850)SLOPEN,BEARN,R1,R
  851 FORMAT('      NUMBER OF TRIANGULAR SURFACES=',2X,F5.0)
      WRITE(2,851)COUNT
C     CALCULATION OF FISHER'S DISPERSION FACTOR
      ESTK=(COUNT-1.0)/(COUNT-R1)
  852 FORMAT('      FISHERS DISPERSION FACTOR=',E12.5)
      WRITE(2,852)ESTK
C
      ENDFILE 6
      ENDFILE 7
      END
C     --------------------------------------------------------
      SUBROUTINE
SUB(AIJ,ALJ,ALKIN,AVALT,BEAR,SLOPE,TOTA,TOTB,TOTC,
```

```
     cCOUNT,SUBNO)
      REAL ORIENT
      INTEGER AIJ,ALJ,ALKIN,SUBNO
C
C    COUNT NUMBER OF TRIANGULAR SURFACES
      COUNT=COUNT+1.
C
C    DETERMINE VECTORS AB AND AC WHERE AB IS (B1-A1)i+(B2-A2)j+
C    (B3-A3)k;FOR CALCULATIONS USING SUBNO 1(ie. TRIANGLES WITH
C    VERTEX DOWN) (B1-A1)=L-I;(B2-A2)=J-J;(B3-A3)=ALT(L,J)-ALT(I,J);
C    THESE CALCS ARE FOR VECTOR AB. FOR VECTOR AC, (B1-A1)=I-I;
C    (B2-A2)=K-J;(B3-A3)=ALT(L,K)-ALT(I,J).  FOR TRIANGLE WITH
C    VERTEX UP(SUBNO 2) CORNERS OF TRIANGLE (A,B,C) ARE (I,J),
C    (L,J),(I,N).  AVALT IN SUBNO 1 ARE STORED IN AVALT(I,J,1);
C    THOSE FOR SUBNO 2 ARE STORED IN AVALT(I,J,2).  SINCE ALT
MATRIX
C    IS REGULAR, SUBTRACTION OF COORDINATES TO GET DIRECTION
NO.
C    IS ELIMINATED.  SIDES OF ISOCELES TRIANGLE ARE 1/6 MI.(880 FT.).
C    HT. OF TRIANGLE IS 880.'.  ALT. CONTOUR INTERVAL IS 80'.
      ABi=880.
      ABj=0.
      ABk=(FLOAT(ALJ)-FLOAT(AIJ))*80.
C
      ACi=880.
      IF(SUBNO.EQ.2)ACi=0.
      ACj=880.
      IF(SUBNO.EQ.1)ACj=-880.
      ACk=(FLOAT(ALKIN)-FLOAT(AIJ))*80.
C
C    DETERMINE CROSS PRODUCT OF VECTORS
C    NORMAL VECTOR IS (ABXAC)i+(ABXAC)j+(ABXAC)k
      ABXACi=(ABj*ACk-ABk*ACj)
      ABXACj=(ABk*ACi-ABi*ACk)
      ABXACk=(ABi*ACj-ABj*ACi)
C
C    CALCULATE GRADIENT VECTOR IN I,J COORDINATES
C    SIGN DETERMINES QUADRANT IN UPHILL DIRECTION
      GVi=-ABXACi/ABXACk
      GVj=-ABXACj/ABXACk
C
C    CALCULATE MAXIMUM SLOPE
```

```
C     AND NUMBER OF RADIANS AND DEGREES FROM X-AXIS (EAST
ORIENTATION)
C     RECALCULATE BEARING WRT. MAP NORTH--ORIENTATION
(ASPECT)
C     CONVERTED TO DOWNHILL DIRECTION
      IF(ABS(GVi).EQ.0.0.AND.ABS(GVj).EQ.0.0)GOTO 720
      IF(ABS(ABXACi).NE.0.0)GOTO 710
      ORIENT=90.0
      GOTO 740
  720 BEAR=180.0
      SLOPE=0.0
      GOTO 730
  710 ORIENT=ATAN(ABS(ABXACj/ABXACi))
      ORIENT=ABS(ORIENT*(57.2958))
  740 SLOPE=(SQRT(ABXACi**2.+ABXACj**2.))/ABS(ABXACk)
      SLOPE=ATAN(SLOPE)*57.2958
C
      IF(GVi.GE.0.0.AND.GVj.GE.0.0)BEAR=270.-ORIENT
      IF(GVi.GE.0.0.AND.GVj.LE.0.0)BEAR=270.+ORIENT
      IF(GVi.LE.0.0.AND.GVj.GE.0.0)BEAR=90.+ORIENT
      IF(GVi.LE.0.0.AND.GVj.LE.0.0)BEAR=90.-ORIENT
C
  730 AVALT=(FLOAT(AIJ)+FLOAT(ALJ)+FLOAT(ALKIN))/3.0
C
C     CALCULATE DIRECTION COSINES OF COMPONENTS OF N VECTOR
      D=SQRT(ABXACi**2.+ABXACj**2.+ABXACk**2.)
      COSA=ABXACi/D
      COSB=ABXACj/D
      COSC=ABXACk/D
C
C     IF NORMAL VECTOR IS POINTED DOWNWARD(INTO GROUND),
MULTIPLY ALL
C     COMPONENTS BY (-) TO GET THE VECTOR IN UPWARD DIRECTION
      IF(COSC.GT.0.)GOTO 750
      COSA=(-COSA)
      COSB=(-COSB)
      COSC=(-COSC)
C
C     SUM THE DIRECTION COSINES FOR ALL N VECTORS
  750 TOTA=TOTA+COSA
      TOTB=TOTB+COSB
      TOTC=TOTC+COSC
C
```

```
      RETURN
      END
C     ------------------------------------------------------
      SUBROUTINE
ALSLBR(AVALT,SLOPE,BEAR,ALTSL,TOTSL,ALTBR,SLOPBR,
     cTSLOPE,SUMALT,NKOUNT,CLASSA,CLASSS,CLASSB)
      DIMENSION TOTSL(23)
      INTEGER ALTSL(23,12),ALTBR(23,12),SLOPBR(12,12)
C     DETERMINE NUMBER OF OBSERVATIONS IN EACH
AVALTITUDE-SLOPE CLASS
C     AND TOTAL OF SLOPES FOR EACH ALT CLASS;STORE AS INTEGER
TO
C     TRUNCATE TO WHOLE NO.;CLASS VALUES ARE CLASS INTERVALS
PLUS
C     0.001 SO NO. IS LESS THAN NEXT WHOLE NO.
      NX1=AVALT/CLASSA+1.
      NX2=SLOPE/CLASSS+1.
      NX3=BEAR/CLASSB+1.
      ALTSL(NX1,NX2)=ALTSL(NX1,NX2)+1
      TOTSL(NX1)=TOTSL(NX1)+SLOPE
      ALTBR(NX1,NX3)=ALTBR(NX1,NX3)+1
      SLOPBR(NX2,NX3)=SLOPBR(NX2,NX3)+1
      TSLOPE=SLOPE+TSLOPE
      SUMALT=AVALT+SUMALT
      NKOUNT=NKOUNT+1
      RETURN
      END
C    ------------------------------------------------------
```

B. APPENDIX B

1. Computer Program SUN Used to Calculate Solar Radiation Loads on Triangular Facets on Any Day of the Year, Accounting for Topographic Shading

```
      PROGRAM SUNBAT
C     AUGUST 4,1982; THIS PROGRAM IS DESIGNED TO BE USED WITH

C     PROGRAM ALTXYZ TO DETERMINE DISTRIBUTION OF SUNLIGHT
ON
C     SURFACES OF THE WATERSHED USING DATA STORED ON AVALT,
C     SLOPE AND BEARING OF SURFACES FROM ALTXYZ PROGRAM AS
INPUT.
C     MODIFIED OCT.17,1982 FROM SUN.FOR TO BE RUN IN BATCH MODE
C     MODIFIED JAN.31,1983 TO ACCOMODATE LARGER ARRAY SIZE
C     MODIFIED FEB.20,1983 TO ALLOW ACCUM.OF DATA IN AN
ARRAY(100)
C     BEFORE WRITING TO DISK
C     MODIFY ON FEB.18,1984--CHANGE FORM OF OUTPUT AND MOVE
C     SBEAR+ROT;MODIFY FEB.19,1984 FOR NDCODE PLACEMENT,LAP
COUNT
C     MODIFY MAR.11,1984 TO ALLOW CALC.OF SDEV.OF
RADIATION;ALSO
C     TO CORRECT CALC.OF TPMXID AND TPLID ON HORIZ.
C     COPY TO FILE SUNBAT2 TO ALLOW OUTPUT OF INTERMED.CALCS.
C     ON APRIL 5, 1984
C     MODIFIED TO SUNBAT4 MAY 18,1984 TO CORRECT FOR ROTATION
ERROR
C     AND TO ALLOW CALC. OF GROUND SURFACE RAD W/O
TOPOG.;ALSO
C     ELIMINATE REPETITIVE CALC.OF TERR VECTORS;CHANGE LINE
C     IF (SALT.LT.BIGANG) TO .LE.
      LOGICAL NAME(11),LF,CR,NALT(11),NOUT(11),NSTOR(11)
      DIMENSION NBRSUN(16),T(40),SBEAR(40),TIME(40),PCIDBR(16)
      DIMENSION Z(40),SUNL(40),SUNM(40),SUNN(40),SALT(40),SLITE(40)
      DIMENSION XLITE(40),SID(25),SSID(25),LALT(25),GSRZ(100)
      DIMENSION IIZ(100),JJZ(100),NNZ(100),AVALTZ(100),SLOPEZ(100),
     cBEARZ(100),DZ(100),PCMXZ(100)
      INTEGER BRSUN(16,12),ALT(40,30),ALTSUN(23,16)
      REAL ID,IO,LAT,IDPOT,IDPMX,M,IDZ(100),IDPOTZ(100)
C     ENTER VALUE FOR LATITUDE,CLASS INTERVALS FOR BEARING
C     AND RADIATION;SCALE FACTOR=880'/INTERVAL ON I AND J AXES.
```

```
C    TID=TOTAL RADIATION RECEIVED DAILY ON WHOLE BASIN
C    TAREA=TOTAL SURFACE AREA OF BASIN ACCOUNTING FOR SLOPE
C    NTOT=TOTAL NO. OF TRIANGLES; ID=RADIATION REACHING
SURFACE
C    AT EACH BEARING, AND ACCUMULATED FOR ALL BEARINGS PER
TRIANGLE
C    BRSUN=SLOPE BEARING-DAILY RADIATION FREQUENCY DISTRIB.
C    CX,CY=COORDINATES OF CENTER OF TRIANGLES
C    SBEAR=BEARING OF SUN; BIGANG=BIG ANGLE
(MAX.),TOPOGRAPHIC
C    SHADING CAUSED BY ANGLE FROM AVALT TO A PT. ON BASIN IN
DIRECTION
C    OF SBEAR; TIME=NO. OF MINUTES DURING WHICH SUN IS ABOVE
C    HORIZON (NOT JUST
TOPOG);RPD=RADIANS/DEGREE;DPR=DEGREES/RADIAN
C    T-HOUR ANGLE;Z-ZENITH ANGLE;AZ-AZIMUTH;NQ-INTERVAL OF
SUN MOVEMENT
C    OF 7.5 DEG. CENTERED ON AZ=0.DEG;
C
C    SET VALUE FOR ATMOSHPERIC TRANSMISSIVITY; GARNIER AND
OHMURA;
C    REVFEIM,K.J.A.1978. J.APPL.METEOR.17:1126-1131.
      P=0.75
C    SET SOLAR CONSTANT;2.00 CAL/CM2/MIN=83680.JOULES/M2/MIN
C    WILLIAMS,L.D.,R.G.BARRY,AND J.T.ANDREWS. 1971.
C    J.APPL.METEOR. 11:526-533.-ALSO CRC PHYSICS HANDBOOK.1979
      LAT=45.5
      RPD=.174533E-1
      DPR=57.2958
      SCALE=880.
      CLASSB=30.001
      CLASSI=.20001E+7
      LF=10
      CR=13
C
  260 FORMAT(' ENTER SUN DECLINATION AND JULIAN DAY AS
F6.2,1X,I3')
  221 FORMAT(80A1)
      WRITE(3,260)
      WRITE(3,221)CR,LF
  261 FORMAT('0 SUN DECLINATION=',F6.2,'  JULIAN DAY=',I3)
  262 FORMAT(F6.2,1X,I3)
      READ(3,262)DECL1,JUL
```

```
C
C    CONVERT LATITUDE AND DECLINATION TO RADIANS
      LAT=LAT*RPD
      DECL=DECL1*RPD
C
  533 FORMAT(' ENTER MONTH, DAY, YEAR; FORMAT I2,1X,I2,1X,I4')
  534 FORMAT(I2,1X,I2,1X,I4)
      WRITE(3,533)
      WRITE(3,221)CR,LF
      READ(3,534)MONTH,IDAY,IYEAR
C
  220 FORMAT(' ENTER 11 CHARACTER CONTROL FILENAME
CONTAINING'/
     c' FILENAMES OF ALTMATRICES, OUTPUT FILES FROM ALTXYZ,
AND'/
     c' DATA STORAGE FILENAMES')
      WRITE(3,220)
      WRITE(3,221)CR,LF
  222 FORMAT(1X,79A1)
      READ(3,221)(NAME(I),I=1,11)
      CALL OPEN(5,NAME,2)
C
  223 FORMAT(1X,11A1,1X,11A1,1X,11A1,1X,F5.1)
  229 FORMAT(1H1,11A1,1X,11A1,1X,11A1)
C
C    ---------------------------------------------
  903 DO 525 J=1,12
      DO 525 I=1,16
      BRSUN(I,J)=0
  525 CONTINUE
      DO 526 I=1,16
      PCIDBR(I)=0.
      NBRSUN(I)=0
  526 CONTINUE
      DO 527 J=1,16
      DO 527 I=1,23
      ALTSUN(I,J)=0
  527 CONTINUE
      DO 528 I=1,25
      SSID(I)=0.
      SID(I)=0.
      LALT(I)=0
  528 CONTINUE
```

```
      READ(5,223,END=902)(NALT(I),I=1,11),(NOUT(I),I=1,11),(NSTOR(I),
     cI=1,11),ROT
      WRITE(2,229)(NALT(I),I=1,11),(NOUT(I),I=1,11),(NSTOR(I),
     cI=1,11)
      WRITE(2,222)(NAME(I),I=1,11)
  286 FORMAT(' DEGREES OF ROTATION OF BASIN=',F5.1)
      WRITE(2,286)ROT
      WRITE(2,261)DECL1,JUL
C
      NTOT=0
      IO=83680.
      IDPMX=0.0
      ID=0.
      IDPOT=0.
      TPLID=0.
      TID=0.
      TPMXID=0.0
      TAREA=0.
      LSTN=0
      TGRAD=0.
      GRAD=0.
      NDCODE=0
      LAP=0
C
      CALL OPEN(6,NALT,2)
      CALL OPEN(7,NOUT,2)
      CALL OPEN(8,NSTOR,2)
C
C     READ DATA-- ALTITUDE MATRIX ARRANGED ON I,J COORDINATES
    1 FORMAT(40(I2,1X))
      DO 5 JA=1,30
      J=31-JA
      READ(6,1,END=11)(ALT(I,J),I=1,40)
    5 CONTINUE
C     ------------------------------------------
      IF(LAP.GE.1)GOTO 100
C
C     CALCULATE NO. OF HOURS IN HALF DAY(H=ANGULAR DIST.(DEG)
C     OF TRAVEL; SELLERS,W.D.); S=NO.OF INTERVALS OF ANGULAR
C     MOVEMENT OF 30 MIN. DURATION (7.5 DEG.); NT=TOTAL NO.OF
C     INTERVALS IN DAY; FHH=NO.OF DEGREES OF MOVEMENT
REMAINING
```

```
C     IN FIRST PARTIAL INTERVAL ABOVE W AND E HORIZON OR
FRACTIONAL
C     HALF-HOUR INTERVAL; SBEAR=BEARING OF SUN
WRT.N=0,S=180,E=90.
C     TIME=NO.OF MINUTES TRAVEL OF SUN DURING INTERVAL OF
PARTIAL
C     INTERVAL;THERE ARE (NT-1) FULL 7.5 DEG.INTERVALS PLUS 2
PARTIAL
C     INTERVALS OF 0.TO 3.75 DEG EACH.
C     ID-DAILY CUMULATIVE RADIATION (JOULES) ON 1M2 AREA ON
GROUND
C     SURFACE INCLUDING TOPOG.SHADING
   11 COH=-((SIN(LAT))/(COS(LAT)))*((SIN(DECL))/
     c(COS(DECL)))
      H=90.-(ATAN(COH/SQRT(1.-COH*COH)))*DPR
      S=H/7.5
      IS=S
      FHH=S-FLOAT(IS)
      FHH=FHH*7.5
      NT=(2*IS)+1
      N=1
C     PARTIAL INTERVAL ON EAST
      T(N)=H-(FHH+3.75)/2.
      TIME(N)=((FHH+3.75)/15.)*60.
      CALL ZENAZ(LAT,DECL,T(N),Z(N),RPD,DPR,AZ1)
      SBEAR(N)=180.-AZ1
      N=N+1
C     FIRST FULL INTERVAL ON EAST SIDE
      T(N)=H-FHH-7.5
      TIME(N)=30.
      CALL ZENAZ(LAT,DECL,T(N),Z(N),RPD,DPR,AZ)
      SBEAR(N)=180.-AZ
      N=N+1
C     ALL REMAINING FULL INTERVALS ON E AND W OF SOUTH
      NQ=(NT+1)/2
      HH=7.5
  290 IF(N.GT.NQ)HH=-7.5
      T(N)=T(N-1)-HH
      TIME(N)=30.
      CALL ZENAZ(LAT,DECL,T(N),Z(N),RPD,DPR,AZ)
      IF(N.GT.NQ)GOTO 89
      SBEAR(N)=180.-AZ
      GOTO 90
```

```
   89 SBEAR(N)=180.+AZ
   90 N=N+1
      IF(N.LT.NT)GOTO 290
C     PARTIAL INTERVAL ON WEST SIDE
      T(N)=T(1)
      TIME(N)=TIME(1)
      Z(N)=Z(1)
      SBEAR(N)=180.+AZ1
C
C     CALCULATE DIRECTION COSINES OF SUN VECTOR; SEE TAFF
C     DETERMINE RADIATION LOSS DUE TO AIR MASS; GARNIER,B.J.
C     AND A.OHMURA. 1968. J.APPL. METEOR. 7:796-800.
C     CALCULATE ALTITUDE OF SUN
      DO 101 N=1,NT
      SBEAR(N)=SBEAR(N)+ROT
      IF(SBEAR(N).GE.360.)SBEAR(N)=SBEAR(N)-360.
      SUNL(N)=(SIN(Z(N)*RPD))*(COS(180.*RPD+SBEAR(N)*RPD))
      SUNM(N)=(SIN(Z(N)*RPD))*(SIN(180.*RPD+SBEAR(N)*RPD))
      SUNN(N)=(COS(Z(N)*RPD))
      M=1./COS(Z(N)*RPD)
      P2THEM=P**M
      SLITE(N)=IO*P2THEM*TIME(N)
      XLITE(N)=SLITE(N)*COS(Z(N)*RPD)
      SALT(N)=90.-Z(N)
  101 CONTINUE
C     ---------------------------------------------
  802 FORMAT(1X,F6.1,1X,2(F5.2,1X),F4.1,1X,F5.1,1X,2(E13.5))
C
  100      N=1
C     READ DATA STORED ON DISC FOR AVALT, SLOPE, BEARING OF
TRIANGLES
    2 FORMAT(3(I2,1X),3(F5.1,2X))
      READ(7,2,END=905)II,JJ,NN,AVALT,SLOPE,BEAR
C
C     DETERMINE COORDINATES OF CENTER OF TRIANGLE
      IF(NN.EQ.1)GOTO 18
      CX=FLOAT(II)+0.25
      CY=FLOAT(JJ)+0.25
      GOTO 160
   18 CX=FLOAT(II)+0.75
      CY=FLOAT(JJ)-0.25
C
```

```
C     CHECK FOR MAX. ANGLE OF TOPOGRAPHIC SHADING; CALCULATE
PTS.
C     OF INTERSECTION ON VERTICAL GRID LINES FOR PTS. YIELDING
C     LARGEST TOPOGRAPHIC SHADING
  160 BIGANG=0.0
      IF(SBEAR(N).EQ.0.0.OR.SBEAR(N).EQ.180.)GOTO 60
      IF(SBEAR(N).GT.0.0.AND.SBEAR(N).LT.180.)GOTO 10
      IF(NN.EQ.1)AX=-0.75
      IF(NN.EQ.2)AX=-0.25
      KODEEW=2
      CALL
SUB1(AX,KODEEW,CX,CY,ALT,AVALT,BIGANG,SBEAR(N),RPD,DPR)
      GOTO 60
   10 IF(NN.EQ.1)AX=0.25
      IF(NN.EQ.2)AX=0.75
      KODEEW=1
      CALL
SUB1(AX,KODEEW,CX,CY,ALT,AVALT,BIGANG,SBEAR(N),RPD,DPR)
C
C     CALCULATE PTS. OF INTERSECTION ON HORIZONTAL GRID LINES
FOR
C     PTS. YIELDING LARGEST TOPOGRAPHIC SHADING
   60 IF(SBEAR(N).EQ.90..OR.SBEAR(N).EQ.270.)GOTO 99
      IF(SBEAR(N).GT.270..OR.SBEAR(N).LT.90.)GOTO 70
      IF(NN.EQ.1)AY=-0.75
      IF(NN.EQ.2)AY=-0.25
      KODENS=4
      CALL
SUB2(AY,KODENS,CX,CY,ALT,AVALT,BIGANG,SBEAR(N),RPD,DPR)
      GOTO 99
   70 IF(NN.EQ.1)AY=0.25
      IF(NN.EQ.2)AY=0.75
      KODENS=3
      CALL
SUB2(AY,KODENS,CX,CY,ALT,AVALT,BIGANG,SBEAR(N),RPD,DPR)
C
C     CALCULATE RADIATION WITHOUT TOPOGRAPHIC FACTOR ON
HORIZ.SURFACE
   99 BIGANG=ATAN(BIGANG)*DPR
      IDPMX=IDPMX+XLITE(N)
      IF(LSTN.EQ.1)GOTO 17
      LSTN=1
C     CALCULATE DIRECTION COSINES(L,M,N) OF NORMAL VECTOR;
```

```
C     SEE PINCUS,H.J.1953. J.GEOLOGY ; WATSON,G.S. AND
C     E.IRVING. 1957. GEOPHYS.J. 7(6): I AND J DIRECTION COSINES
C     CALC. BY THIS MEANS ARE REVERSED FROM THOSE CALC.IN
ALTXYZ PROG
C     WHICH USES N=0.DEG.  THIS METHOD USES AZIMUTH SYSTEM
(S=0.DEG)
C
      TERRL=(SIN(SLOPE*RPD))*(COS((BEAR+180.)*RPD))
      TERRM=(SIN(SLOPE*RPD))*(SIN((BEAR+180.)*RPD))
      TERRN=COS(SLOPE*RPD)
C     DETERMINE MIN. ANGLE BETWEEN SUN AND NORMAL VECTORS;
YOELI,P.
   17 COE=(SUNL(N)*TERRL)+(SUNM(N)*TERRM)+(SUNN(N)*TERRN)
      IF(COE.LE.0.)GOTO 98
      GID=SLITE(N)*COE
      GRAD=GRAD+GID
C
C     IF SUN ALTITUDE IS < MAX. ANGLE OF TOPOG. SHADING SKIP

C     CALC. OF RADIATION
  809 FORMAT(' BIGANG=',F6.2,'  SALT=',F6.2)
          IF(SALT(N).LE.BIGANG)GOTO 98
C
C     -----------------------------------
  803 FORMAT(1X,7(F6.4,1X))
C     -----------------------------------
C
C     ACCUMULATE SOLAR RAD. FOR EACH TRIANGLE FOR ALL SOLAR
BEARINGS
C     PRINT EACH SEPARATELY AFTER CALC.;ID-DAILY SOLAR RAD. IN
JOULES.
C     ID-RAD.ON GROUND SURFACE;IDPOT-POTENTIAL RAD.WHICH
WOULD BE
C     RECEIVED ON HORIZONTAL SURFACE INCLUDING TOPOG.SHADING
FACTOR.
C     RAD ON HORIZ.SURFACE DECREASES AS FUNC.OF COS(Z);SEE
GARNIER ET.AL
C     GID=GROUND SURFACE ID FOR EACH INCREMENT OF SUN
MOVEMENT
      ID=ID+GID
  804 FORMAT(E13.5,1X,F6.4,1X,2(E13.5,1X))
      IDPOT=IDPOT+XLITE(N)
   98     N=N+1
```

```
      IF(N.LE.NT)GOTO 160
C
   NTOT=NTOT+1
 600 FORMAT(1X,I4)
   WRITE(3,600)NTOT
C
C    CALCULATE TOTAL INSOLATION ON HORIZONTAL SURFACE ON
M**2
C    WITHOUT TOPOGRAPHIC SHADING FACTOR FOR DETN.OF MEAN;
C    CALC.PCMX=[RAD./M2/D WITH TOPOG.SHADING ON
GROUND]/[RAD./M2/
C    D W/O TOPOG.SHADING ON HORIZ.SURFACE]
   TPMXID=TPMXID+(IDPMX)
   TGRAD=TGRAD+GRAD
   IF(IDPMX.EQ.0.)GOTO 177
   PCMX=(ID/IDPMX)*100.
   GOTO 178
 177 PCMX=0.
C    -------------
C    CALCULATE RATIO OF GROUND SURFACE RAD. W/TOPOG TO
GROUND
C    SURFACE RAD. W/O TOPOG SHADING
 178 IF(GRAD.EQ.0.)GOTO 179
   GSR=(ID/GRAD)*100.
   GOTO 180
 179 GSR=0.
C    CALCULATE TOTAL SURFACE AREA ON GROUND; FT2
 180 AREA=387200./COS(SLOPE*RPD)
   TAREA=TAREA+AREA
C    CALCULATE TOTAL INSOLATION/BASIN RECEIVED ON GROUND
SURFACE;
C    0.092903 IS CONVERSION FT2 TO M2
   TID=TID+(ID*AREA*0.092903)
C    CALC.TOTAL PLANAR DAILY INSOLATION ON M**2 BASIS TO
ALLOW
C    CALC OF MEAN RAD.INTENSITY ON HORIZ.W/TOPOG.SHADING
   TPLID=TPLID+(IDPOT)
 549 FORMAT('  MONTH',I2,' DAY ',I2,' YEAR ',I4)
C
C    DETERMINE FREQUENCY DISTRIBUTION OF TOTAL DAILY
INSOLATION BY
C    BEARING CLASS;DETN.SDEV.OF ID FOR ALL TRIANGLES
   NX1=(BEAR/CLASSB)+1.
```

```
      NX2=(ID/CLASSI)+1.
      NX3=(AVALT/2.001)+1.
      ALTSUN(NX3,NX2)=ALTSUN(NX3,NX2)+1
      BRSUN(NX2,NX1)=BRSUN(NX2,NX1)+1
      SID(NX3)=SID(NX3)+ID
      SSID(NX3)=SSID(NX3)+(ID*ID)
      LALT(NX3)=LALT(NX3)+1
C
  184 FORMAT('0   I  J   NN  AVALT  SLOPE  BEAR      RAD(ID)
     c     HORIZ.   ID/IDPOT ID/HORIZ',/,'
     c                    JOULES/M2      RAD.
     cW/O TOPOG')
  185 FORMAT(3X,3(I2,2X),2(F4.1,3X),F5.1,1X,2(E13.5,2X),2(F6.2,1X))
      IF(NTOT.EQ.1)WRITE(2,549)MONTH,IDAY,IYEAR
      IF(NTOT.EQ.1)WRITE(2,184)
      IF(IDPOT.EQ.0.)GOTO 187
      D=(ID/IDPOT)*100.
      GOTO 188
  187 D=0.
  189 FORMAT(A1,3(I2,1X),2(F4.1,1X),F5.1,1X,2(E13.5,1X),3(F6.2,1X))
  188 IK=(FLOAT(NTOT)-1.0)/100.
      KI=NTOT-(IK*100)
      IIZ(KI)=II
      JJZ(KI)=JJ
      NNZ(KI)=NN
      GSRZ(KI)=GSR
      AVALTZ(KI)=AVALT
      SLOPEZ(KI)=SLOPE
      BEARZ(KI)=BEAR
      IDZ(KI)=ID
      IDPOTZ(KI)=IDPOT
      DZ(KI)=D
      PCMXZ(KI)=PCMX
      IF(KI.EQ.100)GOTO 610
      GOTO 109
  905 NDCODE=1
  610 WRITE(8,189)(LF,IIZ(KJ),JJZ(KJ),NNZ(KJ),AVALTZ(KJ),SLOPEZ(KJ),
     cBEARZ(KJ),IDZ(KJ),IDPOTZ(KJ),DZ(KJ),PCMXZ(KJ),GSRZ(KJ),KJ=1,KI)
      IF(NDCODE.EQ.1)GOTO 200
C
  109     ID=0.0
          IDPOT=0.0
          IDPMX=0.0
```

```
          LSTN=0
          GRAD=0.0
          GOTO 100
C
C     TID-TOTAL DAILY RAD./GROUND SURFACE AREA OF BASIN
W/TOPOG SHADING
C     IDPOT-POTENTIAL RAD./TRIANGLE WITH TOPOG. SHADING
FACTOR APPLIED
C     IDPMX-RAD.INTENSITY RECEIVED ON MAP HORIZ. SURFACE FOR
EACH
C     TRIANGLE W/O TOPOG SHADING
C     TPMXID-TOTAL POTENTIAL RAD TO HORIZ.SURFACE OF BASIN
C     TPLID-TOTAL BASIN RAD.WITH TOPOG.SHADING FACTOR APPLIED
C     PC1-% GIVEN BY XIDPOT/XIDPMX
C     PC2-% GIVEN BY (TID/TAREA)/XIDPOT
C     PCMX-% GIVEN BY ID/IDPMX;ie.(RAD.ON GROUND
W/TOPOG.SHADING)/
C     (RAD.W/O TOPOG SHADING ON HORIZONTAL)
C     XIDPMX=MEAN RAD.INTENSITY (JOULES/M2/D)ON HORIZ. W/O
TOPOG.
C     XIDPOT= MEAN RAD.INTENSITY (JOULES/M2/D) ON HORIZ.
W/TOPOG
C
 200  XIDPMX=TPMXID/FLOAT(NTOT)
      XIDPOT=TPLID/FLOAT(NTOT)
      XGRAD=TGRAD/FLOAT(NTOT)
  194 FORMAT(///'0    TOTAL DAILY BASIN RADIATION IN JOULES ',/,
     c'     W/TOPOG. SHADING=',E13.5,/)
  295 FORMAT(/,'    MEAN RADIATION INTENSITY (J/M2/D) W/O TOPOG
FOR
     c ALL TRIANGLES=',E13.5/)
  296 FORMAT(/,'    TOTAL NO. OF TRIANGLES=',I4,/)
  297 FORMAT(//,'    [MEAN JOULES/M**2/D ON HORIZ.
W/TOPOG.SHADING]/',/,
     c    ' [JOULES/M**2/D ON HORIZ. W/O TOPOG]=',F6.2,/,'    [MEAN
     cJOULES/M**2/D ON GROUND W/TOPOG.SHADING]/',/,'
[JOULES/M**2/D
     cON HORIZ.W/ TOPOG]=',F6.2)
  298 FORMAT(/,'    MEAN RAD.INTENSITY ON HORIZ. W/O
TOPOG.=',E13.5)
  299 FORMAT(/,'    MEAN RAD.INTENSITY ON HORIZ. W/TOPOG.=',E13.5)
      PC1=(XIDPOT/XIDPMX)*100.
      PC2=(TID/(TAREA*0.092903)/XIDPOT)*100.
```

```
      WRITE(2,194)TID
      WRITE(2,295)XGRAD
      WRITE(2,296)NTOT
      WRITE(2,299)XIDPOT
      WRITE(2,298)XIDPMX
      WRITE(2,297)PC1,PC2
C
C     CALCULATE ROW TOTALS FOR NO. OF SLOPES IN BEARING
CLASSES
C     HAVING GIVEN RADIATION LEVELS
      DO 25 NX2=1,16
      DO 25 NX1=1,12
      NBRSUN(NX2)=NBRSUN(NX2)+BRSUN(NX2,NX1)
   25 CONTINUE
C
C     CALCULATE % OF TOTAL NO. OF TRIANGLES IN GIVEN RAD.
CLASSES
      DO 26 NX2=1,16
      PCIDBR(NX2)=(FLOAT(NBRSUN(NX2))/FLOAT(NTOT))*100.
   26 CONTINUE
C
C     WRITE OUT TABLE OF BEARING-RADIATION FREQUENCY DISTRIB.
   75 FORMAT('1   BEARING-RADIATION FREQUENCY DISTRIBUTION',/,
     c'0BEAR/      0   30   60   90  120  150  180  210  240
     c 270  300  330',/,'  MJ       30   60   90  120  150  180
     c  210  240  270  300  330  360  TOT  %'/)
      WRITE(2,75)
   80 FORMAT(1X,I3,'-',I3,2X,13(I3,2X),F4.1)
      NN=0
      NM=2
      DO 300 NX2=1,16
      WRITE(2,80)NN,NM,(BRSUN(NX2,NX1),NX1=1,12),NBRSUN(NX2),
     cPCIDBR(NX2)
      NN=NN+2
      NM=NM+2
  300 CONTINUE
C
C     WRITE OUT TABLE OF RADIATION-ALTITUDE FREQUENCY DISTRIB.
   76 FORMAT('0   RADIATION-ALTITUDE FREQUENCY DISTRIBUTION',/
     c'0MJOULES/  0   2   4   6   8  10  12  14
     c16  18  20  22  24  26  28  30'/,' ALT       2   4   6
     c   8  10  12  14  16  18  20  22  24  26  28  30  32'/)
      WRITE(2,76)
```

```
  81 FORMAT(1X,I3,'-',I3,1X,16(I3,1X))
     NN=0
     NM=2
     DO 301 NX3=1,23
     WRITE(2,81)NN,NM,(ALTSUN(NX3,NX2),NX2=1,16)
     NN=NN+2
     NM=NM+2
 301 CONTINUE
C
C     DETERMINE MEAN ID OF ALL TRIANGLES BY ALTITUDE
 649 FORMAT(/,'   ALTITUDE=',I2,'-',I2,'  MEAN RAD.INTENSITY=',E13.5/,
    c'                   SDEV.=',E13.5,'  N=',I3)
     DO 648 NX3=1,25
     IF(LALT(NX3).EQ.0)GOTO 648
     X=FLOAT(LALT(NX3))
     AVID=SID(NX3)/X
     IF(LALT(NX3).EQ.1)GOTO 647
     SDID=((SSID(NX3)-(SID(NX3)**2./X)))/(X-1.)
     SDID=SQRT(SDID)
     GOTO 645
 647 SDID=0.
 645 NA=2*NX3-2
     NB=2*NX3
     WRITE(2,649)NA,NB,AVID,SDID,LALT(NX3)
 648 CONTINUE
C
C     CALCULATE TOTAL AREA ON GROUND (FT2 AND M2) AND PLANAR
AREA
     TAREAM=TAREA*0.092903
     PLAREA=((SCALE*SCALE)/2.)*FLOAT(NTOT)
     PLAREM=PLAREA*0.092903
 400 FORMAT('0 TOTAL AREA=',E13.5,' FT2  ',E13.5,' M2',/,
    c'0   PLANAR AREA OF BASIN=',E13.5,' FT2  ',E13.5,' M2')
     WRITE(2,400)TAREA,TAREAM,PLAREA,PLAREM
     WRITE(2,549)MONTH,IDAY,IYEAR
C
     LAP=LAP+1
     ENDFILE 6
     ENDFILE 7
     ENDFILE 8
     GOTO 903
 902 ENDFILE 5
     END
```

```
C
      SUBROUTINE
SUB1(AX,KODEEW,CX,CY,ALT,AVALT,BIGANG,SBEAR,RPD,DPR)
C     KODEEW=CODE FOR BEARING OF SUN (EAST-WEST) TO ELIMINATE
SEARCHING
C     ENTIRE ALT.MATRIX; USE INCREMENT OF 0.5 FOR FIRST GRID
C     INTERSECTION AND PLUS OR MINUS 1. THEREAFTER DEPENDING
ON BEARING
C     CX AND CY=COORD.OF CENTER OF TRIANGLE;
C     AY,AX=INCREMENTS ON X AND Y AXES FOR A GIVEN BEARING TO
SUN WHICH
C     INTERSECT GRID LINES;DALT=DIFFERENCE IN ALTITUDE OF 2 PTS.;
C     PTALT=INTERPOLATED ALT. OF PT. WHERE IT INTERSECTS GRID
LINE;
C     DIST=MAP DISTANCE FROM CENTER OF TRIANGLE TO GRID
INTERSECTION PT.
C     ANGLE=ANGLE (DEGREES) FROM CENTER OF TRIANGE (AVALT) TO
PTALT
      INTEGER ALT(40,30)
      SCALE=880.
      K=0
      V=ABS((90.-SBEAR)*RPD)
      T=SIN(V)/COS(V)
   40 AY=ABS(T*AX)
      IF(SBEAR.GT.90..AND.SBEAR.LT.270.)AY=-AY
      X=CX+AX
      Y=CY+AY
      IF(Y.GT.30..OR.Y.LT.1..OR.X.GT.40..OR.X.LT.1.)GOTO 45
      IX=X
      IY=Y
      IY1=IY+1
      DIF=Y-FLOAT(IY)
      IF(ALT(IX,IY1).EQ.99.AND.ALT(IX,IY).EQ.99)GOTO 81
      IF(ALT(IX,IY1).NE.99.AND.ALT(IX,IY).NE.99)GOTO 42
C     IF ONLY ONE OF THE 2 PTS. IS NOT =99, TAKE THIS AS THE
ALTITUDE
      IF(ALT(IX,IY1).NE.99)CALL SUB3(ALT(IX,IY1),PTALT,CX,CY,X,Y,
     cSCALE,DIST)
      IF(ALT(IX,IY).NE.99)CALL SUB3(ALT(IX,IY),PTALT,CX,CY,X,Y,SCALE,
     cDIST)
      GOTO 43
C
   42 DALT=FLOAT(ALT(IX,IY1))-FLOAT(ALT(IX,IY))
```

```
      PTALT=(FLOAT(ALT(IX,IY))+DALT*DIF)
      DIST=SQRT(AX*AX+AY*AY)*SCALE
   43 TAG=(PTALT-AVALT)*80./DIST
      IF(TAG.GT.BIGANG)BIGANG=TAG
  806 FORMAT(' SUB1 ',2(F5.2,1X),2(F6.2,1X),2(I2,1X),3(F4.1,1X),
     c2(F5.2,1X))
      GOTO 41
C     ALLOW SEARCH THROUGH MATRIX UNTIL 3 SETS OF 99'S ARE
FOUND
   81 K=K+1
      IF(K.EQ.3)GOTO 45
   41 IF(KODEEW.EQ.1)AX=AX+1.
      IF(KODEEW.EQ.2)AX=AX-1.
      GOTO 40
   45 RETURN
      END
C
      SUBROUTINE
SUB2(AY,KODENS,CX,CY,ALT,AVALT,BIGANG,SBEAR,RPD,DPR)
      INTEGER ALT(40,30)
      SCALE=880.
      K=0
      IF(SBEAR.NE.0..AND.SBEAR.NE.180.)GOTO 50
      AX=0.0
      GOTO 55
   50 V=ABS((90.-SBEAR)*RPD)
      T=SIN(V)/COS(V)
   56 AX=ABS(AY/T)
      IF(SBEAR.GT.180..AND.SBEAR.LT.360.)AX=-AX
   55 X=CX+AX
      Y=CY+AY
      IF(Y.GT.30..OR.Y.LT.1..OR.X.GT.40..OR.X.LT.1.)GOTO 46
      IX=X
      IY=Y
      IX1=IX+1
      DIF=X-FLOAT(IX)
      IF(ALT(IX1,IY).EQ.99.AND.ALT(IX,IY).EQ.99)GOTO 61
      IF(ALT(IX1,IY).NE.99.AND.ALT(IX,IY).NE.99)GOTO 52
C     IF ONLY ONE OF THE 2 PTS. IS NOT =99, TAKE THIS AS THE
ALTITUDE
      IF(ALT(IX1,IY).NE.99)CALL SUB3(ALT(IX1,IY),PTALT,CX,CY,X,Y,
     cSCALE,DIST)
      IF(ALT(IX,IY).NE.99)CALL SUB3(ALT(IX,IY),PTALT,CX,CY,X,Y,SCALE,
```

```
    cDIST)
     GOTO 53
C
  52 DALT=FLOAT(ALT(IX1,IY))-FLOAT(ALT(IX,IY))
     PTALT=(FLOAT(ALT(IX,IY))+DALT*DIF)
     DIST=SQRT(AX*AX+AY*AY)*SCALE
  53 TAG=(PTALT-AVALT)*80./DIST
     IF(TAG.GT.BIGANG)BIGANG=TAG
 807 FORMAT(' SUB2 ',2(F5.2,1X),2(F6.2,1X),2(I2,1X),3(F4.1,1X),
    c2(F5.2,1X))
     GOTO 51
  61 K=K+1
     IF(K.EQ.3)GOTO 46
  51 IF(KODENS.EQ.3)AY=AY+1.
     IF(KODENS.EQ.4)AY=AY-1.
     IF(AX.EQ.0.0)GOTO 55
     GOTO 56
  46 RETURN
     END
C
     SUBROUTINE SUB3(ALTPT,PTALT,X1,Y1,X2,Y2,SCALE,DIST)
     INTEGER ALTPT
     PTALT=FLOAT(ALTPT)
     DIST=SQRT((X2-X1)*(X2-X1)+(Y2-Y1)*(Y2-Y1))*SCALE
     RETURN
     END
C
     SUBROUTINE ZENAZ(LAT,DECL,T,Z,RPD,DPR,AZ)
C     DETERMINE ZENITH ANGLE(Z), ALTITUDE OF SUN(SALT)
C     FIND ARCCOS OF Z;SEE SELLERS,W.D.;AZIMUTH OF SUN
WRT.S=0.DEG.
     REAL LAT
     COZ=SIN(LAT)*SIN(DECL)+COS(LAT)*COS(DECL)
    c*COS(T*RPD)
     Z=90.-(ATAN(COZ/SQRT(1.-COZ*COZ)))*DPR
     COAZ=(SIN(LAT)*COS(Z*RPD)-SIN(DECL))/
    c(COS(LAT)*SIN(Z*RPD))
     IF(COAZ.GT.0.999)GOTO 36
     AZ=90.-(ATAN(COAZ/SQRT(1.-COAZ*COAZ)))*DPR
     GOTO37
  36 AZ=0.
  37 RETURN
     END
```

C. APPENDIX C

1. Computer Program CHANLC Used to Computer Solar Radiation Load to Stream Locations, Segments, and Networks, Accounting for Topographic and Canopy Shading

```
      PROGRAM CHANLC
C     THIS PROGRAM IS MODIFIED FROM PROGRAM SUN ON SEPT.2,1982
AND
C     IS DESIGNED TO CALCULATE DAILY INSOLATION FOR ANY DAY OF
C     THE YEAR FOR THE STREAM CHANNEL TAKING TOPOGRAPHIC
SHADING,
C     AV.STREAM WIDTH AND CANOPY TYPE,DENSITY,HT.,GAP WIDTH
INTO
C     ACCOUNT THIS PROGRAM IS DESIGNED TO BE USED WITH AN
ALTITUDE
C     DATA MATRIX FOR THE WATERSHED;MODIFIED OCT.20,1982 TO
ACCOUNT
C     FOR CANOPY SHADING
C     MODIFIED FEB.27,1984 TO CHANGE PLACEMENT OF SBEAR+ROT
C
C     MODIFY MAY 24,1984 TO CORRECT ROTATION OF BASIN WHEN
SBEAR
C     IS GREATER THAN 360
      LOGICAL NAME(11),LF,CR,NOM(11),NAMX(11)
      DIMENSION T(40),SBEAR(40),TIME(40),STAREA(30),KOUNT(30)
      DIMENSION Z(40),SUNL(40),SUNM(40),SUNN(40),SALT(40),SLITE(40)
      DIMENSION RAD(30),TRAD(30),CRAD(30),W(10)
      DIMENSION
MAIN(25),CUMDX(25),CUMDIS(25),CUMAR(25),STRLEN(25),
     cSUBAR(25),CUMDA(25),CUML(25),AVWID(25)
      INTEGER
ALT(40,30),ALTST,ORDER(4,10),SEGSEQ(25,2),TRIB(25),CANHT,
     cCOVER,OR
      REAL ID,IO,LAT,M,IDPMX,IDCAN,LENGTH,MARGIN
      DATA STAREA/30*0./,KOUNT/30*0/,RAD/30*0./,TRAD/30*0./
      DATA CUMDIS/25*0./,CUMDX/25*0./,CUMAR/25*0./,SUBAR/25*0./,
     cCUMDA/25*0./,STRLEN/25*0./,AVWID/25*0./,CRAD/30*0./
C     ENTER VALUE FOR LATITUDE,CLASS INTERVALS FOR BEARING
C     AND RADIATION;SCALE FACTOR=880'/INTERVAL ON I AND J AXES.
```

```
C     NTOT=TOTAL NO. OF TRIANGLES; ID=RADIATION REACHING
SURFACE
C     AT EACH BEARING, AND ACCUMULATED FOR ALL BEARINGS PER
TRIANGLE
C     CX,CY=COORDINATES OF POINTS ON STREAM CHANNEL SPACED
AT 880 M
C     SBEAR=BEARING OF SUN; BIGANG=BIG ANGLE
(MAX.),TOPOGRAPHIC
C     SHADING CAUSED BY ANGLE FROM AVALT TO A PT. ON BASIN IN
DIRECTION
C     OF SBEAR; TIME=NO. OF MINUTES DURING WHICH SUN IS ABOVE
C     HORIZON (NOT JUST
TOPOG);RPD=RADIANS/DEGREE;DPR=DEGREES/RADIAN
C     T-HOUR ANGLE;Z-ZENITH ANGLE;AZ-AZIMUTH;NQ-INTERVAL OF
SUN MOVEMENT
C     OF 7.5 DEG. CENTERED ON AZ=0.DEG;
C     SET VALUE FOR ATMOSHPERIC TRANSMISSIVITY; GARNIER AND
OHMURA;
C          REVFEIM,K.J.A.1978. J.APPL.METEOR.17:1126-1131.
      P=0.75
C     SET SOLAR CONSTANT;2.00 CAL/CM2/MIN=83680.JOULES/M2/MIN
C          WILLIAMS,L.D.,R.G.BARRY,AND J.T.ANDREWS. 1971.
C          J.APPL.METEOR. 11:526-533.-ALSO CRC PHYSICS HANDBOOK.1979
      IO=83680.
C     SET LATITUDE FOR STUDY AREA
      LAT=45.5
      RPD=.174533E-1
      IDPMX=0.
      DPR=57.2958
      SCALE=880.
      ID=0.
      NTOT=0
      STRAD=0.
      RRAD=0.
      IDCAN=0.
      CTRAD=0.
C     TDA=TOTAL DRAINAGE AREA;TLEN=TOTAL LENGTH OF
NETWORK;
C     TMSL=TOTAL MAINSTEM STREAM LENGTH
      TDA=0.
      TLEN=0.
      TMSL=0.
C     SET COEFFICIENT FOR LIGHT PENETRATION OF CANOPY
```

```
      COEF=0.05
      LF=10
      CR=13
  220 FORMAT(' ENTER 11 CHARACTER FILENAME FOR WATERSHED ALT
MATRIX')
      WRITE(3,220)
  221 FORMAT(80A1)
      WRITE(3,221)CR,LF
  222 FORMAT(1X,79A1)
      READ(3,221)(NAME(I),I=1,11)
      WRITE(2,222)(NAME(I),I=1,11)
      CALL OPEN(6,NAME,2)
C
  250 FORMAT(' ENTER 11 CHARACTER FILENAME FOR STREAM
COORDINATES')
      WRITE(3,250)
      WRITE(3,221)CR,LF
      READ(3,221)(NOM(I),I=1,11)
      WRITE(2,222)(NOM(I),I=1,11)
      CALL OPEN(7,NOM,2)
C
  260 FORMAT(' ENTER SUN DECLINATION AND JULIAN DAY AS
F6.2,1X,I3')
      WRITE(3,260)
      WRITE(3,221)CR,LF
  261 FORMAT('0 SUN DECLINATION=',F6.2,'  JULIAN DAY=',I3)
  262 FORMAT(F6.2,1X,I3)
      READ(3,262)DECL,JUL
      WRITE(2,261)DECL,JUL
C
  270 FORMAT(' WRITE CODE, 1=PRINT OUT INSOLATION; 2=NO PRINT')
  271 FORMAT(I1)
      WRITE(3,270)
      WRITE(3,221)CR,LF
      READ(3,271)NCODE
C
  272 FORMAT(' WRITE CODE, 1=WRITE INSOLATION TO DISC,2=NO
WRITE')
      WRITE(3,272)
      WRITE(3,221)CR,LF
      READ(3,271)MCODE
  282 FORMAT(' ENTER FILENAME FOR STREAM INSOLATION STORAGE')
      IF(MCODE.EQ.2)GOTO 283
```

```
      WRITE(3,282)
      WRITE(3,221)CR,LF
      READ(3,221)(NAMX(N),N=1,11)
      CALL OPEN(5,NAMX,2)
C
  275 FORMAT(' ENTER TOTAL BASIN DRAINAGE AREA AND AV.WATER
SURFACE
     cWIDTH USING FORMAT E8.2,1X,F4.1; E8.2 IS 0.2356+7,EG.')
  283 WRITE(3,275)
      WRITE(3,221)CR,LF
  277 FORMAT(E8.4,1X,F4.1)
  278 FORMAT(' DRAINAGE AREA=',E12.4,' AV.WSW=',F4.1)
      READ(3,277)DA,AVWSW
      WRITE(2,278)DA,AVWSW
C
  285 FORMAT(F5.1)
  286 FORMAT(' DEGREES OF ROTATION OF BASIN=',F5.1)
  284 FORMAT(' ENTER NO. OF DEGREES TO ROTATE BASIN,F5.1,eg. 045.0')
      WRITE(3,284)
      WRITE(3,221)CR,LF
      READ(3,285)ROT
      WRITE(2,286)ROT
C
C     DESCRIPTION OF TERMS-- MAIN=SEGMENT NOS.ON MAINSTEM IN
ORDER
C     FROM UPSTR. TO DSTR.; TRIB=SEGMENT NOS.ALONG MAINSTEM
FROM
C     UPSTR.TO DSTR.INCLUDING TRIB.SEG.NOS.AS THEY ENTER MAIN
C     STRLEN=STREAM LENGTH FOR GIVEN SEG.NO.
C     SUBAR=SUB DRAINAGE AREA FOR GIVEN SEG.NO.
C     CUMDA=CUMULATIVE DRAINAGE AREA AT DSTR.END OF GIVEN
SEG.NO.
C     CUMAR=CUM.AREA BY SUMMING SUB AREAS OF SEGMENTS
ALONG MAIN
C     STEM INCL.TRIBS AS THEY ENTER
C     CUMDX=CUM.DISTANCE BY SUMMING LENGTH OF SEGMENTS
ALONG MAIN
C     STEM INCL.TRIBS AS THEY ENTER
C     CUMDIS=CUM.DISTANCE(LENGTH) OF STREAM ALONG MAINSTEM
FROM UPSTR.
C     TO DSTR.
C     ORDER=LIST OF ALL SEG.NOS.OF STREAMS OF GIVEN ORDER
```

```
C     SEGSEQ=LIST OF THE 2 TRIBS WHICH JOIN TO FORM STREAM OF
GIVEN
C     SEG.NO.; LENGTH AND SUBDA ARE INPUT DATA PROVIDED ON
DISC
  135 FORMAT(25(I2,1X))
  140 FORMAT(' MAINSTEM SEQ.=',20(I2,1X)/5(I2,1X))
  141 FORMAT(' TRIB SEQUENCE=',20(I2,1X)/5(I2,1X))
  136 FORMAT(' ENTER SEGMENT SEQUENCE ON MAINSTEM, UPSTR. TO
DSTR.;'/
     c' USE FORMAT(I2,1X); ENTER 99 TO DENOTE END')
  137 FORMAT(' START AT UPSTR.END OF MAINSTEM--ENTER
SEG.NOS.OF MAIN'/
     c' STEM+ALL TRIBS AS THEY ENTER MAINSTEM. INCLUDE
     cALL LOWER ORDER'/,' TRIB SEGS.FOR ANY TRUNK TRIB ENTERING;'/
     c,' USE FORMATJ(I2,1X);ENTER 99 TO DENOTE END')
      WRITE(3,136)
      WRITE(3,221)CR,LF
      READ(3,135,END=12)(MAIN(N),N=1,25)
   12 WRITE(2,140,END=17)(MAIN(N),N=1,25)
   17 WRITE(3,137)
      WRITE(3,221)CR,LF
      READ(3,135,END=13)(TRIB(N),N=1,25)
   13 WRITE(2,141,END=560)(TRIB(N),N=1,25)
C
    2 FORMAT(2(F4.1,1X),I2,1X,2(E8.4,1X),I2,1X,I1,1X,F4.1,1X,I2,1X,I3)
   19 FORMAT(14X,2(E12.4,1X),I2)
  560
READ(7,2,END=561)CX,CY,ALTST,SUBDA,LENGTH,NSEG,CANHT,GAP,CO
VER,OR
C     ----------
C     DETERMINE SUBAREA+SEG.LENGTH FOR EACH SEGMENT;THEN
PRINT TABLE
      SUBAR(NSEG)=SUBDA
      STRLEN(NSEG)=LENGTH
      GOTO 560
C
  561 DO 565 NSEG=1,25
      IF(SUBAR(NSEG).EQ.0.)GOTO 565
      WRITE(2,19)SUBAR(NSEG),STRLEN(NSEG),NSEG
  565 CONTINUE
C     -----------
C     CALCULATE CUMULATIVE DISTANCE ON MAINSTEM USING ONLY
C     MAINSTEM SEGMENTS
```

```
      I=MAIN(1)
      CUMDIS(1)=STRLEN(I)
      N=2
  300 I=MAIN(N)
      IF(I.EQ.99)GOTO 301
      CUMDIS(N)=CUMDIS(N-1)+STRLEN(I)
      N=N+1
      GOTO 300
C     ----------------
C     CALCULATE CUMULATIVE DISTANCE+AREA ALONG MAINSTEM
USING
C     MAINSTEM+TRIB SEGMENTS
  301 I=TRIB(1)
      CUMDX(1)=STRLEN(I)
      CUMAR(1)=SUBAR(I)
      N=2
  303 I=TRIB(N)
      IF(I.EQ.99)GOTO 302
      CUMDX(N)=CUMDX(N-1)+STRLEN(I)
      CUMAR(N)=CUMAR(N-1)+SUBAR(I)
      N=N+1
      GOTO 303
C     -------------------
  310 FORMAT(' ENTER 2 SEG.NOS.(I2,1X,I2)WHICH CONTRIB.TO SEG.='
     c,I2,/' FOR 1ST ORDER TRIBS ENTER ONLY THE 1ST ORDER
     cSEG. NO.,FORMAT(I2)'/,' BEFORE REACHING LAST SEG.NO,
     cIF A SEG.NO.DOES NOT EXIST,JUST HIT NEWLINE'/,
     c'ENTER 99 TO END AFTER FINAL SEG.(I2)')
  333 FORMAT(' SEGMENT NOS.WHICH CONTRIB.TO SEG.NO.=',I2,' ARE',
     cI2,1X,I2)
  319 FORMAT(I2,1X,I2)
  302 I=1
  313 WRITE(3,310)I
      WRITE(3,221)CR,LF
      READ(3,319)(SEGSEQ(I,N),N=1,2)
      IF(SEGSEQ(I,1).EQ.99)GOTO 311
      WRITE(2,333)I,(SEGSEQ(I,N),N=1,2)
      I=I+1
      GOTO 313
C     --------------------
  402 FORMAT(' ENTER ALL SEG.NOS.FOR TRIBS OF ORDER=',I2,/
     c' USE FORMAT(I2,1X);ENTER 99 TO DENOTE END FOR EACH ORDER')
  413 FORMAT(' TRIBS OF ORDER=',I2,' ARE',10(I2,1X))
```

```
 311 L=1
 401 WRITE(3,402)L
     WRITE(3,221)CR,LF
     READ(3,135,END=410)(ORDER(L,N),N=1,10)
 410 WRITE(2,413)L,(ORDER(L,N),N=1,10)
     L=L+1
     IF(L.LT.5)GOTO 401
C    --------------------
C    CUMULATIVE DA OF ANY SEG.=DA OF 2 CONTRIBUTING
SEGMENTS+DA OF
C    THE SEGMENT ITSELF;ORDER PROVIDES SEG.NO.OF A GIVEN
ORDER;
C    SEGSEQ GIVES SEG.NOS. WHICH CONTRIB. TO A GIVEN SEG.NO.
C    CUMDA=CUM.AREA FOR EACH SEG.NO.
     L=1
     N=1
 406 IF(ORDER(1,N).EQ.99)GOTO 407
     J=ORDER(L,N)
     CUMDA(J)=SUBAR(J)
     CUML(J)=STRLEN(J)
     N=N+1
     GOTO 406
 407 L=2
     N=1
 408 J=ORDER(L,N)
     IF(J.EQ.99)GOTO 409
     IF(L.EQ.5)GOTO 411
     JJ=SEGSEQ(J,1)
     KK=SEGSEQ(J,2)
     CUMDA(J)=CUMDA(JJ)+CUMDA(KK)+SUBAR(J)
     CUML(J)=CUML(JJ)+CUML(KK)+STRLEN(J)
     N=N+1
     GOTO 408
 409 L=L+1
     N=1
     GOTO 408
C
 508 FORMAT('0 NSEG  LENGTH    SUBAR    CUMDIS    CUMAR
    c   CUML       CUMDA      AVWID')
 506 FORMAT(1X,I2,2X,2(F7.1,E12.5,1X),F7.1,2X,E12.5,1X,F4.1)
 411 WRITE(2,508)
     N=1
 504 I=TRIB(N)
```

```
      IF(I.EQ.99)GOTO 510
      AVWID(I)=AVWSW*CUMDA(I)/DA
      WRITE(2,506)I,STRLEN(I),SUBAR(I),CUMDX(N),CUMAR(N),CUML(I),
     cCUMDA(I),AVWID(I)
      TDA=TDA+SUBAR(I)
      TLEN=TLEN+STRLEN(I)
      N=N+1
      GOTO 504
C
  509 FORMAT(/'0 NSEG  LENGTH      SUBAR       CUMDIS      CUMDA')
  507 FORMAT(1X,I2,5X,2(F7.2,2X,E12.5,2X))
  510 WRITE(2,509)
      N=1
  505 I=MAIN(N)
      IF(I.EQ.99)GOTO 511
      TMSL=TMSL+STRLEN(I)
      WRITE(2,507)I,STRLEN(I),SUBAR(I),CUMDIS(N),CUMDA(I)
      N=N+1
      GOTO 505
C---------------------
  821 FORMAT(1X,I2,4X,2(F6.2,12X))
  820 FORMAT('0NSEG  SEG LENGTH/TOTAL  SUBAR/TOTAL'/,
     c'              (%)              (%)')
  511 WRITE(2,820)
      N=1
  823 I=TRIB(N)
      IF(I.EQ.99)GOTO 824
      PC7=(STRLEN(I)/TLEN)*100.
      PC8=(SUBAR(I)/TDA)*100.
      WRITE(2,821)I,PC7,PC8
      N=N+1
      GOTO 823
  822 FORMAT('0 TOTAL DRAINAGE AREA=',E12.5/,'  TOTAL NETWORK
LENGTH=',
     cF8.1,' METERS'/,'  TOTAL MAINSTREAM LENGTH=',F8.1,' METERS')
  824 WRITE(2,822)TDA,TLEN,TMSL
C-----------------------------------------------
C    CONVERT LATITUDE AND DECLINATION TO RADIANS
      ENDFILE 7
      LAT=LAT*RPD
      DECL=DECL*RPD
  905 FORMAT(' GOT TO HERE')
C
```

```
C    READ DATA-- ALTITUDE MATRIX ARRANGED ON I,J COORDINATES
   1 FORMAT(40(I2,1X))
     DO 5 JA=1,30
     J=31-JA
     READ(6,1,END=11)(ALT(I,J),I=1,40)
   5 CONTINUE
C
C    CALCULATE NO. OF HOURS IN HALF DAY(H=ANGULAR DIST.(DEG)
C    OF TRAVEL; SELLERS,W.D.); S=NO.OF INTERVALS OF ANGULAR
C    MOVEMENT OF 30 MIN. DURATION (7.5 DEG.); NT=TOTAL NO.OF
C    INTERVALS IN DAY; FHH=NO.OF DEGREES OF MOVEMENT
REMAINING
C    IN FIRST PARTIAL INTERVAL ABOVE W AND E HORIZON OR
FRACTIONAL
C    HALF-HOUR INTERVAL; SBEAR=BEARING OF SUN
WRT.N=0,S=180,E=90.
C    TIME=NO.OF MINUTES TRAVEL OF SUN DURING INTERVAL OF
PARTIAL
C    INTERVAL;NT HAS (2*IS)-1 FULL 7.5 DEG.INTERVALS PLUS 2
PARTIAL
C    INTERVALS OF 0.TO 3.75 DEG EACH.
  11 COH=-((SIN(LAT))/(COS(LAT)))*((SIN(DECL))/
    c(COS(DECL)))
     H=90.-(ATAN(COH/SQRT(1.-COH*COH)))*DPR
     S=H/7.5
     IS=S
     FHH=S-FLOAT(IS)
     FHH=FHH*7.5
     NT=(2*IS)+1
     N=1
C    PARTIAL INTERVAL ON EAST
     T(N)=H-(FHH+3.75)/2.
     TIME(N)=((FHH+3.75)/15.)*60.
     CALL ZENAZ(LAT,DECL,T(N),Z(N),RPD,DPR,AZ1)
     SBEAR(N)=180.-AZ1
     N=N+1
C    FIRST FULL INTERVAL ON EAST SIDE
     T(N)=H-FHH-7.5
     TIME(N)=30.
     CALL ZENAZ(LAT,DECL,T(N),Z(N),RPD,DPR,AZ)
     SBEAR(N)=180.-AZ
     N=N+1
C    ALL REMAINING FULL INTERVALS ON E AND W OF SOUTH
```

```
      NQ=(NT+1)/2
      HH=7.5
  290 IF(N.GT.NQ)HH=-7.5
      T(N)=T(N-1)-HH
      TIME(N)=30.
      CALL ZENAZ(LAT,DECL,T(N),Z(N),RPD,DPR,AZ)
      IF(N.GT.NQ)GOTO 89
      SBEAR(N)=180.-AZ
      GOTO 90
   89 SBEAR(N)=180.+AZ
   90 N=N+1
      IF(N.LT.NT)GOTO 290
C     PARTIAL INTERVAL ON WEST SIDE
      T(N)=T(1)
      TIME(N)=TIME(1)
      Z(N)=Z(1)
      SBEAR(N)=180.+AZ1
C
C     CALCULATE DIRECTION COSINES OF SUN VECTOR; SEE TAFF
C     DETERMINE RADIATION LOSS DUE TO AIR MASS; GARNIER,B.J.
C     AND A.OHMURA. 1968. J.APPL. METEOR. 7:796-800.
C     CALCULATE ALTITUDE OF SUN;DETERMINE DEGREE OF ROTATION
OF
C     BASIN WRT.SUN BEARING BY ADDING ROT TO SBEAR
      DO 101 N=1,NT
      SBEAR(N)=SBEAR(N)+ROT
      IF(SBEAR(N).GE.360.)SBEAR(N)=SBEAR(N)-360.
      SUNL(N)=(SIN(Z(N)*RPD))*(COS(180.*RPD+SBEAR(N)*RPD))
      SUNM(N)=(SIN(Z(N)*RPD))*(SIN(180.*RPD+SBEAR(N)*RPD))
      SUNN(N)=(COS(Z(N)*RPD))
      M=1/COS(Z(N)*RPD)
      P2THEM=P**M
      SLITE(N)=IO*P2THEM*TIME(N)*(COS(Z(N)*RPD))
      SALT(N)=90.-Z(N)
  101 CONTINUE
C     ---------------------------
      CALL OPEN(7,NOM,2)
  100      N=1
C     READ DATA STORED ON DISC FOR COORDINATES OF POINTS ON
STREAM
C     AND ALTITUDE OF PTS.,AREA OF BASIN FOR STREAM SEGMENT,
C     SEGMENT NUMBER
    4 FORMAT(1X,2(F4.1,1X),I2,1X,2(E12.4,1X),I2,1X,I1,1X,F4.1,1X,
```

```
    cI2,1X,I3)
C     CX,CY=COORDINATES OF PT. ON STREAM; ALTST=ALT.OF PT.ON
STREAM;
C     SUBDA=SUB-DRAINAGE AREA; NSEG=NO.OF BLUE LINE SEGMENT

READ(7,2,END=200)CX,CY,ALTST,SUBDA,LENGTH,NSEG,CANHT,GAP,CO
VER,OR
C     ---------------------------
C     AVWID=AV.WIDTH OF A SEG;SHADE=FRACTION OF WATER
SURFACE WIDTH
C     DIRECTLY UNDER CANOPY ON ONE SIDE ONLY--AT LEAST THIS
WIDTH
C     WOULD BE SHADED IF SUN WERE DIRECTLY
OVERHEAD;EFWID=EFFECTIVE
C     WIDTH;W(N)=10 EQUAL INTERVALS FOR DIST.ACROSS EFWID;
C     MARGIN=SPACE AT EDGE OF STREAM BETWEEN CANOPY LINE
AND EFWID
C     WHEN AVWID< GAP;XTRA=SPACE BETWEEN CENTERS OF 10
EQUAL
C     INTERVALS IN EFWID;
      IF(AVWID(NSEG).LE.GAP)GOTO 384
      SHADE=(AVWID(NSEG)-GAP)/2.
      MARGIN=0.
      KGAP=1
      GOTO 385
  384 SHADE=0.
      KGAP=2
      MARGIN=(GAP-AVWID(NSEG))/2.0
  385 EFWID=AVWID(NSEG)-SHADE
      W(1)=EFWID/20.+MARGIN
      XTRA=EFWID/10.
      DO 386 L=2,10
      W(L)=W(L-1)+XTRA
  386 CONTINUE
C
C     CONVERT CANOPY HT.CODE TO HT.(M)
      IF(CANHT.EQ.1)CNHT=1.
      IF(CANHT.EQ.2)CNHT=3.
      IF(CANHT.EQ.3)CNHT=6.
      IF(CANHT.EQ.4)CNHT=11.5
      IF(CANHT.EQ.5)CNHT=20.
C     ---------------------------------------------
```

```
C     CHECK FOR MAX. ANGLE OF TOPOGRAPHIC SHADING; CALCULATE
PTS.
C     OF INTERSECTION ON VERTICAL GRID LINES FOR PTS. YIELDING
C     LARGEST TOPOGRAPHIC SHADING
  160 BIGANG=0.0
C     CALC. MIN.ABSOLUTE ANGLE BETWEEN SUN BEARING AND
CHANNEL ORIENT.
      AA=ABS(SBEAR(N)-FLOAT(OR))
      IF(AA.GT.180.)GOTO 381
  380 IF(AA.GT.90.0.AND.AA.LE.180.)ANG=180.-AA
      IF(AA.GE.0.0.AND.AA.LE.90.)ANG=AA
      GOTO 382
  381 AA=360.-AA
      GOTO 380
C     -----
  382 DIFF=CX-FLOAT(IFIX(CX))
      IF(SBEAR(N).EQ.0.0.OR.SBEAR(N).EQ.180.)GOTO 60
      IF(SBEAR(N).GT.0.0.AND.SBEAR(N).LT.180.)GOTO 10
      AX=-(1.+DIFF)
      KODEEW=2
      CALL
SUB1(AX,KODEEW,CX,CY,ALT,ALTST,BIGANG,SBEAR(N),RPD,DPR)
      GOTO 60
   10 AX=2.-(DIFF)
      KODEEW=1
      CALL
SUB1(AX,KODEEW,CX,CY,ALT,ALTST,BIGANG,SBEAR(N),RPD,DPR)
C
C     CALCULATE PTS. OF INTERSECTION ON HORIZONTAL GRID LINES
FOR
C     PTS. YIELDING LARGEST TOPOGRAPHIC SHADING
   60 DIFF=CY-FLOAT(IFIX(CY))
      IF(SBEAR(N).EQ.90..OR.SBEAR(N).EQ.270.)GOTO 99
      IF(SBEAR(N).GT.270..OR.SBEAR(N).LT.90.)GOTO 70
      AY=-(1.+DIFF)
      KODENS=4
      CALL
SUB2(AY,KODENS,CX,CY,ALT,ALTST,BIGANG,SBEAR(N),RPD,DPR)
      GOTO 99
   70 AY=2.-(DIFF)
      KODENS=3
      CALL
SUB2(AY,KODENS,CX,CY,ALT,ALTST,BIGANG,SBEAR(N),RPD,DPR)
```

```
C     ----------------------------------------
C     IF SUN ALTITUDE IS < MAX. ANGLE OF TOPOG. SHADING SKIP

C     CALC. OF RADIATION
   99 IDPMX=IDPMX+SLITE(N)
         IF(SALT(N).LE.BIGANG)GOTO 98
C
C     ACCUMULATE SOLAR RAD. FOR EACH SEGMENT FOR ALL SOLAR
BEARINGS
C     PRINT EACH SEPARATELY AFTER CALC.;ID-DAILY SOLAR
RAD.(JOULES/M2)
C     W TOPOG.SHADING EFFECT;IDPOT-POTENTIAL RAD.WHICH
C     WOULD BE RECEIVED ON HORIZONTAL SURFACE INCLUDING
TOPOG.SHADING
C     FACTOR.  RAD ON HORIZ.SURFACE DECREASES AS FUNC.OF COS(Z);
C     SEE GARNIER ET.AL..;EXPOS=FRACTION OF CANOPY EXPOSED
      ID=ID+SLITE(N)
C
C     CALC.EFFECT OF CANOPY SHADING;
C     OR=ORIENTATION OF CHANNEL AT POINT ON GRID;
C     PCT=CUM %(FRACTION)OF EFWID RECEIVING SUN--SUMMATION
OF 10
C     EQUAL PARTS;PCTOT=TOTAL % OF AVWID RECEIVING SUN;COEF=
C     0.05 GIVES LIGHT EXTINCTION BY CANOPY;IDCAN=RAD.W/EFFECT
OF
C     CANOPY+TOP./M**2;CANANG=CANOPY ANGLE--FROM CENTER OF
EACH OF 10
C     SEGMENTS OF EFWID TO CANOPY
      XCOVR=FLOAT(COVER)*0.1
      EXPOS=1.0-XCOVR
      IF(ABS(GAP).EQ.0.0)GOTO 102
      CALL TREE(ANG,W,SALT,CNHT,PCT,EFWID,GAP,KGAP,DPR)
      XZ=EFWID/AVWID(NSEG)
      XY=SHADE/AVWID(NSEG)

PCTOT=(PCT*XZ)+(EXPOS*XY)+(COEF*XCOVR*XY)+(1.-PCT)*XZ*COEF*
XCOVR
     c+((1.-PCT)*XZ*EXPOS)
      GOTO 103
  102 PCTOT=EXPOS+(COEF*XCOVR)
  103 IDCAN=IDCAN+SLITE(N)*PCTOT
   98     N=N+1
         IF(N.LE.NT)GOTO 160
```

```
C     -------------------------------------------------
      NTOT=NTOT+1
C     AVWID=AV.WIDTH OF STREAM SEGMENT;SUBDA=SUB-DRAINAGE
AREA;
C     DA=DRAINAGE AREA; RAD=SOLAR RADIATION ON SEGMENT OF
STREAM
C     W/TOPOG. EFFECT ESTIMATED FROM ONE PT.;ALL PTS. IN EACH
SEGMENT
C     ARE AVERAGED ; TRAD=TOTAL RAD.W/O
TOPOG.EFFECT;NOTE-BECAUSE
C     EACH STREAM PT. IS NOT NECESSARILY ASSOC. WITH AN EQUAL
LENGTH
C     OF STREAM, EACH RAD.CAL. FOR EACH PT. IS MULT. BY ENTIRE
STRLEN
C     AND THEN DIVIDED BY NO. OF VALUES ADDED.
C     STAREA=STREAM AREA OF INDIV.BLUE LINE
SEGMENTS;NSEG=SEGMENT NO.
C     KOUNT=NO.OF ALT PTS.ON STREAM SEGMENT;
C     R=TOTAL DAILY SOLAR RAD.FOR SEGMENT WITH TOPOG.EFFECT
C     TR=TOTAL DAILY SOLAR RAD.FOR SEGMENT W/O TOPOG.EFFECT
      RAD(NSEG)=RAD(NSEG)+(ID*STRLEN(NSEG)*AVWID(NSEG))
      TRAD(NSEG)=TRAD(NSEG)+(IDPMX*STRLEN(NSEG)*AVWID(NSEG))
      CRAD(NSEG)=CRAD(NSEG)+(IDCAN*STRLEN(NSEG)*AVWID(NSEG))
      KOUNT(NSEG)=KOUNT(NSEG)+1
      PC=(ID/IDPMX)*100.
      PC4=(IDCAN/IDPMX)*100.
      IF(STAREA(NSEG).GT.0.0)GOTO 25
      STAREA(NSEG)=STRLEN(NSEG)*AVWID(NSEG)
  225 FORMAT(7X,2(F4.1,1X),2(E11.5,1X),4X,F6.2,3X,I2,1X,E11.5,1X,F6.2)
    9 FORMAT(2(F4.1,1X),2(E11.5,1X),F6.2,1X,I2,1X,E11.5,1X,F6.2,A1)
    7 FORMAT('       I    J   ID/M2(JOULES) ID W/O TOPOG  % POT.  SEG.
     c ID W/CAN  %POT')
   25 IF(NTOT.EQ.1)WRITE(2,7)
      IF(NCODE.EQ.1)WRITE(2,225)CX,CY,ID,IDPMX,PC,NSEG,IDCAN,PC4

IF(NCODE.EQ.1)WRITE(2,4)CX,CY,ALTST,SUBDA,LENGTH,NSEG,CANHT,
     cGAP,COVER,OR
      IF(MCODE.EQ.1)WRITE(5,9)CX,CY,ID,IDPMX,PC,NSEG,IDCAN,PC4,LF
      ID=0.0
      IDPMX=0.0
      IDCAN=0.0
      GOTO 100
C     ---------------------------
```

```
C     STRAD=STREAM DAILY SOLAR RAD ACCUM. FOR ENTIRE BLUE
LINE OF BASIN
C     W/O EFFECT OF TOPOG OR CANOPY;SINT=SOLAR
INTENSITY,RAD/M**2
C     RRAD=TOTAL NETWORK DAILY
RAD.W/TOPOG.EFFECT;CTRAD=TOTAL NETWORK
C     DAILY RAD.W/CANOPY EFFECT;
  209 FORMAT(///' SEG. RAD/SEG.  RAD/SEG.   RAD W/TOP/  RAD
     cRAD W/CAN/    AREA       RAD/M2')
  207 FORMAT('      W/TOPOG   W/O TOPOG  RAD W/O     W/CAN
     cTRAD          M**2')
  200 WRITE(2,209)
      WRITE(2,207)
  210 FORMAT(1X,I2,1X,2(E11.5,1X),F6.2,2X,E11.5,1X,F6.2,1X,E13.5,
     c1X,E11.5)
      DO 65 N=1,30
      IF(KOUNT(N).EQ.0)GOTO 65
      R=RAD(N)/FLOAT(KOUNT(N))
      SINT=R/STAREA(N)
      TR=TRAD(N)/FLOAT(KOUNT(N))
      PC1=(R/TR)*100.
      C=CRAD(N)/FLOAT(KOUNT(N))
      PC2=(C/TR)*100.
      WRITE(2,210)N,R,TR,PC1,C,PC2,STAREA(N),SINT
      RRAD=RRAD+R
      CTRAD=CTRAD+C
      STRAD=STRAD+TR
   65 CONTINUE
C
      PC5=(RRAD/STRAD)*100.
      PC6=(CTRAD/STRAD)*100.
  196 FORMAT(//' TOTAL NETWORK DAILY RAD. W/TOPOG
EFFECT=',E11.5,/,
     c' TOTAL NETWORK DAILY RAD.W/O TOPOG.OR
CANOPY(ie.POT.)=',E11.5,/,
     c' DAILY NETWORK RAD.W/TOPOG.SHADING / POTENTIAL
RAD.=',F6.2/,
     c' TOTAL STREAM DAILY RADIATION W/CANOPY SHADING=',E11.5/
     c' RAD WITH CANOPY+TOPOG. SHADING / POTENTIAL RAD.=',F6.2/,
     c' TOTAL NO.OF STREAM POINTS USED FOR NETWORK=',I3)
      WRITE(2,196)RRAD,STRAD,PC5,CTRAD,PC6,NTOT
C     ----------
      ENDFILE 6
```

```
      ENDFILE 7
      IF(MCODE.EQ.1)ENDFILE 5
      END
C     ----------------------------
      SUBROUTINE
SUB1(AX,KODEEW,CX,CY,ALT,ALTST,BIGANG,SBEAR,RPD,DPR)
C     KODEEW=CODE FOR BEARING OF SUN (EAST-WEST) TO ELIMINATE
SEARCHING
C     ENTIRE ALT.MATRIX; USE INCREMENT OF 0.5 FOR FIRST GRID
C     INTERSECTION AND PLUS OR MINUS 1. THEREAFTER DEPENDING
ON BEARING
C     CX AND CY=COORD.OF CENTER OF TRIANGLE;
C     AY,AX=INCREMENTS ON X AND Y AXES FOR A GIVEN BEARING TO
SUN WHICH
C     INTERSECT GRID LINES;DALT=DIFFERENCE IN ALTITUDE OF 2 PTS.;
C     PTALT=INTERPOLATED ALT. OF PT. WHERE IT INTERSECTS GRID
LINE;
C     DIST=MAP DISTANCE FROM CENTER OF TRIANGLE TO GRID
INTERSECTION PT.
C     ANGLE=ANGLE (DEGREES) FROM CENTER OF TRIANGLE (AVALT)
TO PTALT
      INTEGER ALT(40,30),ALTST
      SCALE=880.
      K=0
      V=ABS((90.-SBEAR)*RPD)
      T=SIN(V)/COS(V)
   40 AY=ABS(T*AX)
      IF(SBEAR.GT.90..AND.SBEAR.LT.270.)AY=-AY
      X=CX+AX
      Y=CY+AY
      IF(Y.GT.30..OR.Y.LT.1..OR.X.GT.40..OR.X.LT.1.)GOTO 45
      IX=X
      IY=Y
      IY1=IY+1
      DIF=Y-FLOAT(IY)
      IF(ALT(IX,IY1).EQ.99.AND.ALT(IX,IY).EQ.99)GOTO 81
      IF(ALT(IX,IY1).NE.99.AND.ALT(IX,IY).NE.99)GOTO 42
C     IF ONLY ONE OF THE 2 PTS. IS NOT =99, TAKE THIS AS THE
ALTITUDE
      IF(ALT(IX,IY1).NE.99)CALL SUB3(ALT(IX,IY1),PTALT,CX,CY,X,Y,
     cSCALE,DIST)
      IF(ALT(IX,IY).NE.99)CALL SUB3(ALT(IX,IY),PTALT,CX,CY,X,Y,SCALE,
     cDIST)
```

```
      GOTO 43
C
   42 DALT=FLOAT(ALT(IX,IY1))-FLOAT(ALT(IX,IY))
      PTALT=(FLOAT(ALT(IX,IY))+DALT*DIF)
      DIST=SQRT(AX*AX+AY*AY)*SCALE
   43 TAG=(PTALT-FLOAT(ALTST))*80./DIST
      ANGLE=ATAN(TAG)*DPR
      IF(ANGLE.GT.BIGANG)BIGANG=ANGLE
      GOTO 41
C     ALLOW SEARCH THROUGH MATRIX UNTIL 3 SETS OF 99'S ARE
FOUND
   81 K=K+1
      IF(K.EQ.3)GOTO 45
   41 IF(KODEEW.EQ.1)AX=AX+1.
      IF(KODEEW.EQ.2)AX=AX-1.
      GOTO 40
   45 RETURN
      END
C     ----------------------
      SUBROUTINE
SUB2(AY,KODENS,CX,CY,ALT,ALTST,BIGANG,SBEAR,RPD,DPR)
      INTEGER ALT(40,30),ALTST
      SCALE=880.
      K=0
      IF(SBEAR.NE.0..AND.SBEAR.NE.180.)GOTO 50
      AX=0.0
      GOTO 55
   50 V=ABS((90.-SBEAR)*RPD)
      T=SIN(V)/COS(V)
   56 AX=ABS(AY/T)
      IF(SBEAR.GT.180..AND.SBEAR.LT.360.)AX=-AX
   55 X=CX+AX
      Y=CY+AY
      IF(Y.GT.30..OR.Y.LT.1..OR.X.GT.40..OR.X.LT.1.)GOTO 46
      IX=X
      IY=Y
      IX1=IX+1
      DIF=X-FLOAT(IX)
      IF(ALT(IX1,IY).EQ.99.AND.ALT(IX,IY).EQ.99)GOTO 61
      IF(ALT(IX1,IY).NE.99.AND.ALT(IX,IY).NE.99)GOTO 52
C     IF ONLY ONE OF THE 2 PTS. IS NOT =99, TAKE THIS AS THE
ALTITUDE
      IF(ALT(IX1,IY).NE.99)CALL SUB3(ALT(IX1,IY),PTALT,CX,CY,X,Y,
```

```
     cSCALE,DIST)
      IF(ALT(IX,IY).NE.99)CALL SUB3(ALT(IX,IY),PTALT,CX,CY,X,Y,SCALE,
     cDIST)
      GOTO 53
C
   52 DALT=FLOAT(ALT(IX1,IY))-FLOAT(ALT(IX,IY))
      PTALT=(FLOAT(ALT(IX,IY))+DALT*DIF)
      DIST=SQRT(AX*AX+AY*AY)*SCALE
   53 TAG=(PTALT-FLOAT(ALTST))*80./DIST
      ANGLE=ATAN(TAG)*DPR
      IF(ANGLE.GT.BIGANG)BIGANG=ANGLE
      GOTO 51
   61 K=K+1
      IF(K.EQ.3)GOTO 46
   51 IF(KODENS.EQ.3)AY=AY+1.
      IF(KODENS.EQ.4)AY=AY-1.
      IF(AX.EQ.0.0)GOTO 55
      GOTO 56
   46 RETURN
      END
C     -------------------
      SUBROUTINE SUB3(ALTPT,PTALT,X1,Y1,X2,Y2,SCALE,DIST)
      INTEGER ALTPT
      PTALT=FLOAT(ALTPT)
      DIST=SQRT((X2-X1)*(X2-X1)+(Y2-Y1)*(Y2-Y1))*SCALE
      RETURN
      END
C     ------------------
      SUBROUTINE ZENAZ(LAT,DECL,T,Z,RPD,DPR,AZ)
C     DETERMINE ZENITH ANGLE(Z), ALTITUDE OF SUN(SALT)
C     FIND ARCCOS OF Z;SEE SELLERS,W.D.;AZIMUTH OF SUN
WRT.S=0.DEG.
      REAL LAT
      COZ=SIN(LAT)*SIN(DECL)+COS(LAT)*COS(DECL)
     c*COS(T*RPD)
      Z=90.-(ATAN(COZ/SQRT(1.-COZ*COZ)))*DPR
      COAZ=(SIN(LAT)*COS(Z*RPD)-SIN(DECL))/
     c(COS(LAT)*SIN(Z*RPD))
      IF(COAZ.GT.0.999)GOTO 36
      AZ=90.-(ATAN(COAZ/SQRT(1.-COAZ*COAZ)))*DPR
      GOTO 37
   36 AZ=0.
   37 RETURN
```

```
      END
C     ----------------------
      SUBROUTINE TREE(ANG,W,SALT,CNHT,PCT,EFWID,GAP,KGAP,DPR)
      DIMENSION W(10)
      REAL LEN
      SN=SIN(ANG)
      PCT=0.0
      DO 390 N=1,10
      IF(SN.EQ.0.0)GOTO 391
      LEN=W(N)/SN
      CANANG=ATAN(CNHT/LEN)*DPR
      IF(CANANG.GE.SALT)GOTO 390
      PCT=PCT+0.10
  390 CONTINUE
      GOTO 393
  391 IF(KGAP.EQ.1)PCT=GAP/EFWID
      IF(KGAP.EQ.2)PCT=1.0
  393 RETURN
      END
```

D. APPENDIX D

1. Computer Program PCALT Used to Compute Variables MAXDIR and SLPTPT

```
       PROGRAM PCALT
C     PROGRAM CREATED FEB.26,1983 (DALE.A.MCCULLOUGH)
C     THIS PROGRAM WILL CALCULATE THE MEAN PERCENT CHANGE IN
ALTITUDE
C     FROM ONE POINT TO THE NEXT ON X-AXIS AND THEN Y-AXIS ON
C     ALTITUDE GRID; PROGRAM WILL ALSO COUNT NO.OF CHANGES IN
C     DIRECTION IN SLOPE ON X-AXIS AND Y-AXIS SEPARATELY
C     PTCNG=PERCENT CHANGE IN ALT.; TPTCNG=TOTAL % CHANGE;
C     AVPCC=AVERAGE % CHANGE; GAVPCC=GRAND AVERAGE %
CHANGE;
      INTEGER ALT(40,30)
      LOGICAL NAME(11),CR,LF
      CR=13
      LF=10
  200 FORMAT(' DO YOU WANT TO CONTINUE?; YES=1,N0=2')
   13 WRITE(3,200)
      WRITE(3,101)CR,LF
  105 FORMAT(I1)
      READ(3,105)NCODE
      IF(NCODE.EQ.2)GOTO 999
  100 FORMAT(' ENTER 11 CHARACTER FILENAME OF ALTITUDE
MATRIX')
      WRITE(3,100)
  101 FORMAT(80A1)
      WRITE(3,101)CR,LF
      READ(3,101)(NAME(I),I=1,11)
  102 FORMAT(' BASIN NAME IS ',11A1)
      WRITE(2,102)(NAME(I),I=1,11)
      CALL OPEN(5,NAME,2)
      TPCNG1=0.
      TPCNG2=0.
      IMAT=40
      JMAT=30
      KOUNT1=0
      KOUNT2=0
      KDIR1=0
      KDIR2=0
```

```
      J=JMAT
    1 FORMAT(40(I2,1X))
    2 READ(5,1,END=45)(ALT(I,J),I=1,IMAT)
      J=J-1
      GOTO 2
C     -----------------------
   45 J=JMAT
   20 CALL PCTCI(IMAT,J,TPCNG1,KOUNT1,ALT,KDIR1)
      J=J-1
      IF(J.NE.0)GOTO 20
C     -----------------------
      AVPCC=(TPCNG1*100.)/FLOAT(KOUNT1)
   50 FORMAT(' AVERAGE % CHANGE OF ALTITUDE (PT.TO PT.)ON
X-AXIS= ',
     c F7.3,'  KOUNT1= ',I4)
      WRITE(2,50)AVPCC,KOUNT1
C     ------------------------
      I=1
   40 CALL PCTCJ(JMAT,I,TPCNG2,KOUNT2,ALT,KDIR2)
      I=I+1
      IF(I.GT.IMAT)GOTO 90
      GOTO 40
C     ------------------------
   90 AVPCC=(TPCNG2*100.)/FLOAT(KOUNT2)
      KOUNT=KOUNT1+KOUNT2
      GAVPCC=(TPCNG1+TPCNG2)*100./(FLOAT(KOUNT))
      WRITE(2,60)AVPCC,KOUNT2
   60 FORMAT(' AVERAGE % CHANGE OF ALTITUDE (PT.TO PT.) ALONG
Y-
     cAXIS= ',F7.3,'   KOUNT2= ',I4)
      WRITE(2,70)GAVPCC,KOUNT
   70 FORMAT(' GRAND AVERAGE % CHANGE IN ALT.(PT.TO PT.) ALONG
     c X-AND Y-AXES = ',F7.3,'   KOUNT= ',I5)
  110 FORMAT(' NO.OF CHANGES OF DIRECTION OF SLOPE(NEG.TO
POS.OR
     c POS.TO NEG.) ON HORIZ.AXIS= ',I4)
  115 FORMAT(' NO.OF CHANGES OF DIRECTION OF SLOPE(NEG.TO
POS.OR
     c POS.TO NEG.) ON VERT.AXIS= ',I4)
      WRITE(2,110)KDIR1
      WRITE(2,115)KDIR2
      ENDFILE 5
      GOTO 13
```

```
  999 END
C
      SUBROUTINE PCTCI(IMAT,J,TPCNG1,KOUNT1,ALT,KDIR1)
      INTEGER ALT(40,30)
      XLAST=0.
      I=1
   10 IF(ALT(I,J).EQ.99)GOTO 5
      N=I+1
      IF(ALT(N,J).EQ.99.OR.N.GT.IMAT)GOTO 5
      X=FLOAT(ALT(I,J))
      Y=FLOAT(ALT(N,J))
      PCT=(X-Y)/X
      PCTCNG=ABS(PCT)
      PROD=XLAST*PCT
      IF(PROD.LT.-0.00001)KDIR1=KDIR1+1
      XLAST=PCT
      TPCNG1=TPCNG1+PCTCNG
      KOUNT1=KOUNT1+1
      GOTO 160
    5 XLAST=0.
  160 I=I+1
      IF(I.GE.IMAT)GOTO 15
      GOTO 10
   15 RETURN
      END
C
      SUBROUTINE PCTCJ(JMAT,I,TPCNG2,KOUNT2,ALT,KDIR2)
      INTEGER ALT(40,30)
      XLAST=0.
      J=JMAT
   35 IF(ALT(I,J).EQ.99)GOTO 30
      K=J-1
      IF(ALT(I,K).EQ.99.OR.K.LT.1)GOTO 30
      X=FLOAT(ALT(I,J))
      Y=FLOAT(ALT(I,K))
      PCT=(X-Y)/X
      PCTCNG=ABS(PCT)
      PROD=XLAST*PCT
      IF(PROD.LT.-0.00001)KDIR2=KDIR2+1
      XLAST=PCT
      TPCNG2=TPCNG2+PCTCNG
      KOUNT2=KOUNT2+1
      GOTO 150
```

```
 30 XLAST=0.
150 J=J-1
    IF(J.LE.1)GOTO 135
    GOTO 35
135 RETURN
    END
```

Appendix E. Compilation of data for major basins of the Tillamook Burn area (Benoit 1978).

	Forest land (mi^2)	Gross erosion ($t/mi^2/y$)	Gross sediment	Suspended sediment	Bedload sediment	Roads mi/mi^2	Perennial streams	Man-caused slides ($no./mi^2$)	Natural slides	Mean annual runoff (inches)
MIAMI	35.95	539.97	53.7	28.7	25.0	8.9	1.19	13.86	2.21	97
upper KILCHIS	33.44	360.05	32.0	17.0	15.0	10.9	1.32	14.86	0.54	100
lower KILCHIS	23.45	578.45	98.5	35.7	62.9	10.5	1.07	8.61	0.34	90
SF KILCHIS	10.80	967.23	92.6	77.2	15.4	7.8	1.85	11.94	0.19	95
lower WILSON	74.56	557.07	114.2	38.4	75.8	10.7	0.80	8.84	0.41	100
upper WILSON	89.00	323.97	46.8	27.4	19.4	14.9	0.46	12.90	0.31	104
NF WILSON	25.67	276.72	16.2	22.3	3.8	5.4	0.66	2.45	1.12	94
main TRASK	109.25	718.57	150.9	121.8	29.2	14.6	0.69	3.99	0.16	93
EF TRASK	29.42	985.79	246.4	218.8	27.7	12.6	1.00	6.46	0.24	100
SF TRASK	20.61	240.45	52.9	27.8	25.2	9.7	1.21	22.61	0.29	103