Select Geomorphological Components of Wildlife Habitat in the Ridge and Valley Province of Virginia

by

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(ABSTRACT)

I examined geomorphology as it relates to wildlife and wildlife habitat I sought to make quantitative dimensions of land surface shape (terrain) available for use by natural resource professionals.

Most geomorphic processes operate on longer time scales than the life spans of organisms that inhabit a landscape. So, it is the shape of the land surface, not formative processes that are considered in most environmental sciences.

Terrain molds and is molded by climate, vegetation, and geology. Terrain influences site-specific temperature, precipitation, solar radiation, and winds. Through these climatic effects, terrain influences the distribution of plant species and plant phenologies.

I examined the role of terrain in applied environmental sciences including forestry, soil science, hydrology, and fisheries. Terrain also affects the distribution, movements, energetics, cover, and food habits of wildlife species.

I identified 8 parameters of land surface shape: elevation, slope, aspect, relief, length, area, roughness and texture, pattern and shape. From physical science literature, I identified over 120 descriptors of surface shape that measure 1 or more of these parameters. Through an objective-weighting procedure, I selected 60 descriptors to include in a computer-based system for quantifying land surface shape.

The resulting system, GEODES, integrates a raster-based GIS, vector mapping programs, and a relational data base management system to present these land surface shape descriptors. Specific applications of individual descriptors and of GEODES are suggested.

Individual descriptors or the larger system (GEODES) may be used to reduce variance in wildlife research and management, and to increase managerial control.

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Objectives

1. To conduct a literature review analyzing the major relations between select geomorphic components and associated wildlife habitats in the Ridge and Valley Province of southwest Virginia.
2. To determine the inputs necessary to quantify geomorphic components of this region effectively and efficiently.
3. To develop new computer programs or locate and modify existing computer programs that present geomorphologic information to natural resource managers.
4. To suggest applications of geomorphologically-based information to wildlife research and management.

Introduction and Justification

The General Hypothesis

Most wildlife habitat studies examine the relationships of wildlife to food, cover, or water. Others analyze two-dimensional relationships of edge, area, or the adjacency of habitat types and the role of these relations in wildlife habitat use or in community organization.

Many geomorphic processes operate on a landscape over intervals much greater than the life spans of many of the organisms that inhabit that landscape. Despite the difference in time scales, these geomorphic processes help determine wildlife habitat quality in a landscape, in part through effects on climate and vegetation. This study examines some of the effects of geomorphologic processes on wildlife and wildlife habitat.

I do not hypothesize that geomorphic factors are the primary determinants of habitat quality (though they might be for some species in some situations). If they are not the primary determinants, then they may explain part of the variance encountered in analyses of habitat and population interactions, or in the populations themselves.

This project was not a conventional habitat analysis. It did not focus on animal observation or traditional habitat measurement (i.e., vegetation attributes) and then perform statistical analyses of these relations. Instead, it :

1. Analyzed relations between geomorphic factors and wildlife habitat,
2. Found literature that supported these relations,
3. Developed methods that presented geomorphic information to natural resource professionals cost effectively, and
4. Provided quantitative dimensions of wildlife habitat that were not previously readily available for use in animal habitat studies.

The results of this study may enable managers to more effectively assess terrain effects on natural resources. A better understanding of landforms may allow managers to explain better the variability in wildlife species occurrence, distribution, dynamics, and community composition. Some of the descriptors used to describe landforms may have management or research applications outside the realm of terrain analysis.

Basic Definitions

Geomorphology is a concatenation of Greek root words translated as "earth form study". This science examines the origins, development, classification, and description of landforms and landscapes (Tuttle 1970, Ritter 1978, Howard and Mitchell 1985). Geomorphology studies the land surface of the earth and the modifications of the surface over time. Landforms are an expression of geomorphologic processes (Howard and Mitchell 1985). Herein after, I use "landform" or "form" in a general sense.

More precisely, landforms are, "Terrain features formed by natural processes, which have a definable composition and range of physical and visual characteristics" (Way 1973).

The Forces and Their Interactions

The agents of surface modification are flowing water, ice, wind, waves, volcanism, and tectonic movements. The major surface-modifying process is erosion. Most of this planet's landforms are erosional, created by the removal of matter from a given location on the surface of the earth (Tuttle 1970). Running water is probably the most important agent of erosion. Principal components of this process include weathering, mass wasting, entrainment, transportation, deposition and processes related to human activities such as land subsidence, earth removal, solution channels, etc.

Ninety-five percent of all landforms are shaped by streams (Platts 1979). Stream and landform development occur together. Valley slopes occupy most areas of erosional relief, comprising most of the world's land area (Tuttle 1970, Young 1972).

Elements of geomorphology are incorporated within many of the environmental sciences. Terrain plays an important role in climatology, vegetation and soil science, geology, hydrology, engineering, agriculture (including forestry), fisheries, and natural resource classification and planning.

It is difficult to separate effects of geomorphic processes on the environment from the effects of climatic and vegetational factors. Interactions of these factors make it difficult to attribute environmental features, such as distribution of vegetation or soil types, solely to topography or to geomorphic processes.

The Watershed as Ecosystem

There have been many definitions of *ecosystem* since the term was coined by Tansley in 1935. An ecosystem is not merely a community of organisms interacting with each other and their environment, but also an "Area with a boundary through which the input and output of energy and matter can be measured and related to one or more environmental factors" (Miller

1979:43). This stipulation applies equally well to watersheds. A watershed or drainage basin is "A segment of earth set off from adjacent segments by more or less discrete boundaries and occupied by a particular group of organisms" (Lotspeich 1980:582). Coupling these two definitions, the watershed may be considered an easily recognizable ecosystem.

Both ecosystems and drainage basins develop through the interplay of biotic and abiotic factors (Swanson 1979). Ecosystem processes and drainage basin formation are both generally driven by climate, that is by seasonal and diurnal fluctuations of energy and water (Bailey 1985). The indigenous flora and fauna of an area evolve partly in reponse to climate, much as drainage basins evolve (Bailey 1985). Local climate, in turn, is shaped by the structural characteristics of the ecosystem, especially landforms and local vegetation (Bailey 1985, Swanson et al. 1988). Basin form (including shape, slope, relief, and geology) determines how and where materials (nutrients, soil, and water) and energy (sunlight) are received and processed, thus affecting an area's biotic potential (Rowe 1980). Basin boundaries or drainage divides restrict interactions between adjacent basins by restricting movements of materials and energy between them (Lotspeich 1980, Swanson et al., 1988).

Patterns of landform development are easier to detect than many ecosystem processes (such as nutrient cycling). A knowledge of drainage basin form and process may allow us to recognize ecosystems more easily and to predict the results of ecosystem processes more accurately (Bailey 1985, Swanson and others 1988).

Animal Relations

"Animal behavior seeks to minimize energy expenditure for maintenance and maximize energy available for production." (Geist 1978). Wildlife populations adhere to this principle, in part, through habitat selection. Terrain influences wildlife in part through habitat structure. For many wildlife species seasonal habitat use correlated with topographic elements (Shields and Grubb 1974, Dickinson 1976, Oosenburg and Theberg 1980, Gionfrido and Krausman 1986).

Landforms and the geomorphic processes acting on a landscape help shape habitat structure through effects on vegetation, soil, and climate. Landform attributes such as elevation, slope, and aspect influence vegetation and soil structure through effects on air and ground temperatures, site moisture, and nutrient availability (Whittaker 1956, Hack and Goodlett 1960, Swanson 1979, Swanson and others 1988). Landforms affect flows of matter and energy across a landscape (animal and vegetation dispersal, water, dissolved nutrients, solar radiation, etc.) (Pielou 1979, Rowe 1980, Swanson and others 1988). Plant and animal community development and distribution, particularly in mountainous regions and along streams, can be explained and predicted in part by geomorphic processes and landform structure (Swanson 1979, Flather and Hoekstra 1985). Landscape may be a factor in the ecological separation of species, acting as a barrier to migration or dispersal or as a corridor through an area (Cox and Moore 1980, Bailey 1984). Landforms also affect the distribution of non-geomorphic disturbances like fire, windthrow, and grazing (Cook 1966, Ryan 1983, Swanson 1979).

Geomorphology influences wildlife management beyond population and habitat effects. Topography influences the detection of some wildlife species (Rodgers 1981, Canfield et al. 1986). This is important in estimating relative abundances and distribution of species, and as it affects hunter success. Terrain may affect hunter success indirectly, by inhibiting hunter access (Thomas et al. 1976). Topography is an important consideration in road and trail placement, thus indirectly shaping use of an area by hunters.

Computer-Based Analysis

The computer may have improved wildlife and natural resource management and research. It is a precise quantitative tool capable of storing, manipulating, and displaying large data bases. Its utility has been demonstrated in population and habitat analyses, ecological, physiological, nutritional studies, and in simulation and trend projection (Giles 1978).

Computer-generated analyses are useful in wildlife management for education, resource inventory, planning, law enforcement, research, and decision making (Fales 1969, Ritter 1975). The computer is especially valuable when planning or decision making requires a large data base or rapid simulation of the consequences of decisions. The computer can be used to filter and condense information, to eliminate the irrelevent and highlight the important (Ritter 1975). It is useful in esthetics or the realm of subjective decision as well. Qualitative values can be approximated with quantitative values (Travis et al. 1975). One can weight qualitative values and measure progress made toward the objectives, and then suggest more effective actions (Ritter 1975, Giles 1978). This process encourages more optimal decisions than those based on small samples or on more subjective values.

Geographic and natural resource information systems carry the utility of the computer a step further by geographically referencing and displaying data and analyses. These systems organize and display quantitative information that may aid informed management (Russell et al. 1975, Howard and Mitchell 1985).

This project uses many of these abilities of the computer to make land surface characteristics and patterns more available to the modern resource manager.

Integration of Knowledge

It is inefficient to manage a variety of habitats with only one approach (Bailey 1984). Wildlife management has borrowed principles, tools, and techniques from other disciplines. Physical sciences, including hydrology, computer science, statistics, and physics as well as biological sciences like physiology, biochemistry, and forestry have made significant contributions to wildlife management. Climatological precepts have been examined for use in wildlife management (Lawrence 1976, Anderson 1981, Francis 1980, Bailey 1984:239-253, Wajda, in progress).

For these reasons, the tools and concepts of geomorphology should be reviewed, to determine their utility in natural resource management. A better understanding of geomorphological processes and features may prove useful to the natural resource manager.

Literature Review

Geomorphology in the Ridge and Valley Province

The Processes

Systems theory has contributed to the view of landforms as balanced systems in which process and form are related. This system seems to aim at maintaining a stable form, so that landscape development is a system operation, and not the product or output of a system (Ritter 1978).

The three main geomorphic processes shaping landforms in the Ridge and Valley Province of Virginia are erosion by running water, chemical weathering, and physical weathering. The first two processes are most important in this region (Ritter 1978). The last is locally important.

Physical Weathering

Lands shaped by these processes typically have smooth soil-covered slopes, alternating ridge and valley systems, and often extensive stream deposits (Ritter 1978). In southwest Virginia, ridge and valley development reflects differential erosion of folded sedimentary beds. Clay, shales, and limestone form the lowest parts of basins and valleys. More resistant material like sandstones and conglomerates form the ridges. Valleys in this area are typically 'V' shaped, indicating that the landscape is of fluvial origin (Ritter 1978, Howard and Mitchell 1985, Forman and Godron 1986).

Physical weathering is the collapse of parent material when stress is exerted along planes of weakness. These stresses are greatest at the surface where overburden pressures are the least (Ritter 1978). Physical weathering includes a variety of erosional processes. It is a dominant process in areas of high precipitation and annual temperatures at or below freezing (Ritter 1978).

The processes involved in physical weathering include thermal expansion, hydration or swelling, frost action, and mass wasting (Way 1973, Ritter 1978). In this area, mass wasting is most important. Mass wasting is the movement of earth materials by gravity alone (Hewlett 1982). It occurs when the shear strength of a material cannot support a load increase (Way 1973). Mass wasting depends on loading rates, temperature, pressure, pore fluids, size and shape of formations, and the relative resistance of rock and soil to movement (Way 1973, Ritter 1978, Hewlett 1982). Types of mass wasting are differentiated by the time it takes for them to occur. These processes range from slow processes like soil creep, to more rapid processes like slump and solifluction, to very rapid processes like earth flows and landslides (Tuttle 1970, Way 1973, Hewlett 1982).

Mass wasting moves material downslope where it may be transported by streams. Creep and solifluction transport large amounts of material downslope over long periods of time. They are responsible for much of the sculpting of landforms in this area (Leet et al. 1978, Howard and Mitchell 1985).

Chemical Weathering

Chemical weathering is driven primarily by precipitation and warm temperatures. Rain water is usually slightly acidic, so this weathering process is often one of neutralization. Minerals assimilate H^+ ions from rain water and release cations to the soil liquid (Way 1973, Ritter 1978). Chemical weathering processes include oxidation, carbonation, solution, and hydrolysis (Pearson 1968, Ritter 1978).

Oxidation occurs primarily at the surface of the earth and is usually the first decomposition process to affect rock (Way 1973, Ritter 1978).

Hydrolysis involves the reaction between a salt and water to form an acid and a base. This is the most significant chemical mechanism operating on minerals and rocks with silica cementing agents, including some sandstones (Way 1973, Ritter 1978). Metallic cations in the rock matrix are replaced with H^+ ions.

Solution and carbonation may be the most important types of chemical weathering in the Ridge and Valley province. Water or carbonic acid (water + carbon dioxide) dissolve many minerals. The mineral structure or matrix may become unstable and collapse. This effect is important in the formation of karst topography. It is an important part of valley formation in this region (Pearson 1968, Way 1973, Ritter 1978).

Running Water and Physical Interactions

Water erodes by lifting, bouncing, rolling, or carrying particles in a suspension downslope (Pearson 1968, Leet et al. 1978). Water is a most effective erosion agent in areas subject to heavy precipitation or with steep slopes. Erosion by water occurs in three stages: splash (raindrop impact), wash (overland flow), and fluvial action (Ritter 1978).

The effectiveness of splash as an erosional force depends on a raindrop's mass and kinetic energy, the type of substrate struck, and the local slope. Raindrops may displace considerable amounts of soil and move larger particles by undermining them (Ritter 1978). Splash is quite effective on steep permeable soils. Raindrop impact may weaken soil structure, break apart clays, and make the land surface more susceptible to overland flow (Garner 1974).

Wash is a shallow, sheet-like flow of water over the surface of the land. It occurs where micro relief is low, runoff is abundant, and the eroding force of water exceeds the substrate's resistance (Horton 1945, Garner 1974, Ritter 1978). Because of surface irregularities, this overland flow may become channelized or shift back and forth across a slope so that erosion is even. As the velocity of this concentrated flow increases, particles are picked up and rills are formed (Horton 1945, Way 1973, Garner 1974).

At that point, overland flow becomes fluvial erosion. Fluvial erosion refers to rills, gullies, rivers, and streams (Ritter 1978). The divides between rills may breakdown. New rills form at angles to the initial rill. A slope is created oriented toward the initial rill. This process is known as crossgrading (Horton 1945, Tuttle 1970). Crossgrading continues and a drainage network develops with rilled surfaces forming on each side of the main rill. Lateral slopes develop and secondary rills form when the eroding force exceeds substrate resistance. Stronger rills absorb weaker rills (Horton 1945, Garner 1974). This process description applies to the development of rill, gully, or stream networks. The differences are primarily of scale and the relative permanence of the features that develop. Angular bends in rills, gullies, and streams develop because of crossgrading, differential erosion of the channel substrate, and the lateral thrust of the current on the outside of curves (Garner 1974).

The drainage network develops within a watershed or drainage basin. Drainage basins are usually ovoid or pear shaped, growing in width and length over time (Horton 1945). Two adjacent basins may be separated by a ridge or "belt of no erosion" that divides the water flow into two separate basins (Horton 1945). Basin streams may continue to erode headward (toward their source or the watershed divide). Theoretically, the basin may become so subdivided that in no portion of it will erosive forces exceed substrate resistance. A steady state is reached (Horton 1945). Way (1973) suggested that fluvial processes lower a landscape until the drainage system reaches an equilibrium.

Streams and other fluvial agents erode by hydraulic action, abrasion, solution, vortex action (in eddies), and cavitation (Tuttle 1970). Eroded materials (sediments) are transported by traction, saltation, suspension, and solution (Tuttle 1970, Leet et al. 1978). All or part of this load may be deposited when stream velocity decreases, stream volume declines, or additional material is added to the flow (Pearson 1968).

Valley and stream development occur together. A valley cannot grade below its stream. Valley development provides sediment and runoff which affect both the stream and valley profiles (Horton 1945).

The type, length, and angle of slope that develops depends on the resistance of the soil and underlying rock to erosion (Ritter 1978). Most slopes do not have a uniform gradient from basin divide to stream. A ridge or interfluve is a zone of little or no erosion. The upper slope is somewhat convex in shape, due in part to mass wasting. The lower slope is generally concave, often because of overland flow or wash (Horton 1945, Ritter 1978).

There are three proposed mechanisms of slope evolution. One contends that steep slopes decline or become more gentle with time (the upper slope erodes more quickly than the lower). The result is the upper convex slope. The second mechanism suggests that the steepest angle on a slope is repeatedly replaced by a more gentle angle developing near the slope base. The resulting profile is concave. The last hypothesis states that some slopes evolve by parallel retreat. As a slope retreats headward, its original angle is maintained on the steepest slope segments (Young 1972).

Mass wasting processes interact with fluvial processes to shape the local landscape. Creep, slump, and slides move soil and rock debris downslope, where it may be carried further by water. Deposits of this gravity transported material or colluvium are prevalent and make up the base slopes of many mountains in this area, e.g., Fort Lewis Mt., north of Salem, Virginia (Amato 1968, Garner 1974).

Controlling Factors

Factors controlling the intensity of geomorphic processes at work in the Ridge and Valley Province in southwest Virginia include lithology, climate, and vegetation.

Lithology

Lithology affects slope stability and helps determine landform shape, the rate and the extent of weathering. Geologic structure is partly responsible for the characteristic appearance of each physiographic province (Lotspeich 1980). Geologic structure and the climatic processes are the primary controls of drainage basin shape (Lotspeich 1980). Lithologic factors that shape a landform include rock type, degree of weathering, bedding attitude (dip, strike, and angle of bedding planes), and the degree of jointing and faulting (Swanston 1981).

The Ridge and Valley Province in Virginia is a region about 40-130 km (25-80 miles) wide and 335 km (200 miles) long, consisting of a series of narrow ridges and valleys between the Blue Ridge to the east and the Appalachian Plateau to the west (Smith and Linnartz, 1980). These ridges and valleys reflect the geologically slow horizontal compression of surface layers of sediment. This compression generally caused bending and buckling rather than faulting (Pearson 1968, Smith and Linnartz 1980). The parent material shows signs of low temperature deformation, not metamorphosis (Garner 1974). Ridges in this region are harder and more resistant to erosion than the valley material (Forman and Godron 1986). Few streams cut across the ridges in this region. Rectilinear or trellis drainage patterns predominate, controlled by rock structure and bedding sequence (Way 1973, Smith and Linnartz 1980).

The dominant soils of the ridges and upper slopes are derived from sandstones and shales. Most of these soils are thin, excessively drained, sterile or of low fertility, and acidic (Way 1973, Smith and Linnartz 1980). Lower slope soils are thicker than upper slope soils, reflecting the parent material and colluvium from upper slopes (Garner 1974). Valley soils generally develop from limestone, siltstone, shale, or an interbedded complex of all three. These soils are generally thicker, more fertile, less acidic, and better drained than upper-slope soils (Way 1973, Smith and Linnartz 1980).

The cementing agent generally determines sedimentary rock resistance to erosion (Way 1973). Ridges in this area are often composed of a quartzose sandstone (silica is the cementing agent) that is extremely resistant to erosion, resulting in steep massive slopes (Barlow 1936, Amato 1968, Way 1973, Amato 1974). Downslope from the ridges, rocks range from more friable sandstones and shales to dolomitic limestones, and interbedded associations of siltstones, shales, and limestones that weather easily (Barlow 1936, Amato 1968, Way 1973, Amato 1974).

Climate

Interactions between landforms and other environmental factors confound the analysis of topographic effects on a community or ecosystem. Landscape influences climate and vegetation locally and regionally. Vegetation and climate influence landscape features as well (Forman and Godron 1986). A landform reflects current forces and past ones such as geology and paleoclimates, confounding any analysis (Tuttle 1970, Ritter 1978, Howard and Mitchell 1985). Hybrid sciences like topoclimatology, climatic geomorphology, and phytogeomorphology examine the interactions among climate, vegetation, and geomorphology (Lee 1978, Verstappen 1983, Howard and Mitchell 1985).

Climate may be the key factor in landform development, exerting a strong influence on both the biotic and abiotic properties of a landscape (Rowe 1980). Climate controls the types and rates of geomorphic agents at work (Tuttle 1970, Ritter 1978, Forman and Godron 1986). Landforms of similar geologic structure and composition develop different features under different climatic regimes (Way 1973, Ritter 1978, Lotspeich 1980). Landforms in humid temperate climates have more subdued features than those in arid climates (Ritter 1978). The type and distribution of precipitation affect the erosional agents at work and will determine whether the major process is aeolian, glacial, nival, or fluvial (Tuttle 1970, Ritter 1978).

High precipitation, high humidity, and warm temperatures together with locally steep slopes and thin soils favor erosion by running water, chemical weathering, and slow mass wasting (Ritter 1978, Bailey 1984). Annual precipitation of fifty cm (20 inches) increases mass movement potential by increasing pore water pressure and loading (Burroughs 1985). Short term dramatic changes in the landscape are minimized under these conditions (Forman and Godron 1986).

Vegetation

Vegetation moderates local climatic effects on geomorphic processes. It reduces temperature extremes and increases local humidity. It reduces the rate and amount of erosion by stabilizing soils, covering soils, intercepting rainfall, increasing infiltration rates, and reducing wind strength (Horton 1945, Smith and Wischmeier 1962, Mitchell 1973, Ritter 1978, Swanson 1979, Hewlett 1982, Thomas 1985, Forman and Godron 1986).

Vegetation reduces splash, wash, and mass movements of soil (Thornes 1979, Hewlett 1982, Knighton 1984). Vegetation increases surface roughness and reduces overland flow, and the velocity of running water. By detaining and concentrating water, flow patterns are changed (Embleton et al. 1979, Thornes 1979). Plants reduce local soil moisture through transpiration, encouraging infiltration over runoff, and affecting rates of creep and slump (Swanson 1979, Thornes 1979). These effects and the ability of roots to hold soil, improve slope stability and increase soil porosity (Wischmeier and Smith 1965, Thomas 1985).

Humic acids leached from leaf litter may promote chemical weathering processes in this region (Brunsden 1979).

Landform Effects on Climate

Landforms affect temperature, precipitation, solar insolation, and windflow components of local and regional climates (Olgyay 1973, Swanson et al. 1988). Mountains may interfere with air mass circulation, affecting the amount and distribution of precipitation (Mitchell 1973, Olgyay 1973, Lee 1978, Cox and Moore 1980). Mountains obstruct and channel windflow as well (Mitchell 1973, Olgyay 1973 Swanson et al. 1988). Differential patterns of solar insolation affect windfield circulation (Ryan 1983, Mitchell 1973, Olgyay 1973, Lawrence 1976).

Elevational effects on temperature are well recognized (Young 1972, Olgyay 1973, Lawrence 1976, Lee 1978, Cox and Moore 1980). Over a large range of elevation, altitudinal zonation of ecotypes, similar to latitudinal zonation, can occur (Forman and Godron 1986).

Temperature

Temperature usually decreases 0.6°C for every 100 m increase in elevation (Olgyay 1973, Cox and Moore 1980). This elevation-temperature relationship varies with slope, aspect, and exposure to wind (Swanson et al. 1988). Eastern slopes reach maximum temperatures earliest in the day. South and western slopes attain greater daily temperatures than eastern or northern slopes (Mitchell 1973, Lee 1978). At night, cold air drainage develops on slopes and a warm slope zone forms between the ridgetop and valley bottom (Lee 1978). Minimum temperatures are recorded in depressions, where the cold air collects (Lee 1978). Lowest nightly temperatures are found in broad valleys. In narrow valleys, a proportionately greater volume of air-to-surface area has been exposed to solar warming, and does not cool as much as air in broad valleys (Mitchell 1973).

Precipitation

Spatial distribution of precipitation is influenced by large- and small-scale topographic features. Cloud and rainfall movements are similar to general air movements. Maximum levels of rainfall and cloud cover in valley bottoms are found at night and during winter. Maximum levels along slopes occur by day and during the summer (Mitchell 1973).

As air masses ascend mountain slopes (often because of convection) temperature drops, moisture condenses, and precipitation often occurs. Greater amounts of precipitation tend to fall on windward slopes, while drier adiabatic winds sweep the lee slopes (Mitchell 1973). This rain shadow effect is most apparent in the Rockies, but is important in the Appalachian mountains (Howard and Mitchell 1985). Around small hills or along ridgetops, the situation may be reversed. Wind speed increases as air is forced over ridges and precipitation is deflected leeward where the air diverges and windspeed decreases (Lee 1978).

Solar Radiation

Solar radiation intensity in an area varies with elevation, slope, and aspect (Sellers 1965, Swanson et al. 1988). Elevation affects the amount of solar radiation that reaches a surface, and the spectral range of that radiation. Increased altitude means lower air pressure and a shorter light path through the atmosphere. The effect is greater insolation, particularly in the ultra-violet range at higher elevations (Lawrence 1976). Some have suggested that insolation increases with elevation by as much as 1% per 100 m (Lawrence 1976).

Maximum insolation is on any surface that is normal (perpendicular) to the sun's rays (Mitchell 1973, Howard and Mitchell, 1985). In the northern hemisphere, these normal surfaces are southern slopes. This maximum insolation occurs when the slope inclination equals its latitude, and that slope is oriented toward the sun (Howard and Mitchell 1985).

Solar day length, the period each day that a surface receives direct sunlight, varies considerably with slope, aspect, and season (Mitchell 1973, Lee 1978). Landforms cast shadows, altering solar day length within those shadows. Radiation loads are reduced within the topographic shadow, creating an energy sink at the surface of the earth. Solar insolation intensities affect evapo-transpiration rates, and moisture regimes (Hack and Goodlett 1960, Brown 1973, Breimer at al. 1986). This influences vegetation composition and animal activities in an area (Lee 1978). Differential insolation and heating affect windflow as well (Howard and Mitchell 1985).

Windflow

Slope, aspect, and land use modify wind circulation by diverting or obstructing surface winds and by assisting the creation of local slope and valley winds (Ryan 1983, Lee 1978). Slope winds are caused by differential heating of air along slopes. A temperature gradient develops and air flows parallel to the slope surface (Ryan 1983). Slope winds generally blow upslope by day and downslope by night (Mitchell 1973). Valley winds develop because of temperature gradients between valleys and plains (or larger valleys). Differential heating due to topography results in upvalley air flow by day, downvalley winds at night (Ryan 1983).

Landform Effects on Vegetation

Terrain structure affects vegetational patterns directly and through climatic interactions. It influences the geographic separation of vegetation species (Hack and Goodlett 1960). Variations in slope, aspect, and elevation affect the potential vegetation of a site through modifications in local climate and soil-moisture relations (Carvell and Tryon 1961, Spurr 1952, Olgyay 1973, Lee 1978, Swanson 1979, Howard and Mitchell 1985). Forest stand composition tends to differ systematically with slope, aspect, and elevation because of differences in moisture, radiant energy, soil thickness, and air temperature (Lee 1978, Pielou 1979). Using topographic attributes alone, Fies (1983) reported a 59 to 76% classification accuracy at delineating forest stand types in the Appalachians.

Slope

Slope shape, position, and angle affect species composition and the growth rate of vegetation (site quality) through effects on moisture availability, soil formation, deposition, and mass wasting (Auten 1945, Spurr 1952, Whittaker 1956, Brown 1973, Fies 1983, Breimer et al. 1986). Concave slopes concentrate surface and subsurface waters (and dissolved nutrients) much more than convex slopes (McNab 1985). Uppermost slopes and ridges are generally drier sites than lower slope positions. These sites are less sheltered and often subject to the drying effects of wind. Upper slopes generally have reduced water storage capacity compared to positions downslope because of coarser and thinner soils (Auten 1945, Spurr 1952). Thus, lower slope positions are often more favorable for many tree species than upper slopes (Weitzman and Trimble 1957, Munn and Vimmerstedt 1980, McNab 1985).

Aspect

Aspect also affects site-specific growth rates and species composition of vegetation through soil-moisture relations. South- or west-facing slopes generally have greater solar radiation loads than northern or eastern slopes. These loads are correlated with reduced net photosynthetic rates, greater evapo-transpiration rates, and increased air and soil temperatures, (Auten 1945, Brown 1973, Kessell 1979, Lee 1978, McNab 1985, Breimer et al. 1986). These conditions support those tree species best adapted to dry and exposed positions (Auten 1945, Spurr 1952, Lee 1978). Conversely, northern and eastern slopes favor more mesophytic tree species (Spurr 1952).

Small changes in aspect and soil temperature are equivalent to large changes in latitude (Lawrence 1976). The moisture gradient that Whittaker (1956) used to partition forest cover types of the Great Smoky Mountains incorporated aspect. Munn and Vimmerstedt (1980) considered aspect the most important factor for predicting forest site quality.

Elevation

Elevation affects vegetation growth and species composition through effects on temperature and moisture regimes. An increase in elevation often means lower temperatures, shorter growing season, and more precipitation (including snow) (Kessell 1979, Breimer et al. 1986). In West Virginia, the variation in phenological season is four days for each change of 1° in latitude or 122m (400 ft.) in elevation (Wang 1984). In the Great Smoky Mountains of Tennessee and North Carolina, tree species diversity declined with increasing elevation (Whittaker 1956).

Phenologies

Forest phenologies are affected by aspect and elevation (Bailey 1984). The phenological effects of elevation are primarily temperature effects. Generally, trees on southern slopes leaf out first (Olgyay 1973). In the spring, the same solar intensities found on southern slopes are found on level ground a few weeks later, resulting in a delayed spring on the flat ground (Lee 1978). Upper slopes green first, followed by greening on lower slopes, then on ridges and in coves (Lee 1978). Cove trees lose their leaves first. Concave slopes tend to have poor cold air drainage. These slopes often have higher maximum and lower minimum temperatures and shorter frost free seasons than convex slopes (Spurr 1952).

Geographic distribution of species

Several authors suggested that geomorphic processes, through effects on soil development, slope stability, and wind channeling, may cause a site to develop a topographic or topoedaphic climax instead of the regional vegetational climax (Swanson 1979, Bailey 1984, Swanson et al. 1988). Geomorphology may have the most profound impact on vegetation through its action on soil properties (Swanson et al. 1988). Soil texture (the pattern, distribution, and size of soil particles) affects soil-water relations, including infiltration and runoff, that are critical to vegetation (Hack and Goodlett 1960, Lotspeich 1980, Imeson 1985).

In the Ridge and Valley province of Virginia, the geographic distribution of 20 of the 35 most common tree species were related to slope form (slope angle, aspect, and shape). Tree species assemblages changed abruptly with changes in slope form. Pitch pine (*Pinus rigida*)-table mountain pine (*Pinus pungens*)-chestnut oak (*Quercus prinus*) assemblages were found on ridge crests and convex slopes. Northern hardwoods were found in hollows and on concave slopes, while oaks dominated straight (valley-side) slopes (Hack and Goodlett, 1960).

Distributional patterns of woody vegetation species in bottomland forests of the Ridge and Valley Province of Virginia were related to fluvial landforms and streamflow characteristics (Hupp and Osterkamp 1985). Woody species varied in their susceptibility to destruction by flooding. Flood frequency, flood duration, and inundation period, were closely related to vegetation patterns observed on fluvial landforms (Hupp and Osterkamp 1985).

Fundamental Terrain Characteristics

The basic factors used to characterize terrain can be derived from two measures, elevation (one or more points) and horizontal distance (between two or more points) (Evans

1972, Young 1972). Any series of points on a land surface can be described in terms of elevation, slope, gradient, aspect, and profile and plan form (cross slope convexity) (Young 1972, Evans 1981). Another attribute of surface form, distance, is included in linear, areal, and texture measures (Evans 1972, Gardner 1972).

Slope is determined from the elevation of two points. Slope is characterized by gradient, the inclination of a plane to the horizon (Hays et al. 1981). Consider slope the rate of change of elevation.

Slope may be the most important element of surface form. Slope angles control or modify gravitational forces and affect the cost of doing work (Evans 1972, Verstappen 1983). It is the major landform factor affecting transportation, agriculture,and urban development.

Aspect is the compass direction that the true or maximum slope faces (Evans 1972, Young 1972, Hays et al. 1981). Aspect is the first horizontal derivative of elevation and gradient is the first vertical derivative (Evans 1981).

In the Ridge and Valley province of Virginia, Hack and Goodlett (1960) noted that on average, slopes were steepest on northeast and southeast aspects. They believed this was because of differences in moisture and exposure.

Land surface shape can be described in terms of profile and plan form (convexity) (Young 1972). Together, profile and plan form are known as local convexity, the rate of change of slope (Evans 1972, Evans 1981).

Profile form (also known as profile curvature, profile convexity, or downslope convexity) is the two dimensional shape of a surface along a vertical plane. Profile form is the second vertical derivative of elevation (Evans 1972). It is the change of angle along the true slope (Evans 1972, Young 1972, Evans 1981). By convention, convex slopes have positive curvature, and concave slopes have negative curvature.

Plan form is the shape of a surface along a horizontal plane. It is the second horizontal derivative of elevation (Evans 1972). A spur end slope is an example of a plan convex form. A valley end slope is an example of a plane concave form (Young 1972). Hack and Goodlett (1960) partitioned first order stream valleys into noses, side slopes, and hollows. A nose is the ridge crest and those slopes near the crest that have a convex shape. Side slopes are slopes with little or no curvature. Hollows are concave slopes.

Relief, the range in elevation over a given area, describes the vertical extent of a landscape without reference to slope (Evans 1972, Gardner 1972). Local relief (the maximum difference in elevation) is the most commonly used relief measure (Gardner 1972).

Texture or "grain size", measures the horizontal spacing between maxima, minima, or other features of interest (Evans 1972, Gardner 1972). Texture measures the size of units forming a given landscape (Gardner 1972).

Terrain Classification

Parametric and landscape systems of terrain classification are complementary systems. The landscape system is more easily recognized in the field and easily extrapolated into unknown areas. It unites data into a collective geomorphic base, and encourages treatment of an entire region (Mitchell 1973).

The parametric system is more quantitative. It allows statistical treatment of data, and detailed analyses of small areas (Mitchell 1973). For these reasons, I shall focus on parametric systems of terrain classification.

Parametric terrain classification systems rely on geometric analysis of surface form, with little emphasis on rock type or origin (Howard and Mitchell 1985). Attributes that are recognizable in the field and relevant to land use, are preferred. These attributes are divided into class values. The interval size varies with the purpose of the classification (e.g., forestry or engineering). Parameters include slope or elevation classes, aspect intervals, stream order, drainage densities, etc. (Mitchell 1973, Grender 1976, Howard and Mitchell 1985). Lithology and the mode and sequence of landform development are important, but for many purposes including characterization of terrain for environmental studies, morphometric (parametric) classifications are adequate.

Landform Characterization

Slope

Slope classification schemes vary with the purpose for which they were developed. There are four basic schemes:

- Those based on slope origin (grouped according to causal factor or agency responsible such as climate, vegetation, or rock type).
- Those based on the presence or absence of factors (slope with free face, slope without slope overburden, etc.).
- Those based on surface shape (ridge, knob, valley, saddle, etc.) (Grender 1976).
- Morphometric schemes are primarily quantitative classifications (Young 1972).

Morphometric slope classification schemes appear most applicable over a range of habitats or terrains. Class intervals are used to examine slope angle and orientation (aspect). The intervals used vary with the intended application. Generally, slope ranges are designated level, gentle, moderate, and steep (Hanson 1962, Young 1972, Lee et al. 1976). Feature names may be assigned to slope intervals e.g., $<2^0=$ "flat" or $>40^0=$ "cliff" (Young 1972). Problems with slope class intervals include the possible loss of detail and defining class limits objectively (Gardner 1972). Aspect or slope orientation intervals based on some pre-specified compass sector may be used to group slopes or slope classes (Gardner 1972, Runde and Anderson 1986).

Landform shape

Young (1972) used profile curvature classes based on the degree of slope per unit length. These classes ranged from markedly convex to markedly concave. McNab (1985) carried this system one step further, classifying landform shapes by profile and plan curvature. He used two phrases such as linear-concave to specify profile and plan curvature respectively.

Young (1972) and Mitchell (1973) described a form of profile analysis that united slope and profile classification systems. This analysis divided a profile or landform into several slope units with specific properties. The basic units were segments (profile portions with constant slope angles) and elements (profile portions with constant curvature). A ridge or valley could be described in terms of slope and profile with this system.

Grender (1976) developed a computerized system that expressed profile characteristics. His system grouped elevational points into categories of similar topographic shape and analyzed landscapes based on the frequency distributions of those shapes.

Stream Characterization

Stream characterization by biologists is typically based on stream size, velocity, gradient, substrate, biological zonation, and water quality (Jones 1978, Platts et al. 1983). Geomorphology or morphometry cannot provide all of those variables. However, many geomorphic measures such as channel gradient, stream order, and sinuosity have been used for gross assessments of aquatic ecosystem condition (Platts et al. 1983).

Length

Channel length and related measures (main stream length, mesh length, etc.) have been used to estimate streamflow. Channel length can be used to characterize a stream system and is easily measured (U.S.G.S. 1977, Wetzel and Bettandorf 1986).

Gradient

Gradient or slope steepness affects stream velocity and peak discharge rates. Stream velocity increases with the stream gradient (Tuttle 1970). Specifically, stream velocity varies with the square root of slope inclination (Lee et al. 1976). A stream's erosive energy is proportional to its gradient. Peak discharge increases with slope steepness (Lee et al. 1976).

Relief

Relief suggests the potential energy of a stream system. Channel length and sinuosity modify that potential energy.

Sinuosity

Sinuosity expresses the curvature or meandering of a stream. It may be calculated as stream length divided by the straight line length from stream source to stream outlet (see Schumm 1963).

Order

Stream order is a dimensionless method of ranking streams. Many different methods have been developed for ordering streams (see Gardiner 1981). These systems assume that the assigned order is proportional to the size of the contributing watersheds, channel dimensions, and discharge (Strahler 1964, Gardiner 1981). Different sized streams or watersheds can be compared by order (Strahler 1964).

Horton's (1945) procedure, as modified by Strahler (1957), is probably the most commonly used stream ordering system. Headwater streams are first order streams. The stream segment just below the confluence of two or more first-order streams is a second-order stream. The stream segment just below the confluence of two or more second-order streams is a third-order stream, etc. This ordering system is not additive because low-order channels flowing into a higher order channel do not affect the designated order. There are difficulties in designating first-order streams. There is no provision for seasonal or ephemeral channels (Gardiner 1981).

A variable such as stream order allows comparisons between known and unknown areas. It allows some understanding of a resource with limited information (Platts 1979).

Jones (1978) explored the relationship between water quality parameters and stream order in Missouri. Conductivity, pH, and water temperature tended to increase with stream order. Turbidity and CO_3 (carbonate) levels varied inversely with stream order.

Basin Characteristics

Watershed or drainage basin characteristics often are derived from maps or aerial photographs (U.S.G.S. 1977). Drainage basin description requires measurement of linear, areal, and relief aspects of the basin (Strahler 1964). All three parameters influence water and sediment yield (U.S.G.S. 1977). Specific measures of these parameters are discussed in the "Results" section.

Slope

Slope steepness and surface roughness affect water retention in a watershed (Verstappen 1983). Slope shape affects the distribution of surface and subsurface waters. Convex slopes disperse water, favoring infiltration, while concave slopes concentrate water flows, favoring runoff (Verstappen 1983, Sidle 1985, Wilson 1984). Slope length and angle influence runoff and stream flow velocity (Halasi-Kun 1974, Vuglinski and Semenov 1974).

Area

Drainage basin area is the total area contributing overland flow to a channel segment of a specified order. This includes all lower-order tributaries and all additional surfaces not drained by these tributaries (interbasin areas). Basin area is an index to the capacity of a watershed to collect and store water (Halasi-Kun 1974, Voskresenski 1974). Main channel order increases in proportion to the log of the area it drains (Horton 1945).

Pattern and shape

Drainage pattern, drainage texture, and basin shape are used to compare watersheds (Morisawa 1958, Way 1973). Drainage patterns depend on the slope and the resistance of underlying rocks to erosion (Pearson 1968). In the Ridge and Valley Province, a trellis pattern dominates, and low order basins tend to be elongated (Hack and Goodlett 1960, Amato 1974). In this pattern, water flows over alternating elongated zones of hard and soft rocks (Pearson

1968). Main channel tributaries are parallel to each other and meet the main stem at right angles. This drainage pattern suggests tilted or interbedded sedimentary rocks with the main channel following the strike of the bed (Way 1973). The bifurcation ratio (number of stream segments of a given order/number of segments of the next higher order) suggests the extent of dissection (Strahler 1964, Jones 1978). High values are found where geology distorts the drainage pattern (Strahler 1964).

The size and shape of drainage basins affect stream discharge regimes. Elongated basins have longer time lags between precipitation and peak flow, and extended flood discharge periods than do more circular basins (Strahler 1964, Verstappen 1983). Flood discharge from a circular basin is sharply peaked (Strahler 1964).

Texture

Drainage texture is often characterized as fine, medium, or coarse. Texture indicates the average size of the units making up the local terrain (Gardner 1972). Drainage density stream length/unit area) is one measure of drainage texture (Tuttle 1970, Way 1973). A low drainage density suggests coarse texture. Poorly drained basins have low values (due primarily to resistant rock), while well-drained basins (those with easily eroded soils) have high values (Jones 1978). Drainage density is also an expression of the closeness of channel spacing (Strahler 1964).

Relief and Ruggedness

Relief suggests the intensity of slope erosion in a basin (Strahler 1964). Drainage relief is the difference in elevation between a stream and a ridge or interfluve in a drainage basin (Tuttle 1970). The measure "ruggedness" combines slope steepness, length, and texture (Strahler 1964, Gardner 1972).

Summary

There are many ways to characterize terrain features and their relations with other abiotic and biotic environmental factors. Different techniques for describing terrain features were developed to meet various objectives and needs. The "Results" section of this thesis covers in greater detail the measures I selected for characterizing terrain features.

Part of the purpose of this project was to analyze expressions of terrain features, to isolate their common elements, and to select those elements that may meet some of the current needs of wildlife managers. All managerial needs cannot be met. As land systems are better understood, new needs will arise, and new descriptors will need to be developed.

Geomorphology in Environmental Sciences

In many applications of geomorphology to other sciences, it is the form of the landscape and not its origin or development that is considered (Young 1972). In the life sciences, studies often focus on one level of organization or on one time scale, assuming that lower frequency processes are so slow that they can be considered fixed. Some of the most dramatic interactions between geomorphic processes and ecosystems (disturbance and succession) are often on a scale of decades or centuries (Swanson et al. 1988).

Topography is a major consideration in land use. Slope, elevation, and aspect influence the distribution of soils, natural and induced vegetation, and surface and groundwater resources (Howard and Mitchell 1985). Slope influences the type and extent of mechanized activities. Lands within certain slope ranges may be considered suitable for agriculture. Lands within that range or with greater slopes may be suitable for forestry. Very steep slopes are usually considered useful only for water catchment, recreation, and wildlife management (Howard and Mitchell 1985). Landforms reflect the origin and history of an area, providing information on soil type characteristics and distribution, mechanics of slope failure, drainage, and climate (Swanston 1981).

Forestry

Terrain is an important factor in forestry, as was seen in the section titled "Landform Effects on Vegetation". It has a decided effect on forest site productivity, community structure, phenologies, and harvest strategies.

Site Index

Forest site productivity is best measured by site index, the average height of dominant and codominant trees of a particular species at a reference age (Avery and Burkhardt 1983). Much of the variation in site productivity can be explained by terrain features. The terrain features that seem to affect forest site quality (site index) the most are surface shape, slope position, and aspect. Regression equations have been developed for predicting site index from aspect, slope position, percent slope, and soil depth (Weitzman and Trimble 1957). In areas subject to mid-summer water stress, concave slopes tend to have higher site indices (Spurr 1952, McNab 1985). In at least one study, site index declined with an increase in the percent slope (Weitzman and Trimble 1957). Northern and eastern facing slopes had higher site indices for oaks than south and western facing sites (Weitzman and Trimble 1957). Sites with more northerly aspects in the Ridge and Valley Province of Virginia may be more favorable to regeneration and production of commercial hardwood species (Carvell and Tryon 1961, Fies 1983). This may be due to soil-moisture relations, with more favorable (more mesic) conditions occurring on gentle or more northerly slopes.

Harvest

Terrain is a major consideration in harvest schemes. Slope angle largely determines the feasibility of harvesting a stand, and affects the equipment and harvest scheme used (Giles 1982). Slope angle also affects the expenses of reaching and working harvest and regeneration sites, e.g., road construction costs and siting routes (Thomas 1985).

Hydrology

There is a close relationship between geomorphology and hydrology. Morphometric variables have been used to estimate runoff, flood discharge levels, sediment yields, and other hydrologic characteristics. Geomorphic analyses of drainage basins have been used to approximate stream discharge and other hydrologic parameters when insufficient data were available (Strahler 1964, Welch 1978, Platts 1979, Verstappen 1983). Methods have been developed that rely on geomorphic or topologic properties of drainage basins (because of their influence on local water resources) to estimate unit hydrographs, thus reducing hydrologic data requirements (Dubreuil 1974, Karlinger et al. 1987).

Terrain features are especially useful for calculating peak discharge and for identifying areas subject to flood damage and areas of high sediment production (Mark 1983, Verstappen 1983). Land surface shape and the relative size of watersheds are quite important in these analyses.

Mean basin elevation is an important parameter because of the effect it has on precipitation and evapotranspiration within a drainage basin (Voskresenski 1974, Vuglinski and Semenov 1974). Mean runoff for ungauged mountain streams have been estimated using relations between runoff and altitude from locally gauged streams (Voskresenski 1974).

Soils

"Geomorphology provides the framework on which climate, acting through vegetation, forms the soil" (Howard and Mitchell 1985:43).

The parent material, climate, and local topography affect the rate and type of soil development and its fertility (Pearson 1968, Way 1973, Navarra 1979, Forman and Godron 1986). Nutrient availability (carbon, nitrogen, and phosphorus) generally increases downslope, in part due to increases in soil water concentrations (Schimel and others 1985). Sharp or narrow ridges have greater soil turnover rates and shallower soils than areas of gentle topography (Swanson 1979). After fire or other disturbances when nutrients are freed from the biomass on a site, nutrient and soil loss from a site is enhanced by steep slopes and thin soils (Bailey 1984).

Slope length and slope angle affect the depth, texture, profile, and erosion of soil (Wischmeier and Smith 1965, Pearson 1968, Swanston and Dyrness 1973, Way 1973, Verstappen 1983). In the Ridge and Valley province, as slope length and drainage area increase, the coarseness of ground debris increases. There is a larger area contributing water to wash or sheetflow and a greater potential volume in that surface flow, consequently larger particles may be moved. Short, steep slopes were correlated with fine textured soils. Soil particle size increased as one proceeded downslope into the hollows (Hack and Goodlett 1960).

Landforms evolve in part through the displacement of soil, or through chemical and biological processes operating within the soil (Imeson 1985).

Resource Classification

Natural resource classification and inventory systems have been developed for many different purposes. Most incorporate geomorphic elements on at least one level. Geomorphic elements may express factors of ecologic importance (i.e., proximity to water) and may reflect management considerations (i.e., hazard or erosion potential) (Bastedo et al. 1984). Division of large land areas by natural areal units such watersheds, drainage systems, landtype associations, or physiographic province encourage a hierarchical classification system (Gardner 1972, Bailey et al. 1978). A division of areas by landscape, particularly in rugged terrain, may be easily recognized in the field or on a map, and at a gross level, more immediately significant than divisions based primarily on soil or vegetation type (Mitchell 1973, Welch 1978, Smalley 1984, Howard and Mitchell 1985).

The use of terrain features in these classifications relies on identification of recurring patterns, an important element in classification systems (Welch 1978). The watershed or drainage basin is one naturally occurring feature that has been proposed as a basic unit for resource classification and management systems. This unit has two advantages as a classification and management feature: it is recognizable in the field, and environmental factors such as precipitation or insolation interact as a unit at that scale (Giles 1977, Lotspeich 1980, Rowe 1980).

Engineering

Terrain is an important consideration in engineering. Landscape features of primary importance are slope, aspect, relative relief, drainage patterns, and soil and slope stability (Mitchell 1973, Way 1973, Verstappen 1983, Sidle 1985, Burroughs 1985, Thomas 1985). These features influence development costs, choice of sites or routes for development, and determine the feasibility and extent of development.

Fisheries

Significant correlations have been found between geomorphic measures like basin size, and fish habitat and populations. Fish and aquatic invertebrate population size and species diversity were significantly correlated with variables like elevation, channel gradient, and stream order (Platts 1979, Minshall et al. 1985). Biological productivity of streams appears related to watershed characteristics that control drainage patterns, stream flow regimes, and channel gradients (Parsons et al. 1981, Fausch et al. 1988).

Geomorphic variables have been used in models of natural habitat quality (a component of a model used to assess fish habitat suitability) and in models predicting standing crops of fish. In a regression model developed to predict a fish habitat index (an estimate of natural habitat quality), the 4 most significant parameters were basin perimeter, basin relief, basin area, and a compactness coefficient (Parsons et al. 1981). The model based on these 4 map-derived variables had an R^2 of 0.60 ($n = 38$ undisturbed streams in Siuslaw National Forest). The resulting model might have been different had it used variables that were not correlated with one another (basin perimeter and basin area are highly correlated, see Gardiner 1975 and Ebisemiju 1979).

Fausch and others (1988) reviewed nearly 100 models predicting fish standing crop from habitat variables. Two of the reviewed models were based exclusively on geomorphic variables measured from maps. The variables used included basin area, mean basin length, mean basin slope, total stream length, and mean basin elevation. One of the resulting models accounted for 66% of the observed variance in standing crop of cutthroat trout (*Salmo clarki*). Three other models relied on variables from geomorphology and channel morphometry. The geomorphic variables used included basin perimeter, channel gradient, mean elevation, drainage density, relief ratio, mean basin length, and mean basin slope. One of these models (trout in rangeland streams) demonstrated a high degree of generality and had an R^2 of 0.64.

Wildlife

Distribution

Structural and microclimatic components of the environment affect habitat selection by individual species and thus, distribution patterns of these species. The configuration and height of landforms affect the distribution of animals primarily through the interspersion of habitats (McKeever 1954, Swanson 1979, Swanson et al. 1988). The immediate effects are on environmental gradients such as temperature, moisture, and solar insolation. Changes in altitude, exposure, and slope affect a site's microclimate, and influence the potential and realized vegetation at that site. It is the interaction between climate, physiography, and soils, not physiography alone, that is responsible for local differences in flora and fauna composition (McKeever 1954, Swanson 1979, Swanson et al. 1988).

The distribution and abundance of five species of mice (genus *Peromyscus*) at a New Mexico site varied with elevation, aspect, and vegetation composition (Wilson 1968). Species richness and abundance of bats declined with increasing elevation in Peru (Graham 1983). These differences in richness, distribution, and abundance might be explained by changes in temperature, foliage height diversity, and vegetation composition (Graham 1983). Landform structure is a factor in all three explanations. Secondarily, landforms act as corridors (i.e., drainage networks) for, or as barriers (i.e., ridges) to the dispersal of terrestrial vertebrates (Swanson 1979, Forman and Godron 1981, Swanson et al. 1988).

Topography is a major factor affecting the distribution of desert bighorn sheep (*Ovis canadensis*) (Leslie and Douglas 1979). Washes and low country act as geographic barriers to the distribution of this species. Elevation and the shape of landforms were significant factors in explaining the distribution of elk (*Cervus canadensis*) in both summer and winter (Wood 1943, Holroyd 1979). Kessell (1979) reported that gradients of elevation and slope steepness were important factors for explaining the distribution of moose (*Alces alces*), mountain goats (*Oreamnos americanus*), and mule deer (*Odocoileus hemionus*) in Glacier National Park.

In the Atlantic provinces of Canada, topography exerted a strong or moderate influence on habitat selection by diverse species such as moles, arctic hare (*Lepus arcticus*), beaver (*Castor canadensis*), caribou (*Rangifer tarandus*), and white-tailed deer (*Odocoileus virginianus*) (Prescott 1979). Slope and aspect had moderate effects on habitat selection by moose, beaver, and white-tailed deer.

Small mammal species richness and abundance in hardwood forests of the southeastern U.S. increased with elevation (Gentry et al. 1968). Richness and abundance of small mammals declined in oldfield succession sites with an increase in elevation.

The current distribution of many mammals in the Ridge and Valley Province of Virginia reflects previous changes in climate and associated vegetation. Topography plays a role in the disjunct distributions of some of these animals. Examples include the distributions of many insectivores, rodents, and lagomorphs. Distributions of species such as the smokey shrew (*Sorex fumeus fumeus*), water shrew (*Sorex palustris punctulatus*), big-tailed-shrew (*Sorex dispar dispar*), rock vole (*Microtus chrotorrhinus*), snowshoe hare (*Lepus americanus virginianus*), and New England cottontail (*Sylvilagus transitionalis*) are related to the distribution of vegetation types that are currently restricted to higher elevations and northerly aspects (Handley and Patton 1947, McKeever 1954, Handley 1979, Hoar 1980, Healey and Brooks 1988). Many of these species are boreal relicts, species that have retreated upslope and northward with the advance of the Holocene (Woodward and Ruska 1986). Some of these species may be found where elevation and topography favor cooler and more moist habitats (i.e., north facing slopes or mountain tops). In Virginia, the northern flying squirrel (*Glaucomys sabrinus*) and the wood frog (*Rana sylvatica*) are limited to high elevations (Conant 1975, Cox and Moore 1980, Wells-Gosling 1985). In this region, the northern flying squirrel is restricted to northern coniferous or northern hardwood forests (Hoar 1980, Wells-Gosling 1985). Forest stands in Virginia suitable for this species are not normally found below 1200 m (3900 ft.), so its distribution is patchy (Hoar 1980, Wells-Gosling 1985).

Byrd (1979) identified 4 bird species of special concern that were most likely to breed in the Ridge and Valley Province of Virginia. The threatened Bewick's wren (*Thryomanes bewickii*) breeds primarily in clearings and brushy habitats at higher elevations. The black-billed cuckoo (*Coccyzus erythropthalmus*) nests in high altitude hardwoods and forest edges. Both the yellow-bellied sapsucker (*Sphyrapicus varius*) and the alder flycatcher (*Empidonax traillii*) breed above 1065 meters (3500 feet) in Virginia (Byrd 1979).

The greatest variety of salamanders in Virginia are found in the highlands of the Ridge and Valley and Blue Ridge Provinces (Tobey 1979). Four species are limited to mountain tops in Shenandoah National Park or the spruce-fir zone of Mt. Rogers-Whitetop (Tobey 1979). Nine species are most abundant in the Ridge and Valley Province (Conant 1975). Most of these species are found at higher elevations, in cool, shady ravines, or in mountain streams (Conant 1975, Tobey 1979). One species, the Cow Knob salamander (*Plethodon punctatus*) is only found along 2 ridges on the Virginia-West Virginia border, between 732 and 1317 m (Dodd 1979, Buhlmann et al. in press). Two important factors for predicting the presence of this species were elevation and aspect (Buhlmann et al. in press).

Topography also plays a role in the distribution of species that are not restricted to the Appalachian uplands. Gaudette and Stauffer (1988) reported that slope was an important factor in several models of winter habitat use by white-tailed deer. The importance of slope may reflect the selection of higher quality habitats (higher site indices) by deer. Wood (1943) reported that altitude, exposure, and relief influenced the distribution of elk in southwest Virginia.

Movements

Many species of birds and large mammals migrate between seasonal ranges. In the North American west, many mammals show distinct seasonal movements. Seasonal movements of mammals like elk, bighorn sheep, and wolverine (*Gulo luscus*) vary in elevation, slope, and aspect. Deer (*Odocoileus* spp.), bighorn sheep, moose (*Alces alces*), and mountain lions (*Felis concolor*), often winter in lowlands or valleys and use higher elevations as summer ranges (Shannon et al. 1975, Logan and Irwin 1985). Seasonal use of certain slope and elevational ranges may be due to abiotic or biotic factors associated with those ranges. Shannon and others (1975) hypothesized that seasonal movements of bighorn sheep were related to the distribution and availability of highly digestible forages. Whitman and others (1986) suggested that seasonal movements of wolverines were related to prey distribution and abundance.

The Carolina junco (*Junco hyemalis carolinensis*), in the Smoky Mountains, migrates from high elevation breeding grounds to lower elevation wintering grounds (Rabenold and Rabenold 1985). Caribou move to higher elevations as summer progresses, yet stay on the most gentle slopes as they migrate (Oosenbrug and Theberge 1980). In Virginia, introduced elk herds were found at altitudes of 700-1220 m (2300-4000 ft) throughout the year (Wood 1943). Their seasonal movements reflected stable temperature regimes. In summer, they were found primarily on northern slopes and higher elevations. In winter, they were found most often on south-facing slopes and at lower elevations.

The cruising ability of an animal is partly determined by the limits of its physical abilities and by the difficulty traversing terrain (Bailey 1984). Terrain can be a barrier to animal movements (Cox and Moore 1980). Probably because of geomorphic changes in geologically recent times, moles (family *Talpidae*) are no longer found in the geographic center of their range in North America, the Rocky Mountains (Pielou 1979).

Energetics

Much of the use of topography for cover and movements by wildlife species may be considered energy budgeting. A species may select habitats with specific topographic attributes as part of an energy conservation strategy. Many species orient themselves spatially to take advantage of favorable energy fluxes, to minimize convective heat losses, or to reduce the amount of energy required for travel (Wood 1943, Clapperton 1961, Rayburn 1972, Moen 1973, Geist and Petocz 1977, Geist, 1978, Moen 1978, Strong and Vriend 1979, Bailey 1984, Weiss et al. 1988).

In Wyoming, prairie falcon (*Falco mexicanus*) eyries are oriented primarily toward the south (Runde and Anderson 1986). Energy conservation is favored because convective updrafts are more likely to develop below south-facing cliffs and increased insolation at this orientation may moderate cold temperatures during incubation. During high winter winds, caribou bedded in irregular terrain (Henshaw 1968). This behavior could reduce convective heat loss. Despite food preferences, six wintering passerine species in the forests of New Jersey and West Virginia were found primarily on south-facing slopes (Shields and Grubb 1974). Checkerspot butterfly (*Euphydryas editha*) larvae orient their bodies topographically (slope and aspect) to raise their body temperature above the ambient temperature, reducing maintenance energy requirements and maximizing weight gains (Weiss et al. 1988). In each of these instances, animals may be using topography to maintain favorable energy balances (Moen 1973, Lawrence 1976).

During winters with deep snow, white-tailed deer in the Adirondacks were more commonly found on steep south- and southwest-facing slopes, than in valley bottoms (Dickinson 1976). These areas had less snow cover than bottomlands because of steep slopes, aspect, and prevailing winds. Similar behavior was observed in elk and bighorn sheep (Shannon et al. 1975, Strong and Vriend 1979). Moen (1973) attributed this behavior to greater energy fluxes on south facing slopes, reduced snow depth due to wind action and insolation, and an increase in available food because of reduced snow depths. It is energy expensive for these animals to move in deep snow (Rayburn 1972, Moen 1978).

In northern Canada, in early winter, moose may orient themselves above the timberline during sunny days (Geist 1978). For every kcal of heat gained from sunlight, 0.33 kcal of fat is saved from oxidation (Geist 1978).

Game trails generally converge in saddles or on slopes and diverge on flatlands. The cost of climbing is responsible for the convergence of these trails (Geist 1978). Domestic sheep require 11 times more energy to climb than to walk on level terrain (Clapperton 1961). Game trail convergence in areas that require greater energy expenditures to traverse is understandable, trails tend to follow the easiest route over steep terrain. Elk in Virginia selected the easiest travel routes (gaps, passes, along ridges or streams) (Wood 1943). The energetic cost of climbing also explains Geist's (1978) observation that the trail systems used by mountain goats tend to run along hill contours instead of perpendicular to the contours.

Phenologies and physiology

Many small animals exhibit differences in life-history phenologies, particularly breeding, along elevational gradients. Long term response to temperature differences may play an important role in explaining differences in phenology. In England, spawning of the common frog (*Rana temporaria*) is delayed 6 days for every 100 m increase in elevation (Beattie 1985). Millar and Innes (1985) reported that deer mice (*Peromyscus maniculatus*) had longest breeding seasons at low elevations. Perhaps as a compensatory mechanism, post-partum estrus was significantly more common for high elevation populations. Conaway and others (1974) reported that the litter size of eastern cottontail rabbits (*Sylvilagus floridanus*) decreased with increasing elevation. As elevation increased, the onset of reproduction in cottontails was delayed.

Populations of the long-toed salamander (*Ambystoma macrodactylum*) breed later in the season with increased elevation (Howard and Wallace 1985). These salamanders have longer breeding seasons at lower elevations. Female salamanders lay fewer but significantly larger eggs at high elevations. Hatchlings from these eggs are larger as well. Salamanders from the high elevation populations metamorphosed 2 to 3 summers later than those at low elevations.

Golden-mantled ground squirrels (*Spermophilus lateralis*) have successively later emergence times and shorter above-ground activity seasons as elevation increases (Bronson 1980). Females from high elevations breed at a later age and have greater survivorship rates than their low elevation counterparts. Females from high elevation populations have lower ovulation rates and reduced embryonic mortality rates when compared to low elevation populations (Bronson 1980).

Montane environments are generally subject to lower temperatures and lower barometric pressures than sea level environments. Keys and others (1986) found hematocrit levels in resident brown-headed cowbirds (*Molothrus ater*) increased with elevation. The implication is that residents of a given species at higher elevations must increase their ability to provide tissues with an adequate supply of oxygen, compared to individuals of the same species at lower elevations.

Compass orientation (aspect) of a site can affect small animal phenologies as well. Pupation in the checkerspot butterfly was as much as 1 month later on north-facing slopes than on south-facing slopes (Weiss et al. 1988). This phenological difference appears to be primarily because of lower daily temperatures on north-facing slopes.

Cover

Topography provides thermal, reproductive, and escape cover for many wildlife species. Terrain may provide cover from wind, storms, insects, and flooding, and provide secure areas for reproduction (Henshaw 1968, Oosenbrug and Theberge 1980, Bailey 1984, Williams 1985, Runde and Anderson 1986).

Caves, talus slopes, and cliffs are edaphic habitats that were developed by geomorphic processes. These are important roosting and reproductive sites for bats, mice, woodrats, bobcats (*Lynx rufus*), and raptors (Maser et al. 1979). In the Ridge and Valley Province of Virginia, Hooper et al. (1975) reported that ravens (*Corvus corax*) preferred cliffs for nesting. In a study to estimate population variation of pikas (*Ochotona princeps*) due to habitat factors, the perimeter of talus slopes accounted for 81% of the variation in population (Bunnell and Johnson 1974).

Bighorn sheep rely on steep, rugged terrain, and avoid gentle slopes (Krausman and Leopold 1986). The utilization of elevation, slope, and topographic position by bighorn sheep is related to visibility, available forage, and proximity to escape cover (Gionfriddo and Krausman 1986). These sheep concentrate their activities within 50 m of escape terrain. Escape terrain for these animals is steep, rocky terrain along upper slopes and ridges, where they can outmanuever predators (Leslie and Douglas 1979, Gionfriddo and Krausman 1986). Elk in shrub-steppe habitat used topographic cover such as gullies and ravines for security and travel cover (McQuordale et al. 1986).

In the mountains of Arizona, bighorn sheep prefer northerly aspects, apparently for summer shade, foraging, and bedding (Gionfriddo and Krausman, 1986). Eighty-five percent of summer habitat use by these sheep is at the base of large, north-facing cliffs, where a cool, moist microclimate prevails (Gionfriddo and Krausman 1986).

Proximity to streams and stream size are habitat considerations for some wildlife species. Prescott (1979) noted the importance of proximity to water for many wildlife species including shrews, moles, beaver, muskrats, and raccoons. Conner (1973) reported that in the Ridge and Valley Province of Virginia, pileated woodpeckers (*Dryocopus pileatus*) selected forested areas within 60 m of running water for nesting and roosting cavities. In Quebec, beaver (*Castor canadensis*) select primarily second- through fifth- order streams with low gradients (slope of $\leq 1.5^0$) to build their dams (Naiman et al. 1986).

Topography or microtopography of drumming sites is important for some populations of ruffed grouse (*Bonasa umbellus*). In the Driftless Area of Wisconsin, and in Alberta, drumming logs are generally oriented along slope contours, and seldom on slopes exceeding 25^0 (Boag and Sumanik, 1969, Rodgers 1981). In some localities, suitable drumming sites may limit populations rather than food or other cover types (Rodgers 1981).

In West Virginia, wild turkey (*Meleagris gallopavo*) broods preferred forest openings, white oak (*Quercus alba*) cover types, slopes less than 30^0, and north-facing slopes (Pack et al. 1980). Many of these preferences may be related. Gentle slopes and northerly aspects suggest a greater likelihood of broods locating permanent water (gentle slopes are usually along valley floors, and soil evaporation is lower along northerly exposures). The apparent preference for white oaks may have been because white oaks were more abundant in gentle terrain. The preference of northerly aspects may suggest more abundant herbaceous vegetation (Pack et al. 1980).

Food Habits

Terrain is a factor in foraging habitat selection by many wildlife species. Bobcats in Maine avoided the steep portions of their home range (Litvaitis et al. 1986). Energetics may be part of the explanation for habitat use, or bobcats may avoid these areas because of low prey densities.

In summer, caribou forage on hydric vegetation like sedges (*Carex* spp.) that are found at upper elevations and on gentle slopes (Oosenbrug and Theberge 1980). In winter, caribou feed on ridges and flats that are snow free or where snow cover is thinner than in bottomlands (Henshaw 1968).

The mountain lion prefers steep terrain for stalking and feeding (Logan and Irwin 1985). Rugged topography may convey an advantage to lions in stalking and capturing its prey.

The ecological separation of three ungulate species in North America is related to forage preferences and elevation. Mule deer and elk use habitats similar in slope, aspect, and elevation, but differing in preferred forages. Elk and bighorn sheep have similar forage preferences, but use different terrains as foraging habitats (Bailey 1984). Bright (1984) found that slope and aspect were important factors in assessing elk habitat, particularly winter foraging habitat. Elk selected feeding sites, low elevations in winter, where the ratio of food intake to energy expenditure was optimal.

Wildlife as Geomorphic Agents

Wildlife influence the geomorphic processes working on a landscape. The geomorphic effects of animals on a landscape include increased erosion, homogenization of soils, altered rates of infiltration, sediment entrapment, and sediment production (Van Zon 1981).

Grazing by domestic and feral livestock, and ungulates may remove forest litter and expose mineral soil to erosive forces (Imeson 1976, Swanson et al. 1988). Burrowing by rodents, rabbits, crayfish, earthworms and other animals cause mixing and mineral transfer in the soil (Mielke 1977, Embleton and Thornes 1979). Their activities create passages in the soil through which water can move. This increases overburden weight and pore fluid pressure, contributing to mass movements of earth (Brunsden 1979). Earthworms are known to deposit at the surface as much as several tons of earth per hectare per year (Brunsden 1979). Burrowing animals are responsible for much of the exposed soil above river channels in humid temperate forests (Imeson 1976, Imeson and Kwaad 1976). One effect of burrowing is preparation of material for transport by overland flow (Thornes 1979). Burrowing animals influence slope development in northern climates (Price 1971, Abaturov 1972). In the semi-arid U.S., burrowing pocket gophers (*Geomyidae*) altered soil texture, mineral availability, and soil moisture, thus affecting plant growth in the immediate environment (Mielke 1977).

On a more visible scale, the beaver is a significant agent of geomorphic development. The dam-building habit of beavers alters basin hydrology, regulating surface flow of water, decreasing water velocity, increasing sediment deposition, and at times promoting riparian vegetation (Neff 1957, Naiman et al. 1986, DeBano and Heede 1987). Carbon and nutrients bound up in these sediments may affect the overall productivity of an aquatic ecosystem (Naiman et al. 1986). The effects of beaver activity, particularly alluvial deposits and vegetation patterns, may remain a part of the landscape for centuries (Neff 1957, Naiman et al. 1986).

Summary Comments: Literature Review

The preceding review outlines most of the ways in which the geomorphology of a wildlife management area may be characterized. This review also explores the interactions between terrain, climate, vegetation (forestry), and hydrology. There are two types of terrain effects on wildlife: direct and indirect. Direct effects of terrain on wildlife include but are not limited to: the energetic costs of activity (moving across terrain); acting as a barrier to dispersal; and providing thermal (i.e., wind), stalking (i.e., visual), and feeding cover. The indirect effects are primarily on habitat as modified by the interactions of topography, climate, vegetation, and soils. Many of the most apparent examples of the influence of geomorphology come from areas of great relief. That influence may be less apparent in areas of less relief, but is there nonetheless.

Methods

Steps to Meet Project Objectives

The project objectives were met in three major steps:

1. I examined the role that terrain or land surface shape plays as a component of wildlife habitat, by reviewing the literature of wildlife biology and management. Terrain affects wildlife directly through its effects on species distribution, movements, energetics, and phenologies, cover, and the food habits of wildlife. The results have been presented in the Literature Review. The intended focus of that review was the Ridge and Valley Physiographic Province of Virginia, though some of the best examples of the effects of terrain on wildlife pertain to areas outside the region.
2. I combed literature in geology, geography, geomorphology, hydrology, and other natural resource fields for descriptors of land surface shape. I grouped these descriptors into functional sets of elevation, slope, relief, linear, areal, and textural measures, and measures that focus on patterns between and within drainage basins. These

pattern-based measures were subdivided into groups focusing on drainage network topology, drainage network extent, and drainage basin shape.

3. There were 3 stages in developing a terrain descriptor system aimed at the natural resource professional: design, implementation, and demonstration. The general system was designed early in the project, but was modified considerably during implementation, i.e., the actual programming of a functional system. Demonstration refers to using the prototype system with a test data set, and does not imply extensive testing of the system.

The next section describes the development of this terrain descriptor system.

Descriptor Selection

From a review of the scientific literature of terrain analysis, I identified over 120 descriptors of land surface shape. This body of literature includes soil science, hydrology, geology, forestry, and geomorphology. There are several reasons for this profusion of variables. Some variables were designed as general purpose measures, others were developed for specific purposes. Some of these variables are dimensionless, others have dimensions of length, area, or volume (Gardiner 1975).

These terrain descriptors are expressions of what I consider to be the 7 major aspects of terrain : elevation, slope, relief, length, area, texture or roughness, and pattern. Elevation and slope are both point attributes (Table 1). Relief is an expression of the vertical scale of landforms, and does not refer to the horizontal plane (see Table 1). Relief is a measure of land surface amplitude (Mark 1975). It has been used as a surrogate for slope in many studies (Ebisemiju 1979, Gardiner 1982b), though slope expresses both vertical and horizontal scales. Length (linearity) and area are important characteristics of many surface features (Table 2). Texture or roughness descriptors combine 2 or more of the above measures. Texture and roughness are expressions of landform wavelength. (Table 3). Pattern includes both the shape of land features (e.g., individual drainage basins), and the spatial arrangement of those individual features in a region (Table 3).

Once these descriptors were identified, the next problem was deciding which descriptors should be incorporated into the prototype terrain description system. Cost was a limiting factor. It would require too much time or effort to program all of the identified descriptors into a system. Based on the literature review, some descriptors were better than others in describing a specific aspect of terrain. The immediate objective was to identify and select the best descriptors from each general category of terrain factors (such as relief descriptors) for inclusion in the system. Then, cost considerations could be imposed on the selection decision.

Initial Evaluation

Formula clarification was the first step in this process. Many descriptors had the same name, but different researchers used different formulas to calculate these descriptors. There are at least two formulas for calculating the elevation-relief ratio (Pike and Wilson 1971, Evans 1972). The denominator in each equation is the range in elevation, but the numerators differ. One equation uses the difference between the mean and the maximum elevation, the other uses the difference between the mean and minimum elevation. Elevational data are not usually normally distributed (Strahler 1952, Gardiner 1981), so these descriptors could give quite different results when used on the same data set. Other examples include the four different methods for determining basin land slope (U.S.G.S. 1977) and the two different constants-of-channel maintenance reported in the literature (Smith 1950, Leopold et al. 1964).

The second step in reducing the number of useful descriptors was to eliminate redundant descriptors, i.e., descriptors with different names, but the same formula. This was confusing and made selection of descriptors difficult. For instance, the maximum elevation of a drainage basin has also been called absolute altitude (Nir 1957). Channel gradient is identical to stream slope. One measure of drainage basin shape, circularity II is also called the compactness coefficient, and Patton's diversity index (U.S.G.S. 1977, Hays et al. 1981). The lemniscate index

Table 1. Elevation, slope, and relief-derived descriptors identified in this study

Elevation	
Mean Elevation	Minimum Elevation (Outlet Elevation)
Maximum Elevation (Absolute Altitude)	Mesh Source
Elevation Classes or Intervals	Elevation Frequency Distribution
Slope or Gradient	
Degrees	Percent
True (Maximum) Slope	Apparent Slope
Minimum Slope	Mean Slope
Slope Position	Slope Classes
Characteristic Angle	Limiting Angle
Upland Slope	Slope Frequency Distribution
Slope Tangent	Slope Sine
Stream Gradient	
Channel Gradient	Slope Ratio
Main Channel Slope	Basin Land Slope I - IV
Basin Slope	Mesh Slope
T-Factor	
Aspect	
Aspect	Slope Orientation Classes
Stream Azimuth	
Convexity	
Plan Convexity	Profile Convexity
Relief Descriptors	
Local Relief (Relative Altitude)	Average Relief
Available Relief (Total Relief)	Dissection Index
Elevation - Relief Ratio I - II	Mesh Relief
Cumulative Relief Frequency Curve	Stream Relief
Concavity Index	Basin Relief I - II
Average Total Relief	Total Relief Ratio
Main Channel Relief	
Mean, Standard Deviation of Elevation Frequency Distribution	

Table 2. Length, linear, and areal morphometric descriptors identified by this study

Profile Analysis	
Segment	Element
Slope Length	
Slope Length	
Stream Length	
Map Length	Corrected Stream Length
Cumulative Stream Length	Percent of Total Stream Length
Mean Stream Length	Stream - Length Ratio
Hydraulic Sinuosity	River Sinuosity
Basin Length	
Basin Length I - III	Channel Length/Basin Perimeter
Mesh Length	Total Channel Length
Basin Width	Basin Diameter
Basin Perimeter	Relative Perimeter
Mean Height of Water Divide	Mean Slope of Water Divide
Length of Overland Flow	Average Length of Overland Flow
Area	
Planimetric Drainage Area	Surface Drainage Area I - II
Area - Length Association	Drainage Area/Stream Order
Drainage Area Ratio	
Constant of Channel Maintenance I - II	

Table 3. Texture, roughness, and pattern morphometric indices identified by this study

Texture and Roughness-Based Descriptors	
Hypsometric Integral	Elevation - Relief Ratio I & II
Relief Ratio I - IV	Elevation/Area Ratio
Ruggedness Number	Relative Density
Ruggedness Ratio	Valley Spacing
Cell Length	Structural Similarity Factor
Roughness Index	Concavity Index
Total Terrain Roughness	Surface Roughness
Avoidance Factor	Surface-Planar Area
Spectral Analysis of Landforms	Fourier Analysis of Elevation
Depression Density	Mean Solution Depression Density
Composite Terrain Texture	Regional Convexity
Mean and Standard Deviation of a Gradient Distribution	
Standard Deviation of Profile and Plan Convexity Distributions	
Stream Order	
Strahler	Scheidigger
Shreve	Graf
Number of Streams/Area	Number of Streams/Order/Area
Bifurcation Ratio	Conservancy of a Drainage
Drainage Network Patterns	
Drainage Density	Density of Perennial Drainage
Density of Seasonal Drainage	Density of Temporary Drainage
Micro Link Density	Macro Link Density
Stream Frequency	Langbein Index
Channel Length/Basin Perimeter	Relative Density
Shape or Form	
Shape Factor	Form Factor I - II
Shape Index I - II	Basin Shape Index
Ogievsky	Zavoianu
Hexagonality	Triangularity
Elongation Ratio I - II	Delta
Compactness Coefficient I - II	Lemniscate Index or Ellipticity index
Lemniscate Ratio	Circularity Ratio
Circularity I - III	Dual Axis Fourier Analysis
Boyce and Clark	Symmetric Difference Metric
Compactness	

of Chorley et al. (1957) is identical to the ellipticity index of Stoddart (1965). I chose to combine each set of identical measures under one name (usually the simplest or first-reported name).

I eliminated all statistically derived terrain descriptors because they could be obtained with commercially available statistical software such as SAS. I excluded all descriptors based on properties of frequency distributions of terrain features, such as elevation, slope, or relief frequency distributions, though they may be effective descriptors of landforms (Strahler 1952, Hobson 1972).

Objective Weighting

To discriminate further between descriptors, I used a formal strategy for assessing each descriptor. I used an objective weighting procedure that was discussed in Churchman and Ackoff (1954) and refined in Giles (1978) to distinguish descriptors. This procedure generates performance or effectiveness scores for each possible action taken toward a set of objectives. With a slight reformulation, the procedure can be used to evaluate how well a term or descriptor meets a list of criteria (i.e., objectives).

My "objectives" were the criteria I would use for assessing each descriptor. I settled on 4 for evaluating each descriptor: literature-based justification for the descriptor, ease of measuring the descriptor, ease in computing the descriptor, and the minimum number of inputs necessary for using the descriptor.

Selection Criteria

The most important criterion I used in selecting the best terrain descriptors was the literature-based justification for these descriptors. Had authors other than the developer of a given descriptor either used or commented (positively or negatively) on its value? Is the descriptor currently used in any field? Descriptors that I did not find evaluated in the literature were given a low effectiveness rating. Each type of comment (not each comment) on a descriptor was worth 1 point, either positive or negative depending on the nature of the comment (i.e., the descriptor was useful in predicting the hydrologic response of a basin to a precipitation event, the descriptor was not useful in explaining species richness or diversity at a site, etc.). The values for each descriptor were summed, and the results for each class of descriptors were converted to a 10-point scale. Ten was the best score, and 0 meant either that the positive and negative points cancelled each other or that there were no comments found in the literature for a particular descriptor. This is not to say that the descriptors with scores of 0 are necessarily less useful than the higher scored variables. Rather, I did not find any examples of the application of these low-scoring descriptors other than by the originators of these measures. These descriptors have been compiled and are reported in Table 4. My review of terrain description literature was extensive, but I do not claim to have reviewed all of the literature on terrain description. I have examined and reported most of the simple measures and indices of land surface shape.

The next criterion was the ease of measuring a particular descriptor. Are the measurements or inputs needed for a formula easily obtained from raster or vector format data? Is it necessary to refer repeatedly to topographic maps or sampling grids to collect the necessary data? As an example, Table 4 lists 4 procedures for estimating basin land slope. One is the mean slope of a basin, and the necessary data is easily obtained from a raster data set. This variable would be assigned a high score. The other 3 descriptors require measuring contour intervals, counting the number of times a contour crosses the sampling grid, and measuring the total length of the grid lines. These 3 descriptors require more effort and were assigned lower scores.

The third criterion was the ease of calculating a variable. Some descriptors are easier to calculate than others. A simple algebraic relation is easier to calculate than an integration or differentiation. Strahler's (1952) hypsometric integral is more difficult (or more time consuming) to calculate than one of the elevation-relief ratios (Mark 1983).

The final assessment criterion was the number of inputs necessary to calculate a descriptor. Measures requiring the least number of inputs were assigned the highest scores. All scores were then transformed to a 10 point scale.

Table 4. Geomorphic and morphometric descriptors

Name	General Equation/Description	Inputs
A. Elevation Descriptors		
Mean	$\bar{E} = \frac{(\sum E_i)}{n}$	Elevation of 2 or more points
Minimum (Outlet)	$E_{min} \leq E_i$ E_{min} is measured at the outlet unless karst is present	Elevation of 2 or more points Elevation, outlet or karst
Maximum (Absolute Altitude) (Nir, 1957)	$E_{max} \geq E_i$ E_{max} is measured on the perimeter	Elevation of 2 or more points Elevation, perimeter
Elevation Classes or Intervals		
Elevation Frequency Distribution (Strahler, 1952)	$\overline{X}$ and σ, and skewness and kurtosis of the distribution	
Mesh Source (Mark, 1983)	The elevation on the divide for that point obtained by following the stream orientation to the divide	
Elevation Ratio	$\frac{E_{max}}{E_{min}}$	Maximum and minimum elevations
B. Slope Descriptors		
Slope The plane tangent to the surface at a given point and specified by gradient and aspect (Evans, 1981).		
Gradient The maximum rate of altitude change with horizontal displacement - a vertical derivative of elevation (Evans, 1981).		
Degrees	$\theta = \tan(\frac{\lvert E_i - E_{i-1} \rvert}{D})$	Elevation and horizontal distance between points
(Map)	$\theta° = arctan \frac{\theta}{100}$	"

Table 4. Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Percent	$\frac{\lvert E_i - E_{i-1} \rvert}{D} \times 100$	" "
(Map)	$\theta = \frac{\lvert E_i - E_{i-1} \rvert \times m \times c}{D}$	Elevation of points, map scale as decimal, conversion factor (c)
Slope Measures		
True (Maximum) (Strahler, 1950)	The slope along the maximum angle $\theta_{max} \geq \theta_n$	" "
Apparent	Any other slope angle less than the maximum	" "
Minimum Slope for an Area	$\theta_{min} \leq \theta_n$	" "
Mean (Strahler, 1950)	$\bar{\theta} = \frac{\sum \theta}{n}$	" "
Slope Position (Hinkle, 1978)	$\frac{\text{distance from point to ridge}}{\text{total slope length}} \times 100$	" "
Characteristic Angle (Young, 1961)	Most frequently occurring angle or angle interval with the maximum frequency	Slope/gradient
Limiting Angle (Young, 1961)	The range of slope angles within which a a given form (landform, animal etc.) occurs.	" "
Upland Slope (Dennis, 1967)	Mean slope starting a specified distance above a channel	"
Slope Frequency Distribution (Strahler, 1950)	$\bar{X}$, σ, skewness and kurtosis of the distribution	elevation, or slopes for an area

Table 4. Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Slope Tangent (Isotangent) (Strahler, 1956)	$\tan\theta = \frac{dy}{dx}$ the rate of slope change	slope angle, or horizontal and vertical distance components
Slope Sine (Isosine) (Strahler, 1956)	$F_s = \sin\theta$	" "
Stream Slope or Gradient		
Channel Gradient (Stream Slope)	$\frac{\lvert E_i - E_{i-1} \rvert}{L}$	Elevation of stream source and outlet, horizontal stream length
Slope Ratio (Horton, 1945)	$\frac{S_c}{S_g} = \frac{\text{channel gradient}}{\text{ground slope}}$	channel gradient, ground slope (or mean slope)
Main Channel Slope	$S_c = \frac{E_{.85} - E_{.10}}{L_{c.85\text{-}.10}}$ elevation diferences between points 10% and 85% of the distance between outlet and the basin divide divided by the channel length between those 2 points	Elevations and channel length
Basin Land Slope (National Handbook, 1977)		
I (Mean Basin Slope) (National Handbook, 1977)	$\overline{B}_B = \overline{\theta} = \frac{\sum\theta}{n}$ (for a basin)	Elevation
II (National Handbook, 1977)	$B_{B2} = 1.571\,\frac{HN}{L}$ H = Contour interval, N = # times contour crosses grid, L = total length of grid lines	

Table 4. Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Basin Land Slope		
III (National Handbook, 1977)	$B_{B3} = \frac{HL}{A}$ A = Basin Area	same as II and Basin Area
IV	$B_{B4} = \frac{\sum(a \times B_{B3})}{A}$	
(National Handbook, 1977)	a = the area bounded by 2 successive contours	
Basin Slope (Mark, 1983)	$\frac{\text{Basin Relief}}{\text{Basin Length}} = \frac{\overline{R}}{L_{B1}}$	Perimeter elevations, outlet elevation, distance
Slope Class Intervals		Slope
Mesh Slope (Mark, 1983)	$\frac{\text{Mesh Relief}}{\text{Mesh Length}}$	Mesh source and outlet elevations, distance
T-Factor (Potter, 1953)	$T = \frac{\text{Length of Main Stream}}{\sqrt{\text{Channel Slope}}}$	Main channel length, and channel slope
Aspect		
Aspect (Evans, 1972)	The direction of altitude change in the X,Y plane. The maximum slope at a point, measured azimuth from the north in degrees or in major compass directions	Slope of points north
Slope Orientation Classes (Dennis, 1967)	Class intervals covering 45 degrees	The 8 compass directions

Table 4. Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Stream Orientation		
Stream Azimuth (Strahler, 1958)	Primary direction of stream flow in compass direction or degrees azimuth (Azimuthal deviation of the stream segment vector from the basin axis)	Compass direction, stream orientation, axial length
Convexity	Rate of change of slope over distance	Slope, distance, aspect
Plan Convexity (Evans, 1972)	Rate of change of aspect along a contour	Distance, aspect (plan form or cross slope convexity)
Profile Convexity (Profile form or Profile curvature)	Rate of gradient change along the slope line for 3 downslope lengths: p, q, r	Slope, distance
(Young, 1972)	$C_q = 100 \times \frac{\theta_p - \theta_r}{.5D_p + D_q + .5D_r}\ °/100m$	
C. Relief Descriptors		
Local Relief (Relative Altitude, Relative Relief, Nir, 1957)	Maximum difference in elevation for a basin or region (a possible surrogate for mean slope) $E_{max} - E_{min}$	Elevations in a basin
Available Relief (Total Relief) (Coates, 1958)	Difference in elevation for an area from the highest point to the base level $E_{max} - E_{min}$	Elevation for an area or region
Dissection Index (Nir, 1957)	$\frac{\text{Local Relief}}{\text{Absolute Altitude}}$	
Cumulative Relief Frequency Curve	Relief of an area is described in terms of skewness and kurtosis of a cum. relief freq. dist.	Elevations of an area of an area

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Elevation Frequency Distribution (Hobson, 1972)	$\overline{X}$ and σ are used to indicate Relief	Elevation
Elevation - Relief Ratio		Elevations for an area, or the mean, minimum, and maximum elevations
I (Evans, 1972)	$ER_I = \frac{E_{max} - \overline{E}}{E_{max} - E_{min}}$	" "
II (Wood and Snell, 1960)	$ER_{II} = \frac{\overline{E} - E_{min}}{E_{max} - E_{min}}$	" "
Relief Ratio		
I (Schumm, 1956)	Expresses overall steepness of a drainage basin	Basin relief, distance along line relief is measured (axial length or basin length), channel slope
	$R_R = \frac{\text{Basin Relief}}{\text{Parallel Basin Length}}$	
	$R_R = \tan(\text{channel slope})$	
II (Maxwell, 1960)	$R_R = \frac{\text{Relief along Basin Length}}{\text{Parallel Basin Length}}$	Elevation, basin length
III (Relative Relief, Melton, 1957)	$R_r = \frac{\text{Basin Relief}}{\text{Basin Perimeter}}$	Basin relief, basin perimeter
IV (Schumm, 1954)	$R_r = \frac{\text{Basin Relief}}{\text{Basin Diameter}}$	Basin relief, basin diameter

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Ruggedness Ratio (Lewis Slope; Melton, 1965)	$R_G = \frac{H_{max}}{\sqrt{A}}$	Basin relief, basin area
Average Relief	$\overline{R} = \sum \frac{\mid E_i - E_{i-1} \mid}{n}$	Elevations for an area
Basin Relief		
I (Melton, 1957)	Same as Local Relief	Elevation for a basin
II (Schumm and Hadley, 1961)	Ave. Elevation of the Divide (Perimeter) - E_{min}	Elevations for a basin
Average Total Relief (Morisawa, 1962)	$\overline{R}_u = \overline{R}$	Elevations for a basin
Total Relief Ratio (Morisawa, 1962)	$R_t = \frac{\overline{R}_u}{\overline{R}_{u+1}}$	Average total relief, basin orders
Stream Relief		
Stream Relief	$R_s = E_{max} - E_{min}$	Elevation of stream segments at the link nodes
Mesh Relief	$R_m = E_{max} - E_{min}$	Elevation of stream segments at the divide and nodes
Main Channel Relief (Main Channel Fall)	Relief measured from the source to the outlet of the main channel	elevation, link nodes

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Concavity Index	$\frac{2 \times \text{Depression}}{R_s}$	Elevation along stream course or stream relief and depression
Elevation/Area Ratio	$\frac{\text{Available Relief}}{\text{Area}}$	Elevation or available relief of an area, and the area
D. Area-Based Descriptors		
Planimetric Drainage Area	Area of a basin derived from a map,photo,etc.	Boundary of a basin, map or photo scale
	$A_{map} = \text{Area} \times m \times c$	
	m = map scale, c = conversion factor (metric or english)	
Surface Drainage Area (Strahler, 1956)	Planar area corrected for mean slope	Area of map, mean slope or mean basin slope
	$A_{surface} = \frac{A_{planar}}{\cos \alpha}$ where α = mean slope	
Area - Length Association (Hack, 1957)	$L_c = 1.4A_c^{0.6}$	Basin area
Constant of Channel Maintenance	the area needed to maintain 1m of channel	
I (Texture Ratio) (Schumm, 1956)	$C = \frac{1}{D_d}$	Drainage density
II (Texture Ratio) (Smith, 1950)	$C = \frac{N}{P_b}$	Topographic map, basin perimeter
	N = number of contour crenulations in a basin from the contour with the most crenulations (measures the average size of units forming a given topography)	

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Drainage Area/Stream Order (Horton, 1945)	The area in a basin contributing overland flow to a channel segment of a given order	Order, stream length, mean stream length, drainage density, bifurcation ratio, basin area
	$S = 1 + \dfrac{\log[(1-p)D_d \times \frac{A}{L_u}]}{\log R_b}$	
	$p = \dfrac{r}{R_b} = \dfrac{\text{stream length ratio}}{\text{bifurcation ratio}}$	
Drainage Area Ratio (Schumm, 1956)	$R_A \simeq \dfrac{\bar{A}_u}{\bar{A}_{u-1}}$	Basin area, order
E. Length-based and Linear Morphometric Descriptors		
Profile Analysis - The division of a profile into segments and elements (Young, 1972).		
Segment	A portion of a profile with a constant angle (rectilinear). It may be classified as maximum, minimum, crest, or basal.	
Element	A portion of a profile with a constant curvature It may be classified as convex or concave.	
Slope Length	$C = \sqrt{(E_i - E_{i-1})^2 + D^2}$	
Stream Length		
Map Length	L_{map}	Measured from topos, aerial photos, DEMs etc.
Corrected Stream Length	$L_c = \dfrac{L_{map}}{\cos \alpha}$ α = stream slope	Stream length, stream slope

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Cumulative Stream Length (Total Stream Length) (Zavoianu, 1985)	$\sum L_n$	Stream lengths for an area
Percent of Total Stream Length	$\% = \frac{L_i}{\sum L_n}$	Total stream and segment lengths
Mean Stream Length	$\bar{L} = \sum \frac{L_i}{n}$ for a given order	Stream lengths by order
Stream - Length Ratio (Horton, 1945)	Mean stream length of order n compared to mean stream length of order n-1 $r = \frac{\bar{L}_n}{\bar{L}_{n-1}}$	" "
Hydraulic Sinuosity (Schumm, 1963)	L_c/L_B or (channel length/basin length)	Channel length, basin length
River Sinuosity (Topographic Sinuosity in the Mountains) (Schumm, 1963)	$\frac{\text{Channel length between 2 pts.}}{\text{Straight line length between 2 pts.}}$	Channel length, map length
Basin Length		
Basin Length I (National Handbook, 1977)	L_{B1} = straight distance from E_{max} to outlet	Maximum elevation, basin outlet
II (Zavoianu, 1985)	L_{B2} is the distance from the outlet to the most distant point on the divide	Basin perimeter, basin outlet
III	L_{B3} =a line from the outlet to a point on the divide that divides the basin into equal areas	Basin perimeter, outlet, basin area

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Total Channel Length (Gardiner, 1981)	The surface distance from the maximum elevation to the outlet, parallel to the basin length	Basin length,mean slope, outlet
Mesh Length (Mark, 1983)	A straight line from outlet to source on the divide following the general stream orientation.	Outlet, source, divide
Basin Width (National Handbook, 1977)	Average width of the basin $W_B = \frac{\text{Basin Area}}{\text{Basin Length}}$	Basin Area, basin Length
Basin Diameter (National Handbook, 1977)	D_B = the diameter of the smallest circle that encompasses the basin	Basin perimeter or outline the basin center
Basin Perimeter (National Handbook, 1977)	P_b = the curve that defines the surface divide of the drainage basin	Derived from topos,aerial photos, DEMs, etc.
Relative Perimeter (Gardiner, 1981)	$\frac{P_b^2}{\text{Basin Area}}$	Basin perimeter, basin area
Mean Height of Water Divide (Zavoianu, 1985)	$\overline{H} = \frac{1}{2} \times (\text{mean peak height} + \text{mean saddle height})$	Basin perimeter, peaks and saddles
Mean Slope of Water Divide (Zavoianu, 1985)	$I_p = 2 \times \frac{\text{Maximum Height of Divide}}{P_b}$	Basin perimeter, maximum elevation on the perimeter
Length of Overland Flow (Horton, 1945)	$L_o = \frac{1}{2 \times D_d} = \frac{1}{2} \times \frac{A}{\sum L_n}$	Basin area, total length of streams
Average Length of Overland Flow (Horton, 1945)	$\overline{L}_o = \frac{1}{2 \times D_d \sqrt{1 - (\frac{S_c}{\overline{B}})^2}}$ S_c = mean channel slope	Mean basin slope, mean channel slope, total stream lengths, basin area

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
F. Texture and Roughness-Based Descriptors		
Total Terrain Roughness (Zakrzewska, 1963)	Number of crossings of 100′ contours by the circumference of a 3 mile circle	Topographic map, area
Surface Roughness (Stone and Dugundi, 1965)	Integrate Average Relief, Mean Slope, the Average number of changes in elevation for a given distance, and the periodicity of changes (wavelength, or the distance traveled to encounter normal variations)	Elevation, slope, distance
Avoidance Factor (Stone and Dugundi, 1965)	Expresses the difficulty in crossing terrain $P \times \bar{R}$ or Slope Range × Mean Relief	Elevation, slope
Surface-Planar Area (Hobson, 1972)	$\frac{A_{surface}}{A_{Planar}}$	Surface and planar areas or planar area and mean slope
Mean and Standard Deviation of a Gradient Distribution (Evans, 1981)		
Standard Deviation of Profile and Plan Convexity Distributions (Evans, 1981)		
Hypsometric Integral (Strahler, 1952)	Derived from the cumulative frequency of Elevation plotted against Area	Elevation and area
Elevation-Relief II (Wood and Snell, 1960)	$ER_{II} = \frac{\bar{E} - E_{min}}{E_{max} - E_{min}}$	" "
Valley Spacing (Evans, 1972)	$1/D_d$ (same as Texture Ratio)	Drainage density, or total area and cumulative stream length of an area
Cell Length (Stone & Dugundi, 1963)	$C_L = L(1 - \frac{1}{2}\sqrt{\frac{\sum a_n^2}{\sum n^2 a_n^2}})$	Length of traverse, areas

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Structural Similarity Factor (Stone and Dugundi, 1963)	$K = (\sum a_n^4/(\sum a_n^2)^2)$	Areas
Ruggedness Number (Melton, 1957)	R_N = Total Relief of an area × D_d (combines slope steepness and slope length)	Total relief, drainage density, or elevations of a basin, basin area, and total stream lengths
Spectral Analysis of Landforms (Evans, 1972)		Elevation
Fourier Analysis of Elevation (Evans, 1972)		Elevation
Depression Density (Gardner, 1972)	Number of depressions/ unit area	Area, depressions,concavo-convex segments
Mean Solution Depression Density (Gardner, 1972)	Mean depression area at uppermost closed contour	" " Topographic map
Composite Terrain Texture (Gardner, 1972)	Number of contour reversals/ unit length in a series of traverses in an area	Distance, topographic map
Roughness Index (Hook, 1959)	$RI = \frac{N \times M/4}{A} \times 10$ N = number of intersections of contour lines with perpendicular grid lines M = distance between grid lines	Area, distance
Concavity Index (Peguy, 1942)	$\frac{\text{Length of longest contour}}{\text{Mean contour length} \times \tan(\text{Mean slope})}$	

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
G. Pattern-Based Morphometric Descriptors		
Stream Order		
Stream Order Strahler (1952) Scheidigger (1970) Shreve (1966) Graf (1975)	Hierarchical quantitative descriptions of drainage network composition; Order is not final,but may change depending upon the source of information,the scale of spatial data, and the definition rules used (blue lines,contour crenulation, channel width, etc.)	Digitized from topo maps, aerial photos, or extracted from DEMs. Theoretically, it is possible to calculate order given area, channel length, basin perimeter, and relief
Number of Streams/Area	$\sum$links per area of all orders	Stream link counts
Number of Streams/Order/Area	$\sum$ of links per order for an area	Stream link counts,orders
Bifurcation Ratio (Horton, 1945)	$R_b = \frac{N_u}{N_{u+1}}$ $R_b = \frac{\text{\# segments of order u}}{\text{\# of segments of the next higher order}}$	Number of segments, orders
Conservancy of a Drainage (Melton, 1958)	$S_u = \frac{N_u - 2(N_{u+1})}{2(N_{u+1})} = \frac{R_{b+1}}{2} - 1$ where $S_u = 0$ is maximum conservancy (the minimum number of segments to achieve maximum stream order)	" "
Drainage Network		
Channel Length/Basin Perimeter (Melton, 1957)	Measures the development of the drainage network in a basin $\frac{\text{Channel Length}}{P_B}$	Channel length, basin Perimeter

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Langbein Index'	expresses the effective volume of water in a basin $LI_{u+1} = \sum a \times L_u$ a = the area bounded by 2 successive contours	Area of a given order, areas of lower orders in a basin, stream segment lengths, stream order
Drainage Density (Horton, 1932)	Expresses the degree of drainage development in an area $D_d = \frac{\sum L_n}{A}$	Total stream length, area
Density of Perennial Drainage (Zavoianu, 1985)	$D_{dp} = \sum L_p / A$	Lengths of perennial streams, area
Density of Seasonal Drainage (Zavoianu, 1985)	$D_{dp} = \sum L_s / A$	Lengths of seasonal streams, area
Density of Temporary Drainage (Zavoianu, 1985)	$D_{dp} = \sum L_t / A$	Lengths of temporary streams, area
Microscopic Link Density (Smart, 1972)	Expresses network density in a low magnitude exterior basin $\phi = \frac{l^2}{a}$	Channel length, basin area
Macroscopic Link Density (Smart, 1972)	$K = \frac{L^2}{NA} = \frac{\bar{L}D_d}{N} = \frac{\bar{l}^2}{\bar{a}}$ L = cum. channel length, N = number of channel links A = Total Area	Channel link length, area of link basin
Stream Frequency (Drainage or Channel Frequency) (Horton, 1945)	$F_s = \frac{N}{A}$ N = number of streams, A = Area	Number of streams, area

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Relative Density (Melton, 1958)	$\frac{F_s}{D_d^2}$	Stream frequency, drainage density
Basin Shape or Form		
Shape Factor (Horton, 1932)	Departure of a basin from a circular shape $\frac{L_B}{W_B}$	Basin length and basin width or basin area
Shape Index I (Army Corps of Engineers, 1947)	$\frac{(L_B)^2}{A}$	Basin length and area
Shape Index II (Gibbs, 1961)	$S = \frac{1.273A}{L_B^2}$	Basin area, basin length
Basin Shape Index (Hobba & Robinson, 1972)	$\frac{\text{Main Channel Slope}}{\text{Average Valley Side Slope}}$	
Form Factor I (Horton, 1932)	$F_{f1} = \frac{\text{Basin Diameter}}{L_B}$ L_B = Maximum Basin Length	Basin diameter, maximum basin length
II (Horton, 1945)	$F_{f1} = \frac{A}{L_B^2}$	Basin area and maximum basin Length

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Ogievsky (Zavoianu,1985)	$F_{f2} = \frac{A}{L_B^2}$ L_B^2 = Area of a square with perimeter equal to the perimeter of the basin L_B is not necessarily the maximum basin length	Basin area, basin length
Zavoianu(1985)	$F_{f3} = \frac{16A}{P^2} = \frac{A}{(P/4)^2}$ compares basin area to the area of a square with a perimeter equal to basin perimeter	Basin perimeter,basin area
Hexagonality	$\frac{A}{3(\frac{P^2}{72} - \frac{P^2}{144})}$ compares basin area to the area of a hexagon with the same perimeter	Basin area,basin perimeter
Triangularity	$\frac{A}{(\frac{P^2}{18} - \frac{P^2}{36})}$ compares basin area to the area of a triangle with the same perimeter	" "
Elongation Ratio		
I	$R_{E1} = \frac{\text{Diameter of a circle of an area = basin area}}{L_B \mid\mid \text{to the main stream in a basin}}$	Basin length, basin area
(Schumm, 1956)	$R_{E1} = \frac{D_c}{L_B} = \frac{2\sqrt{A}}{L_B\sqrt{\pi}} = 1.129\frac{\sqrt{A}}{L_B}$	Basin area, basin length
II (Gardiner, 1981)	$R_{E2} = \frac{A}{L_B}$	Basin area, basin length

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Circularity		
I (Area Method; Miller, 1953)	compares area of a basin to the area of a circle with the same perimeter	Basin area, basin perimeter
	$R_{c1} = \frac{A_{\text{basin}}}{A_{\text{circle}}} = \frac{4\pi A_{\text{basin}}}{P_B^2} = 2\frac{\sqrt{\pi A}}{P_B}$	
II (Perimeter Method or Compactness Coefficient or Patton's Diversity Index; Gravelius, 1914)	$R_{c2} = \frac{P_B}{P_{\text{circle}}} = \frac{P_B}{2\sqrt{A\,\pi}}$	" "
III (Bosch, 1978)	$C = 4A/L_B P_B$	Basin area, basin length and perimeter
Circularity Ratio (Griffith, 1982)	$A \times P_B^2$	Area, basin perimeter
Compactness Coefficient		
I (Perimeter Circularity)	Same as the perimeter method of circularity above	
II (Luchisheva; (*in* Zavoianu, 1985)	$\frac{P_B}{P_c} = \frac{.282P_B}{\sqrt{A}}$	Basin perimeter, basin area
Lemniscate Ratio (Chorley et al., 1957)	compares rotundity to basin perimeter	Rotundity and basin perimeter or basin area, length, and perimeter
	$R_L = \frac{R_R}{P_B} = \frac{\frac{\pi(L_B)^2}{4A}}{P_B}$	
Lemniscate Index (Chorley et.al., 1957 or Ellipticity index Stoddart, 1965)	$k = \frac{\pi(L_B)^2}{4A} = \frac{1}{R_{E1}^2}$	Basin area and basin length, or elongation ratio

Table 4 Geomorphic and morphometric descriptors (continued)

Name	General Equation/Description	Inputs
Delta (Smart and Surkan, 1967)	$\delta = \frac{L_B}{\sqrt{\frac{\pi}{2} A}}$	Basin area, basin length
Radial Shape Index (Boyce & Clark, 1964)	Measured lenths of fixed numbers of radials at specified angles	
	$S_{rv} = \sum \lvert (100 r_i / \sum r_i) - (100/n) \rvert$	
	$S_{rv} = 0$ means circle , 175 means line r_i = radial length , n = number of radials	
Dual-Axis Fourier Analysis		
Symmetric Difference Metric (Lee & Sallee, 1970)	Comparison of a shape to a standard or reference shape	Basin area, reference
	$\frac{A \cap A_s}{A \cup A_s}$	
Compactness (Cole, 1964)	A/A'	Basin area, area of the circle
	A' = Area of the smallest circle to enclose the basin	
Transport Efficiency Factor		
Lustig (1965)	$T_1 = R_B \times$ Total Stream Length	Bifurcation ratio, total stream length

The Procedure

Each objective or criterion was weighted according to its importance relative to the other objectives. I was concerned that the weights assigned to the objectives not be misplaced or inaccurate. So, I evaluated each group of descriptors with 3 different weighting schemes. In the first evaluation, the objectives were unweighted (i.e., the objectives were of equal but unspecified weight). In the second run, weights from 1-10 were assigned to the different objectives. Literature-value was given a weight of 10, ease of measuring a 7, ease of calculating a 6, and the number of inputs were assigned a weight of 4. The weights used were based on my judgement of the relative importance of each criterion. In the final run, a rank (order) was assigned to each objective according to its importance (i.e., 1, 2, 3, and 4). The ranks were treated as weights.

Each descriptor was considered a potential action that could be taken to meet the objectives. A descriptor was assigned a separate value for each criterion, based on its estimated effectiveness in meeting that criterion. This value or *effectiveness rating* for a given descriptor was multiplied by the *importance weight* assigned to each criterion. The product, an *importance-weighted effectiveness score*, was summed for each descriptor. The result was a single value for each descriptor, called a *performance score*. This score was a measure of how well a descriptor fit the criteria. Table 5 is an example of calculation of the performance scores. A program written in BASIC was used (R. H. Giles, Jr., Dept. Fisheries and Wildlife Science, VPI & SU) to perform the necessary calculations and present the final performance scores.

The ideal descriptor would meet each objective perfectly. I did not expect any descriptor to receive a perfect score. Descriptors were chosen for GEODES that best met the criteria (had the highest scores).

The final performance scores were transformed to a 100 point scale, sorted in ascending order and plotted. If the curve of performance scores was asymptotic, descriptors above the inflection point would be selected, otherwise, approximately 50% of the descriptors (those with the highest scores) would be selected from the group of ranked descriptors. If there were

2 or more descriptors at the 50% cutoff point with tied scores, I examined scores for the weighted and unweighted groups as well. The Results section titled "Descriptor Selection" presents performance scores and plots for each group of descriptors.

Terrain Descriptor System

System Design

The terrain descriptor system was an important part of the effort to meet two of the overall objectives of the project:

1. To quantify geomorphic and topographic features of a land management area in the Ridge and Valley Province of Virginia.
2. To develop new computer programs, or to locate, use, or modify existing programs to present geomorphologic data of potential interest to land managers.

The system that was developed is called GEODES (GEOmorphic DEscription System). GEODES is a general system designed to generate variables that present an integrated description of the terrain of a natural resource area. A general system model consists of inputs, outputs (or objectives), processes, and feedback and feedforward mechanisms set in an appropriate context (Giles 1978). The *context*, or realm of relevant concern, is an automated terrain description for natural resource management. The necessary *inputs* are raster or matrix-based data and vector or line-based data. Raster data provides information on slope, elevation, or aspect within each cell. Vector data (lines, points, and polygons) stores information on boundaries. This description system *processes* vector and raster data,

Table 5. Demonstration of performance score (P) calculation for some relief descriptors, weighted criteria

Criteria (K):	L	M	C	I	P
Importance Weights (W):	× 10	× 7	× 6	× 4	
Descriptors		**Effectiveness Ratings**			
Local Relief	8 × 10 = 80	10 × 7 = 70	10 × 6 = 60	10 × 4 = 40	250
Available Relief	2	10	10	10	190
Dissection Index	4	10	7	7	180
Elevation-Relief I	2	10	7	7	160
Elevation-Relief II	7	10	7	7	210
Average Relief	1	10	10	7	166
Basin Relief II	3	10	3	7	146
Average Total Relief	1	10	10	7	166
Total Relief Ratio	1	7	3	3	89
Stream Relief	1	10	10	10	180
Mesh Relief	3	7	10	10	179
Concavity Index	0	3	3	3	51
Main Channel Relief	3	10	10	10	200

L = Literature value or use

M = Ease of measuring

C = Ease of calculating

I = Minimum number of outputs necessary

P = Sum of the importance-weighted effectiveness scores

$P = \sum K_i W_i$

manipulating and transforming it to produce the desired *outputs*, which are expressions of terrain form. *Feedforward* is incorporated in the system through the structure of the data base management system (DBMS) used. The DBMS used, REVELATION (COSMOS 1985), ensures that the system has flexibility for future change. The system anticipates the use of descriptors that are not now readily available, and includes some descriptors that are not used extensively, but may be in the future. *Feedback*, the continuous modification of all elements of the system to meet changing demands, has been ongoing. REVELATION has many feedback elements. Future use of this system, and future changes to this system will be encouraged by widespread distribution of the system. With this system, both feedback and feedforward are functions that are ultimately directed by the user.

Objectives and Constraints

The first step in the design process was to clarify the objectives toward which, and the constraints under which I was working. There were many operational objectives and constraints that I sought to meet while designing and implementing this system. These were in addition to the broad objectives listed above.

This system should be user-friendly to encourage its use by natural resource professionals. Explanations of the outputs and the features of the system should be available to the user during a session. A series of menus were created to offer the user the opportunity to leave the system or to explore particular features of the system in detail.

If this system is to be useful to resource managers, it should be flexible. An "open-loop" system (Walters 1986), one that is not adaptable to changing conditions or needs, is not likely to be used by professionals. The size or the structure of the data base should not seriously constrain the use of this system. A well-designed DBMS offers flexibility independent of the constraints due to the structure of a data base (Kerr and Neal 1976). By design, it can grow or expand as needed. It is also versatile enough to allow programs, subroutines, files, and descriptors to be added or removed as needed.

Closely tied to the objective of flexibility was the constraint of compatibility. This system was designed to interface with at least some existing mapping, data storage and data retrieval systems to ensure its use. The system was designed to interface with 1) a micro-computer GIS, 2) a program for vector-to-raster data conversion, and 3) a suite of vector-based mapping programs used at the Department of Fisheries and Wildlife Sciences at VPI & SU.

This system works within the constraints of 2 software packages that were available within the Department of Fisheries and Wildlife Sciences, the Map Analysis Package (MAP) (Tomlin 1986), and REVELATION (COSMOS 1985). MAP, a raster-based GIS, could generate slope and aspect from elevational data, eliminating the need to write programs for those functions. REVELATION is a relational data base manager that facilitates analysis and manipulation of spatial data.

I considered it important that GEODES present variables that are tangible to the resource manager. The necessary inputs should be concrete and easily obtained. The derivation of the descriptor should be fairly apparent. Some of these measures may not be the best measures of a particular aspect of terrain, but they have demonstrated utility, or they are related to the abiotic or biotic processes at work in a resource area. A dual axis fourier analysis may be one of the best measures of a drainage basin's shape, but the derivation is difficult and the measure is not easily interpreted (Griffith 1982). Measures of circularity and elongation are easier to calculate, to work with, and may be quite suitable for explaining a basin's hydrologic response to precipitation. Walter's (1986) suggestion that there may not be any "best" models (of anything) applies to quantification of terrain as well as to ecological models. Even models with a degree of uncertainty or unexplained variance may be valuable for placing subprocesses into perspective.

This system incorporates raster and vector data formats, to provide the user with the best available information for the lowest cost. When the costs of data entry, manipulation, and processing efficiency are considered, neither data format alone is sufficient for quantifying surface shape. At a given level of resolution, vector format data requires fewer numbers, less data storage, and provides a more accurate representation of boundaries than raster format data (Burroughs 1986, Berry 1987b). However, areas within vector polygons are more generalized than areas represented by a raster format at the same scale. Raster data processing is generally simpler than processing vector data (often just an iterative application of simple arithmetic operators). Accurate definition of linear features such as streams with raster formatted data requires far greater data storage (and a finer level of resolution) (Peuquet 1977, Burroughs 1986, Berry 1987b).

This system should provide as much information as possible from a given set of inputs. The challenge is to reduce the number of variables without compromising the suitability of a model, to encourage the recognition of patterns in a landscape by eliminating extraneous "noise" (additional variables), and to provide for a variety of application conditions and purposes (Kerr and Neal 1976).

The last 2 constraints were exportability, and automated processing. The descriptor system must be exportable to most micro-computer systems typically available to the modern resource manager. Access to a mainframe computer should not be needed. This system was automated so that mundane and potentially error-prone processes such as data entry can be performed mainly by the system (e.g.,reading MAP overlays and digitized data files), not by the user.

Design Process

System design is an ongoing process. The structure of GEODES was modified as it developed. My overall strategy was a combination of the top-down approach, and the working-outward approach. In the top-down approach, goals are examined broadly and broken into subobjectives at a finer level of detail. These subobjectives are then dissected further, until individual tasks are identified. Working-outward meant keeping the desired outputs of the system in mind, and at each step in the system's development, examining the effects of that step on the end products (Walters 1986). I identified and developed the desired products of this system (land surface descriptors), and then specified the variables and processes necessary. Finally, I elaborated on the pathways and boundaries of the system, including the menus, prompts, and programs needed to get the user to the descriptors and final reports.

This process of design and development is a logical progression from a manager's objectives to the system programmer's perspective. The manager may want to know what benefits a new tool, technique, or system may provide. How much time and effort does it require? Is the output usable, and what does it mean? These questions are also part of the criteria for system evaluation (Jones 1976). The programmer may be more interested in the structure of the system than in the mechanics. System design requires familiarity with both points of view.

System design involved decomposition of the problem. At first, the end products were simply descriptors of land form. Later, I added descriptors that measured a particular land attribute (i.e., relief). Finally, I considered specific descriptors.

I judged that numeric values alone were inadequate. Rather, the user must be offered the option of viewing the generalized equation and an explanation of the meaning or potential use of each descriptor. I hoped that this design would encourage the use of this system.

The integration of 2 different software packages favored development of modules for each specific task. Linking MAP to REVELATION, manipulating vector and raster data, menus, and report generation are very different tasks that encourage modular programming. Initially, I envisioned the system in 3 pieces: data, data manipulation and analysis, and report generation. With further work, the system grew to contain 6 components: menus, data input, raster data processing, vector data processing, raster-vector processing, and report generation.

The main system operation was manipulating and transforming data to generate descriptors. The necessary data were in 2 formats, raster-based MAP overlays of slope, elevation, and aspect, and digitized vector data (stream channels and watershed boundaries).

The first task the system would perform was converting MAP overlays of elevation, slope, or aspect into a form usable by the DBMS, REVELATION. Next, the system would retrieve or mark specific entities within a region or overlay for further analysis (e.g., such as a particular watershed). Smaller features within the identified watershed such as slopes or stream segments were retrieved. A linkage between vector and raster processing was established. Finally, a format for reporting descriptors was developed.

I worked on each task in sequence to completion. As each component was completed, the link with the previous component was examined by generating measures that required both the current component and its precursors. As an example, examining the raster-based component required reading and converting a MAP overlay into a format usable by REVELATION, then generating specific sample descriptors such as an elevation-relief ratio from the raster data.

System Overview

GEODES manipulates raster or gridded data (elevation, slope, or aspect) and vector data (digitized points and lines) to generate descriptions of regions, or individual features (watersheds and streams) within a region. Fig. 1 is a simplification of the operating system. Later topics in this section review the system's components in detail.

GEODES consists of several REVELATION files, and a virtually unlimited number of user-specified MAP overlays (DOS files). There are separate REVELATION files for programs and subroutines, descriptor equations, digitized data, text fields, report forms, and data base parameters. The equations used to generate raster-based descriptors are kept in the file RASTER.DATA. Equations for vector-based descriptors are in the file VECTOR.DESCRIPTION. Most of the catalogued programs and subroutines (independent of the actual equations used to generate descriptors) are maintained in another file (MAP.BP). Two additional files contain subroutines and functions (written by A. B. Jones III, Department of Fisheries and Wildlife, VPI

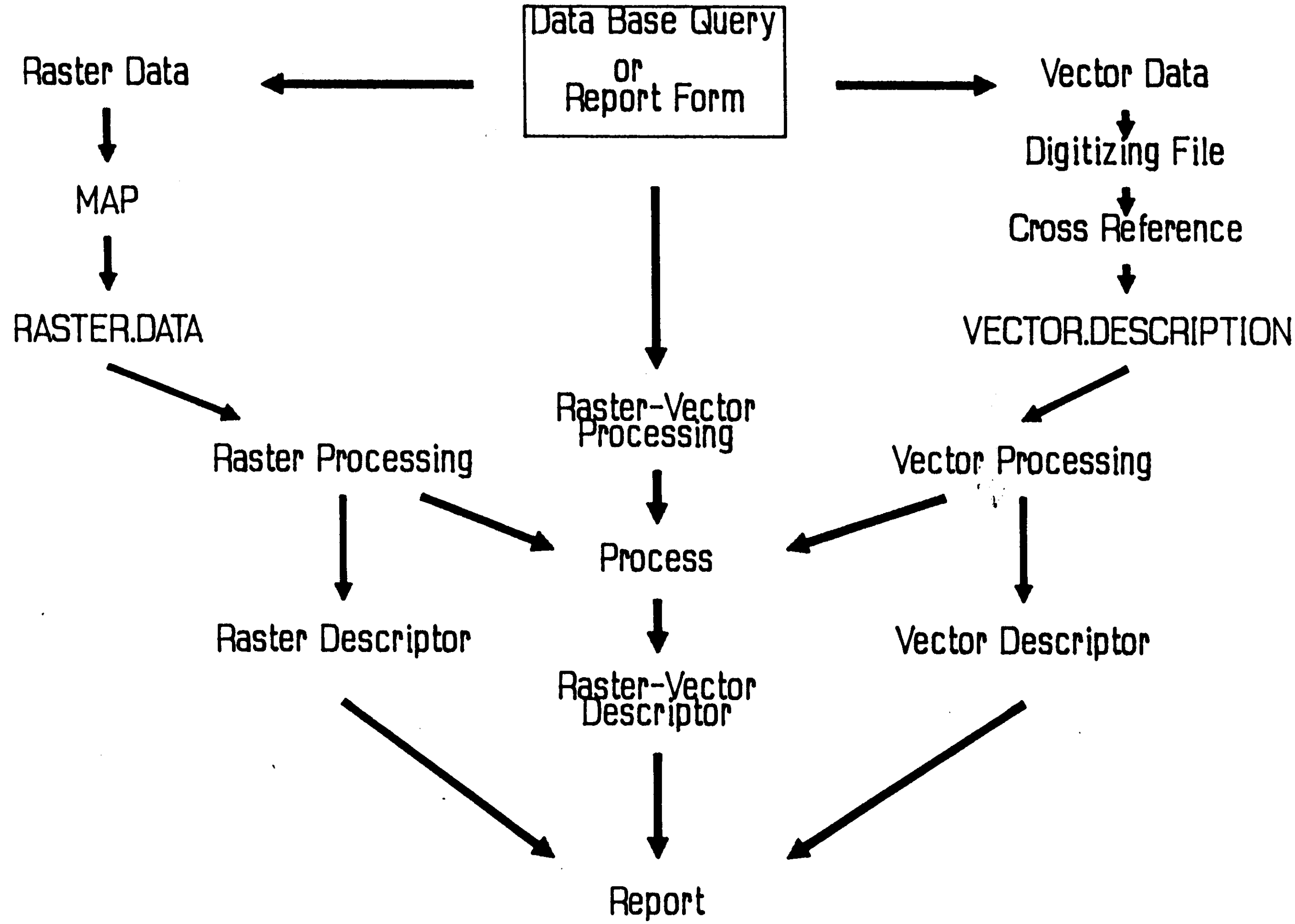


Figure 1. Overview of the terrain description system, GEODES

& SU) that were used for manipulating data. Electronically digitized vector data (from a digitizing tablet) are stored in the file, DRAINAGES.HAVENS. Vector data entered by hand (at the keyboard) are stored in the file HAND.DIGITIZE. Text fields or explanations of the various components of GEODES are kept in a separate file (TEXT.BP). General dimensions of MAP overlays and the digitized data are entered and stored in a PARAMETERS file. Finally, there is a file that contains the formats used in reporting descriptors (GEO.FORM). The actual raster data reside in MAP overlays (DOS-based single factor maps) outside the REVELATION-based system.

The master or principal file is RASTER.DATA. The study area name is the key record in this file, and defines the general region or map to be examined. RASTER.DATA generates 2 kinds of descriptors, regional (descriptors that apply to an entire map or region) and local (descriptors that describe one feature within a region or map i.e., a basin or stream). All descriptors that require raster data or both raster and vector inputs are calculated by symbolic fields in RASTER.DATA. This file accesses vector data and equations by file translation (XLATES) to VECTOR.DESCRIPTION and the digitized data files, or by an inverted feature list stored in RASTER.DATA (created by cross referencing the field VECTOR.FEATURE in the VECTOR.DESCRIPTION file). The file, RASTER.DATA, accesses raster data 2 ways, by opening, reading, and translating MAP overlays, and by using MAP to generate a DOS file that summarizes an overlay. REVELATION reads and processes that DOS file.

The key record in VECTOR.DESCRIPTION is the name of a vector feature, e.g., a specific watershed. Using that name, and a cross referencing system, this file extracts from the digitizing file, e.g., DRAINAGES.HAVENS, the names, attributes, and digitized coordinates of the lines and points that make up that specific watershed. It also generates user-specified vector-based descriptors.

GEODES is a menu-driven system. Each menu accesses both specific functions (i.e., vector-to-raster conversion, descriptor calculation, etc.) and explanations of those functions. Explanations include the data types used, hardware and software requirements, how the system functions, and how the system may prove useful to the natural resource manager. A user familiar with the system can choose to bypass these explanations. Users may page back through the menus to review the explanations.

If necessary data are not currently available to the system, the user is directed through the process of accessing raster and/or vector data. If raster-based data are needed, RASTER.DATA invokes catalogued programs and subroutines for opening and reading MAP overlays and translating the data into a format that REVELATION can process. Vector data are accessed through the secondary file VECTOR.DESCRIPTION. A routine is available for converting vector data to a raster format.

There are 2 options for descriptor reports. The user may either choose a report form, or develop a query sentence. A report form is a compilation of all the descriptors available for a given type of data processing (raster, vector, or raster-vector processing). The user chooses a report form and lists the names of the drainage basins to be examined. Submitting (choosing) a form causes GEODES to calculate values for all of the descriptors listed on the form. The results are printed in a report format that includes headings, descriptor names, and units of measure.

In a query, the user specifies a study area, 1 or more features and 1 or more descriptors. A query or R/LIST sentence is created. The execution of this sentence generates the selected descriptors. The results are presented in tabular form to the microcomputer monitor or printer.

System Components

Data

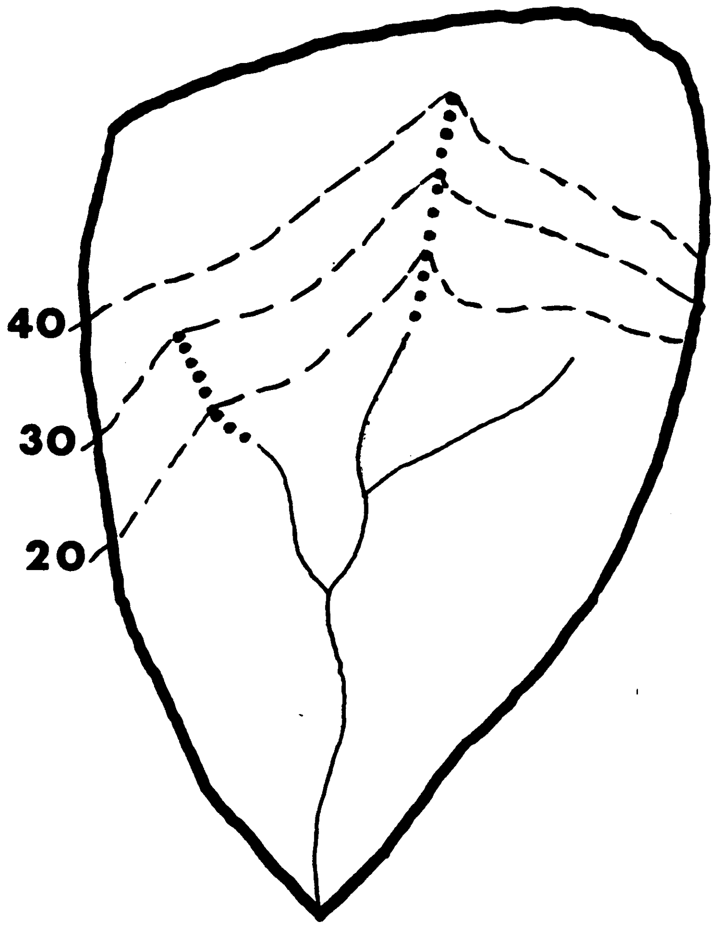
Raster data are accessed by the RASTER.DATA file from Map Analysis Package overlays of elevation, slope, and aspect. Vector data resides in the REVELATION file to which it was digitized. Data for development and demonstration of GEODES were obtained from maps of the 2,833 ha (7,000 ac) Havens State Wildlife Management Area, in Roanoke County, Va.

The basic raster data set was elevational data encoded by K. Dombrowski (Department of Geography, VPI & SU) in 1986. A square sampling grid scaled to 1 ha was used to collect elevational data from two 1:24,000 USGS topographic maps that cover the Havens area (Glenvar and Salem quadrangles). One elevation was recorded for each 1 ha (100 x 100 m) cell. The final matrix measured 80 rows by 110 columns.

Vector data consisted of digitized watersheds and stream channels. The portion of the study area for which elevational data was available was outlined on Salem and Glenvar quadrangle 1:24,000 USGS topographic maps. Sample watersheds were outlined on the topographic maps with the highest local contours interpreted as drainage divides. In eastern Kentucky, Mark (1983) found that this technique corresponded well with field delimitation of watersheds. Eighty-two first-order and 25 second-order drainage basins were outlined and digitized. No third order basins were entirely within the study area, so none were digitized.

Many researchers have examined the problem of defining first-order streams from maps (Morisawa 1962, Drummond 1974, Mueller, 1979, Mark 1983). I chose to use the contour crenulation system described in Mark (1983). Each channel was extended upslope beyond the blue line shown on the topo maps to a point at which 3 or more successive contours had crenulation angles more than 150^0, or 2 successive contours had angles greater than 100^0 (see Fig. 2). Points called mesh sources were located by extending the drainage channel to the divide, following the approach used by Mark (1983). These points were digitized because some mesh-based descriptors were identified by the objective weighting process as potentially important (See Results, Descriptor Selection).

I used the generic digitizing option in the REVELATION-based digitizing program, XY.DIGITIZE (written by A. B. Jones III), a Numonics 2300-1 digitizing tablet, and an IBM Personal Portable PC (640K RAM with an Intel 8087 math coprocessor) to digitize the watersheds and stream channels in the study area. I copied XY.DIGITIZE to



Key

— blue line streams

•••• crenulated streams

– – contour lines

Figure 2. Map channel extension by contour crenulation

DRAINAGES.HAVENS, and added a validity check routine to test the attributes and ensure that they were in the correct format before they were written to the file DRAINAGES.HAVENS.

Each digitized line consisted of a unique record identifier, up to 7 attributes, and the X,Y coordinates (in UTMs). A record identifier allows the user to reference a specific line and its attributes. Attributes define a line's position relative to other digitized features and specify what the line is. The first attribute was the type of line, recorded as B for boundary, S for stream, and M for mesh source. The second attribute, study area, was assigned as a check to ensure that only data for 1 study area are incorporated in the calculation of a descriptor. If the line type was B, the next attributes assigned were the names of the features of which the line is a part. In the data set used for developing this prototype, a boundary line can be a part of as many as 4 different features (2 first order watersheds and 2 second order watersheds). If the line type was S or M, the next attributes were stream order (Strahler order), watershed name, and the next-higher-order feature of which the stream is a part (if there is a higher-order-feature in the region).

Hardware

GEODES was developed on an IBM AT, equipped with a 1280 K memory, 8087 math coprocessor, two 320 K floppy disk drives, a 20 megabyte hard disk, and a 20 megabyte Geniebox (TM). The minimal computer that will run GEODES is a function of the hardware requirements of its component software, MAP and REVELATION.

MAP can be modified to run on a minimal DOS 2.0 computer consisting of two 320 K disk drives, 256 K RAM, and without the Intel 8087 math coprocessor, or the IBM Virtual Device Interface software (Tomlin 1986). With this minimal system, the package must be recompiled without the extensive help facility, or the SHOW and DRAIN commands, processing is slow and limited to a maximum base map of approximately 100 x 100 cells. A system configured to allow faster manipulation of larger matrices and the use of the help facility would include the 8087 math coprocessor, more RAM, and a hard disk.

REVELATION requires a minimum of 320 K RAM and two 320 K disk drives. However, COSMOS (1985) recommends 512 K, and a math chip (Intel 8087).

Based on the requirements of the component software, an adequate or minimal machine for operating this system would possess 512 K (to 640 K), a math chip, and a fixed disk.

Software

MAP

MAP is a raster-based set of tools or computer programs for collecting, retrieving, transforming, and displaying spatial data for regions or maps (Burroughs 1986, Tomlin 1986). GEODES uses MAP to format elevation data, to generate overlays of slope and aspect from elevation data, and to summarize overlays for descriptor generation.

The GRID (row-by-row data entry) or POINT (row-by-row, column-by-column data entry) commands, read elevational data into a base map. The command DIFFERENTIATE created overlays of average slope from the elevation base map. The command ORIENT PRECISELY created overlays of slope orientation (aspect) in degrees for each cell in the matrix. The commands COVER and RECODE were used to generate overlays of specific features within a region or map.

REVELATION

REVELATION is an integrated collection of programs and data files that allows the user to enter, store, extract, manipulate, and report information (COSMOS 1985). The flexibility of REVELATION eases the development of system software. This DBMS allows variable length files and fields within files. REVELATION accomodates the use of multi-valued fields, either as dimensioned or dynamic arrays. The heart of the system is the dictionary. REVELATION can simultaneously access multiple files, fields, and records with the dictionary. There are 3 features of REVELATION that GEODES uses, R/LIST, R/DESIGN, and R/BASIC.

R/LIST is a query language that allows the user to select and display information. It is used primarily to select specific records from a database and to generate decriptor reports. During a GEODES session, the user may compose an R/LIST sentence or query by concatenation. This sentence specifies the region, and feature (s) within the region to examine, and the terrain descriptors to calculate. Executing this sentence links MAP overlays with REVELATION files, extracts data from the overlays, links different REVELATION files to exchange information, and generates the specified descriptors.

The function of R/DESIGN is to create, define, and modify the database. Through R/DESIGN, I have created all the necessary files, defined fields within files, cross referenced fields in different files, created data entry screens, and developed menus for this terrain description system. During field definition, the user decides if a field is "pure" (data are actually stored there), "symbolic" (contains no data, but processes data from other fields to generate a value), or "group" (pulls data together from several fields within a file and displays them as 1 field). Symbolic field are used to extract data from MAP overlays, the digitized data file, and generate descriptors. R/DESIGN provides a menu template that can be modified as needed. In the menu, each option is linked with a specific REVELATION command. Selection of any menu option executes an associated command.

R/BASIC is REVELATION's programming language. R/BASIC is used in this system's programs, subroutines, functions, and in the symbolic field formulas. All equations for extracting and manipulating data were written in R/BASIC. R/BASIC allows GEODES to manipulate REVELATION data and DOS files, and to run MAP and the rasterization routine (RASTBUG).

RASTBUG

RASTBUG is an MS FORTran routine written by M. Scott and F. Cotton (Department of Fisheries and Wildlife, VPI & SU). This routine converts vector data (points, lines, and streams) from a MOSS (Map Overlay Statistical System) format into a grid cell or Row-Column format that is ready to be input into MAP. RASTBUG is included within the set of programs that make up GEODES. Rasterizing vector data allows GEODES to identify specific features (basins, streams, and mesh sources) within a map overlay, and to associate gridded data with specific features.

System Structure and Processing

MAP

The structure and data requirements of MAP constrained development of GEODES in terms of data, attributes, and processing. MAP accepts only integers as cell values, so, all input data had to be converted to, or entered in integer format. This is the reason that feature names are integer strings.

In MAP, all base maps and overlays must be rectangular. A base map is a matrix with integer values stored in all of the cells. The raster data set used for system development consisted of 8800 cells. There were only 4300 cells with valid elevational values (4500 cells were empty). These cells covered most of Havens Wildlife Management Area and much of the surrounding area. To get the necessary rectangular matrix for MAP processing, the study area outline had to be padded with missing values. Because MAP requires integer values in the cells of a matrix, missing values were represented by zeros.

The MAP subroutine SLOPE (used to calculate both slope and aspect) was rewrittten so that zeros (missing data points) were not included in the calculation of slope or aspect for cells in the matrix (see Appendix A). MAP calculates slope and aspect cell by cell. The slope or aspect value assigned to a given cell is the average of the values calculated between that cell and its 8 neighbors. In the rewritten subroutine, if a cell has a value of 0, processing moves to the next cell. If 1 of the neighboring cells has a value of 0, it is excluded from calculations of slope and aspect. If 2 or more of the 8 neighbors are 0, then slope and aspect are calculated using the Rook's Case algorithm (O'Neill and Mark 1987). In the Rook's Case, a value is calculated from 1 or more pairs of 4 connected, 2 orthogonal neighbors. These are cells at right angles to one another, the vertex of the angle is the cell for which slope or aspect is calculated. If a cell has only 1 neighbor with elevational data, slope and aspect are calculated using only the elevational values for the 2 adjacent cells.

In GEODES, MAP processes 3 types of overlays or data layers, fundamental overlays, feature overlays, and specific feature overlays. Fundamental overlays are overlays of slope, aspect, or elevation. These are overlays of a single factor for an entire map. They are fundamental because they are essential in the generation of any descriptors, either map-wide or local, that require raster data. Feature overlays are overlays of rasterized vector data. These are overlays of all of the mesh sources, streams, or basins for an entire map. MAP's RECODE and COVER commands are used to process fundamental and feature overlays to create overlays of specific features. These are single feature overlays that apply only to a particular stream or drainage basin. A specific feature overlay might be an overlay of slope for a given basin or the elevation along a specified stream. Specific feature overlays are used to generate descriptors requiring both raster and vector data.

REVELATION

The structure and processing of GEODES depends on REVELATION and on MAP. REVELATION is dictionary-driven. Dictionaries in REVELATION are used to manipulate and understand data. An entry in a dictionary may refer to a field, a functional equation, comments, etc. The dictionary is an interface between the data base and the user. A menu may access a dictionary, but the dictionary controls access to the data. Given the unique identifier of a record (hereinafter called a key or id), a nearly unlimited number of related fields, values, or equations may be looked up in the dictionary of a file. GEODES uses dictionary entries within REVELATION files to calculate descriptors. A dictionary entry may calculate a descriptor, call external subroutines or functions, or call another dictionary entry to calculate a descriptor. Descriptor calculation is little more than a query of the data base that is mediated by the relevant dictionary entry.

Raster Data Processing

Before processing raster data, GEODES examines the file of raster and vector parameters (PARAMETERS). It extracts the name of the fundamental overlay to be processed and the directory path from GEODES to the MAP overlay.

Raster-based terrain descriptors are quite simple to calculate (Fig. 3). GEODES starts the Map Analysis Package, the user selects the desired base map, then GEODES selects the appropriate fundamental overlay and summarizes the data in that overlay with the MAP command, DESCRIBE. A DOS file is created that contains the data summaries (a tabular listing of values and the number of points associated with each value). GEODES opens and processes this DOS file to calculate raster-based descriptors of the base map.

Vector Data Processing

In vector data processing, linear and areal measures of specific landscape features are derived from digitized coordinate pairs (Fig. 4). The name of a specific feature such as watershed '101' accesses the record ids of the group of lines that have '101' as an attribute (because of cross referencing). A specific dictionary definition or field such as CHANNEL.GRADIENT determines whether mesh, stream, basin, or all 3 types of basin elements are used to calculate a descriptor.

With the record ids of the digitized lines, the dictionary field in VECTOR.DESCRIPTION can extract the associated XY coordinates from the digitized file (DRAINAGES.HAVENS OR HAND.DIGITIZE). The actual processing of vectors involves consecutive ordering of digitized lines, measuring distances between coordinate pairs, and calculating areas within polygons.

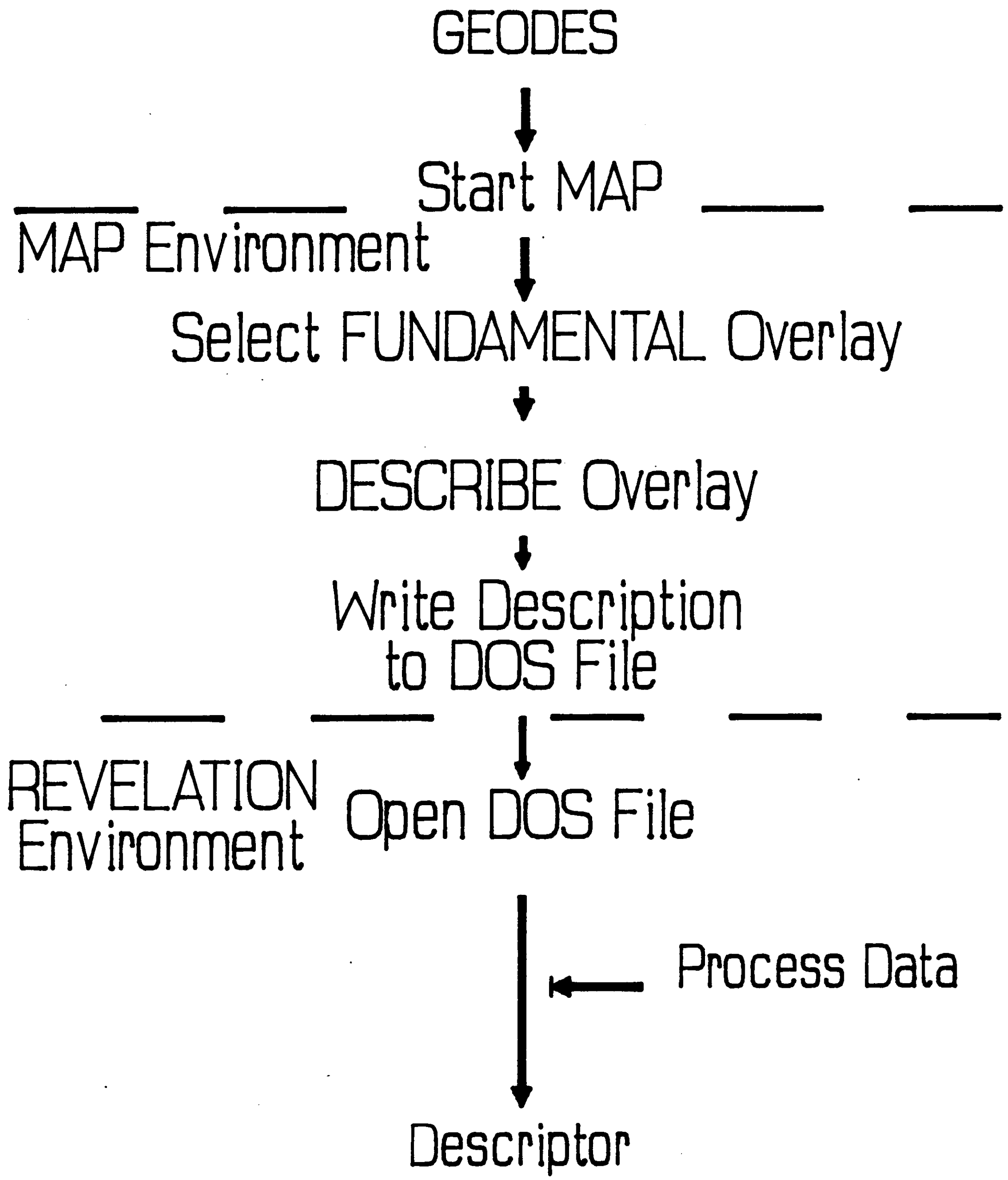


Figure 3. Raster data processing in GEODES

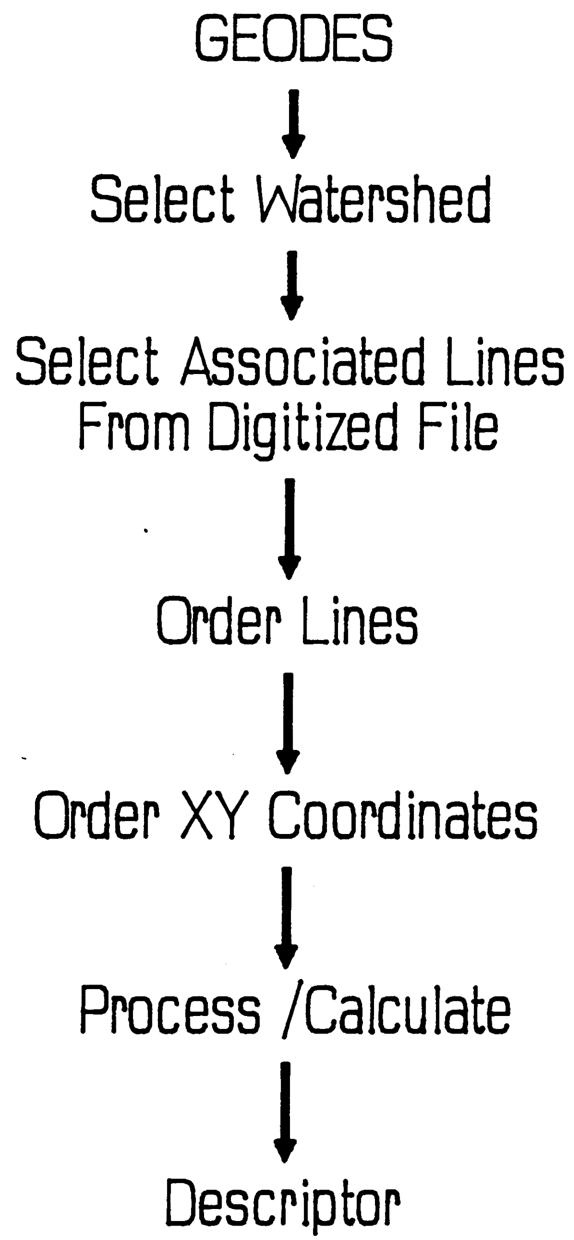


Figure 4. Vector data processing in GEODES

Many of the vector descriptors require measures that were generated by other dictionary fields in VECTOR.DESCRIPTION. Shape descriptors, for instance, may require measurements of area, length, and perimeter. To improve processing efficiency, a vector measure such as CHANNEL.LENGTH that is used in calculating many different descriptors is stored in a "pure" field, rather than recalculating it each time it is needed.

Raster-Vector Processing

In raster-vector processing, raster elements (elevation, slope, and aspect) are combined with linear and areal vector elements to generate descriptors of elevation, slope, area, length, relief, texture, or pattern for specific drainage basins within a map (called local descriptors) (Fig. 5). Rasterizing vector data allows GEODES to access the raster data associated with a specific vector feature. Rasterized vectors define an area within a map to be described. Raster-vector descriptors may consist of raster measures that apply only to a vector-defined feature (e.g., minimum elevation of a basin) or may be the product of vector measures translated from VECTOR.DESCRIPTION and raster-based measures (e.g., surface area combines PLANIMETRIC.AREA, a vector descriptor, and the mean slope of a basin, a raster measure).

Some raster-vector descriptors require GEODES to read raster values from specific locations on a MAP overlay (i.e., *Main Channel Slope, Basin Length 1,* and *Main Channel Relief*). GEODES examines the file of raster and vector parameters (PARAMETERS), extracts the name of the overlay to be processed, the directory path from GEODES to the MAP overlay, and the dimensions of the overlay (number of rows and columns). Vector coordinates are converted to raster (row-column) coordinates. GEODES then associates raster values with given vector locations, by calculating the locations in an overlay (in bytes) to read data from. The basic formulae are:

Location =

(Row x Number Columns) – Number Columns + Column Position

Number Bytes Read = (Overlay Location × 2) + 1920

The overlay is opened and values are read in 2 byte increments. Those increments correspond to cell values. These values are translated from binary integers to base-10 integers.

System Demonstration

GEODES was developed using a 492 item vector data base and an 8800 element raster data base. These data sets are useful in demonstrating the full scope of the system, and may be valuable in future studies, but with such complex datasets, the validity of the system output may be questioned. To resolve such questions and to refine descriptor processing, I applied GEODES to 2 test data sets.

After processing the test data sets, GEODES generated descriptors for 6 sample watersheds from the Havens Wildlife Management Area (3 first- and 3 second-order drainage basins). The purpose of this exercise was to explore the range of descriptor values for an area in the Ridge and Valley Province of Virginia. When discrepancies in values for related descriptors were noted (i.e., between *Main Channel Slope* and *Channel Gradient* for first-order basins), I calculated and reported correlation coefficients (R values) for the descriptor comparisons. These descriptors were reported to be correlated (see Gardiner 1975, Gardiner 1982, Mark 1983) and I hoped that correlation coefficient values might indicate logic errors in the descriptor programming.

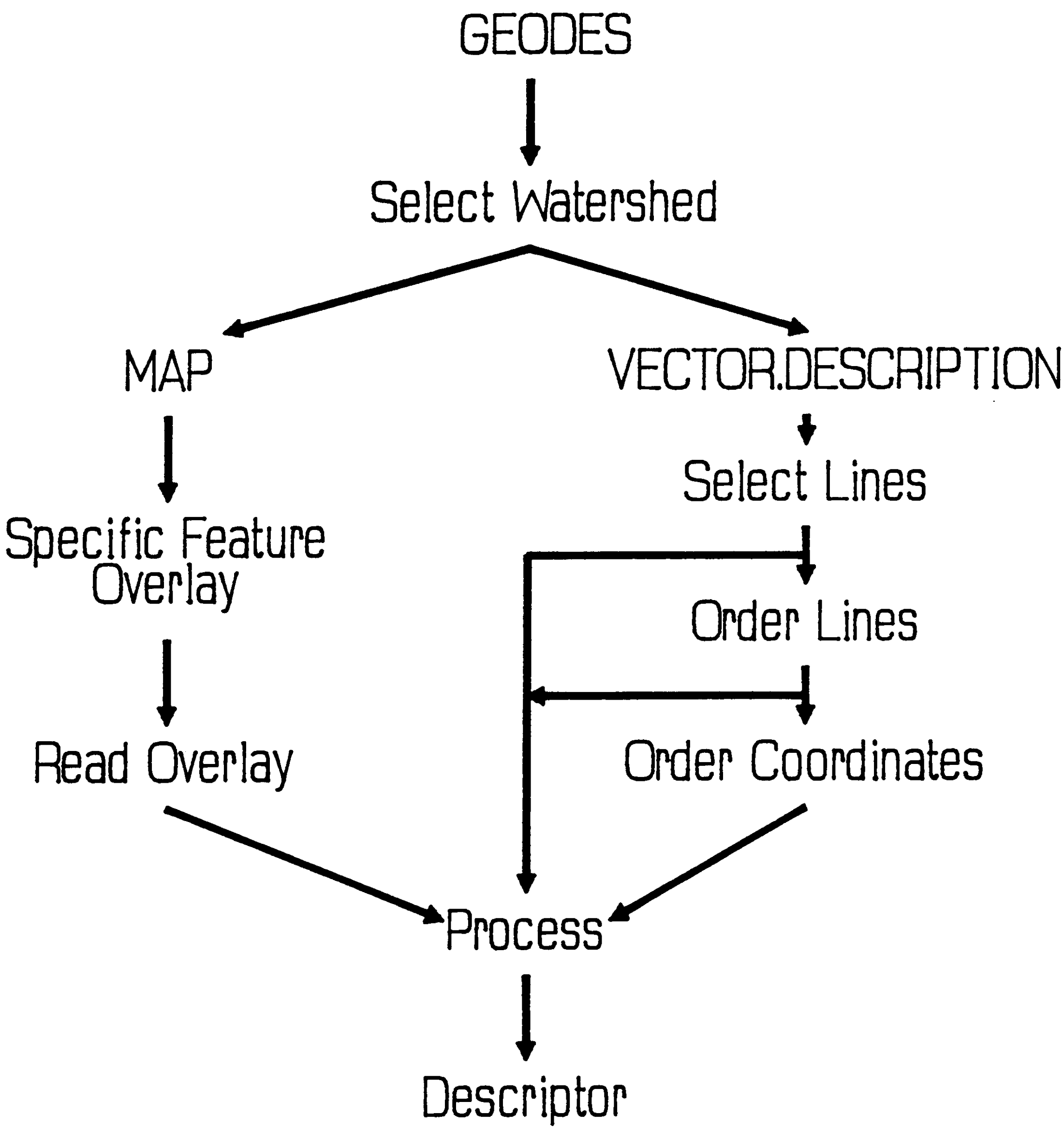


Figure 5. Raster-vector data processing sequences employed in GEODES

Results

Descriptor Selection

A performance score was calculated for each descriptor in each descriptor group (i.e., slope, relief, linear measures, etc.) for each of the 3 objective-weighting regimes (i.e.,equal weights, weights, and ranks). The resulting scores for each weighting regime were arranged in ascending order, scaled in proportion to the highest score for a given descriptor group and plotted (Fig. 6). The plot of a descriptor group shows the transformed performance scores of descriptors for the 3 regimes.

The graphs of equally weighted criteria are slightly irregular when compared to the graphs of the weighted or ranked criteria. In general, the graphs of weighted and ranked criteria appear linear. By weighting or ranking the criteria, I placed a greater emphasis on the literature value of descriptors than on the other 3 criteria. Some descriptors received higher scores under the weighting schemes than they received in the unweighted run. In Fig. 6, descriptors 2 and 9 (channel gradient and main channel slope) are very good examples of this. They may be useful descriptors, but are more difficult to measure than many of the other descriptors, hence the low unweighted score.

The order of individual descriptors correspond well between the 3 curves. I included in GEODES the top 50% of the descriptors (those at the top half of the curve) because there were no readily apparent inflection points, and because of cost and time constraints. The decision to use 50% was arbitrary. Some of the descriptors at the lower end of that range may not be as useful as the descriptors with the highest scores. The next sections review the selected descriptors for each aspect of terrain analysis based on the 4 selection criteria: literature value and utility, ease of measurement, ease of calculation, and number of inputs.

Elevation Descriptors

I did not conduct objective weighting of the elevation descriptors for 2 reasons: 1) There were only 7 identified elevation descriptors; 2) many other descriptors, especially slope, relief, and texture descriptors relied on some of these point or summary elevation values. Instead, I chose to include all 7 elevation-based descriptors in GEODES.

Slope Descriptors

Beside the basic measures of slope (percent slope and slope measured in degrees), I identified 22 other slope or gradient descriptors (Table 4). I found very little information on 3 of the descriptors, *basin land slope II - IV*. Because all 3 are similar in formulation and rely on similar inputs, I grouped them as 1 descriptor in the evaluation process. Two descriptors, *characteristic angle and slope frequency distribution* are statistically derived and were not considered for inclusion in the system. Two other descriptors, *maximum* and *minimum slope for an area* were not considered because they are regional generalizations of 2 descriptors that were considered (*maximum and minimum slope*). I selected the 9 slope descriptors with the highest performance scores under the ranked criteria (see Table 6). The decision to select the top 50% of the descriptors for inclusion in GEODES was an arbitrary rule that was applied to each group of descriptors. For slope descriptors, based on the performance scores for all 3 criteria, the first 8 descriptors are the most important. If the decision rule had been the upper 35%, the choice of the best 6 descriptors would have been consistent under both weighted and ranked criteria.

Fig. 6 compares performance scores of slope descriptors for the 3 sets of criteria weights. The graphs for weighted and ranked criteria are very linear while the graph of unweighted (or equally weighted) criteria shows 2 strong dips. This suggests that the informational value of these descriptors offsets the number of inputs needed, the difficulty in measuring the inputs, or the difficulty in calculating them.

Mean slope (or gradient) is commonly used in land description, physiographic classification, wildlife habitat evaluation, and trafficability studies (Gardner 1972, Mark 1975a, Hays et al., 1981). In Tomlin's (1986) Map Analysis Package (MAP) mean slope is 1 option of the slope command DIFFERENTIATE, which suggests its general utility.

Mean slope relates horizontal and vertical scales (Mark 1975a). Abrahams (1980) reported that it controlled the size of a stream's source area. It may be the primary control of the planimetric form of a fluvial landscape (Abrahams 1984). Mark (1975) suggested that mean slope is not as sensitive to the recording interval used as is maximum slope. On the scale of a small drainage basin, it is correlated with both relief and Melton's ruggedness number (Mark 1975a). Many other descriptors use mean slope to convert from map dimensions to an approximation of surface dimensions (Zavoianu 1985). Mean slope is an abstract measure, however, and does not reveal anything about actual slope angles or the proportions of angles in a given area (Gardner 1972). Mean slope is easy to calculate, and requires only 2 inputs, actual measurements of slope, and a tally of the number of samples taken.

Channel gradient may be the most important or the most often used slope descriptor (Ruhe 1975). Channel gradient affects stream energy, sediment transport rates, channel stability, and bedform geometry (Platts et al. 1983, Knighton 1984, Paustian et al. 1984, DeBano and Heede 1987). It is a factor controlling stream hydraulics and affects both fish passage and fish community composition (Welch, 1978, Platts 1979, Paustian et al. 1984). Channel gradient

Table 6. Slope descriptors and scaled performance scores

Descriptor	Equal Weights	Weighted	Ranked
1 Mean slope	100	100	100
2 Channel gradient	76	84	87
3 Slope class	91	87	85
4 Slope position	85	83	83
5 Limiting angle	88	82	81
6 True slope	91	83	80
7 Slope tangent	91	80	78
8 Slope sine	91	80	78
9 Main channel slope	62	67	70
10 Apparent slope	82	70	66
11 Minimum slope	82	70	66
12 Basin land slope I	76	64	61
13 Upland slope	71	61	59
14 Mesh slope	56	53	52
15 Basin slope	50	44	43
16 Basin land slope II - IV	35	28	26
17 Slope ratio	29	25	23

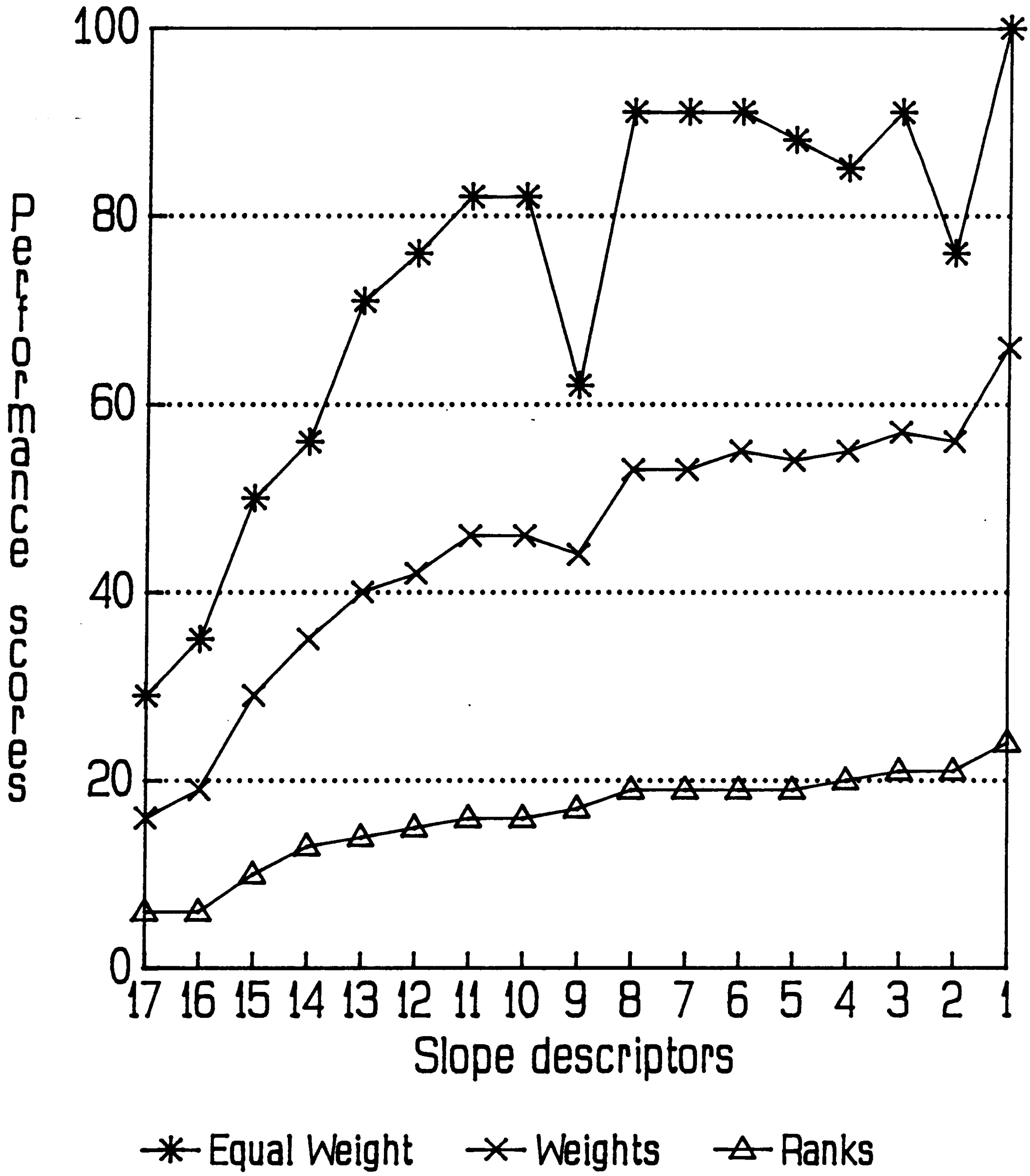


Figure 6. Scaled plots of performance scores of slope descriptors under 3 weighting schemes

is an important characteristic of the vertical aspect of the drainage network and has been reported to be strongly inversely correlated with runoff and basin area (Morisawa 1962, Gardiner 1975, Ruhe 1975). It is positively correlated with relief ratio and relative relief (Gardiner 1975, Ruhe 1975). Channel gradient is commonly used for converting mapped stream lengths to an approximation of true channel length (Zavoianu 1985). Gregory and Walling (1973) cautioned that different channel profiles can yield the same gradient value.

Channel gradient is more difficult to measure from a map than some of the other slope descriptors. It requires outlet and stream source elevations and stream length. Drummond (1974) and Mark (1983) discussed the difficulty of locating stream sources on maps and the role played by cartographic generalization. Compared to many other slope or gradient descriptors, channel gradient is more difficult to calculate and requires several kinds of inputs.

Slope classes or intervals are widely used as descriptive tools. They have been used for designating slope stability hazards, land classification, timber harvest regimes, wildlife habitat evaluation, and for other uses (Zakrezewska 1967, Lee et al. 1976, Fowler and Dealy 1987). The difficulties are in choosing meaningful class limits and accepting some loss of information that occurs when this technique is used (Gardner 1972). The necessary inputs are minimal, and the measurements and calculations are easily made.

Slope position is an important factor in forestry and plant ecology. Slope position influences soil-water relations and soil depth, affecting forest species growth and community composition (Auten 1945, Whittaker and Niering 1965, McNab 1984). Slope position is useful in estimating site index. Munn and Vimmerstedt (1980) found a significant positive correlation between tree height and slope position. Avery and Burkhart (1983) used slope position to calculate site index on deforested slopes. Like most of the other slope descriptors, the necessary inputs are few and easily measured.

The *limiting angle* has been useful in wildlife habitat evaluation, slope stability studies, land form classification, forest harvest activities, and recreation. Many wildlife studies reported that a particular species (bighorn sheep, cottontail, caribou, elk, bobcat, ruffed grouse, etc.) or certain key habitat requirements (i.e., bedding sites or drumming logs) may be found only within certain slope limits (Cook 1966, Boag and Sumanik 1969, Shannon et al. 1975, Strong and Vriend 1979, Oosenbrug and Theberge, 1980, Gionfriddo and Krausman 1986). Limiting angles have been used in slope stability and landslide studies (Megahan and King 1985, Furbish and Rice 1983), and in landform evaluation and classification (Breimer et al. 1986, Fabos and Caswell 1977). It has been used in forestry, engineering, and recreation, for laying out roads and trails, and planning harvest activities (Hewlett 1982).

Young (1972) considered *true* or *maximum slope* a fundamental measure. It is widely used in landform and landscape analysis (Travis et al. 1975, Tomlin 1986). Harding (1978) considered it fundamental to hydrologic dynamics.

Other than Strahler's 1956 study, little has been written on either *slope sine* or *slope tangent*. Slope sine is proportional to the downslope component of gravitational acceleration (Strahler 1956, Mark 1975a). Slope tangent has been used to calculate potential error in relief estimates derived from gridded data (Mark 1975a). There is not much in the literature to recommend these 2 descriptors. They were selected because they are point or instantaneous measures that require only 1 sample point and are very easily calculated. Because of the apparent limited value of these 2 descriptors, I chose to select an additional descriptor to include in GEODES, main channel slope.

Main channel slope was recommended for use in hydrologic and geomorphic studies (Gregory and Walling 1973, Gardiner, 1975). It has been used successfully to estimate basin slope (requiring less effort to measure than basin slope), and is a better estimate of basin slope than the relief ratio (Kabir and Orsborn 1982, Wetzel and Bettandorf 1986). It has been used to calculate average overland flow, and to estimate streamflow (Horton 1945, Novitzki 1985). This descriptor received a low performance score despite its utility because it requires more inputs and is more difficult to measure than most of the other simple slope descriptors.

Aspect Descriptors

Relatively little research has been conducted to improve quantification of aspect (slope orientation). Despite this, aspect has been an important measure in physical and biological sciences such as forestry, plant ecology, geomorphology, and climatology (Hack and Goodlett 1960, Geiger 1965, Whittaker and Niering 1965, Howard and Mitchell 1985). I chose not to evaluate the few descriptors that I located (Table 4). Tomlin's (1986) Map Analysis Package (with which my descriptor system interfaces) allows easy computation of aspect in azimuthal degrees or in terms of compass orientation. MAP also allows the user to group values into class intervals. To do more than to develop local summaries of aspect would be redundant.

Relief Descriptors

Table 4 lists 22 relief descriptors. Relief descriptors are linear measures of the vertical component of a land surface (Drummond and Dennis 1968). Out of the 22 identified relief descriptors, 2 are statistically based and can be obtained with a commercially available statistical package (e.g., *cumulative relief frequency curve* and the *elevation frequency distribution*). I combined *local relief* and *basin relief* for evaluation purposes. They are essentially the same descriptor at the scale of a small order drainage basin. Of the 19 remaining variables, I selected 8 descriptors with the highest ranked performance scores and chose 2 of the next 4 descriptors to reach the required 50% limit. Based on the scores in Table 7, I could have chosen any combination of the 4 descriptors (*average relief, relief ratio II, relief ratio III,* or *average total relief*). The decision was arbitrary. The top 6 or 8 descriptors appear to be the most useful based on the performance scores under all 3 objective criteria.

Local relief/basin relief I is probably the most widely used relief descriptor. Drummond and Dennis (1968) reported no fewer than 9 different definitions of local relief. In Fig. 7, the comparison of relief descriptors for all 3 weighting methods, local relief had the highest score.

Table 7. Relief descriptors and scaled performance scores

Descriptor	Equal Weights	Weighted	Ranked
1 Local relief/basin relief I	100	100	100
2 Relief ratio I	89	92	92
3 Elevation - relief II	82	84	86
4 Main channel relief	87	80	78
5 Available relief	84	76	74
6 Dissection index	74	72	73
7 Stream relief	82	72	68
8 Mesh relief	79	72	68
9 Average relief	74	67	66
10 Relief ratio II	74	68	66
11 Relief ratio III	74	68	66
12 Average total relief	74	67	66
13 Elevation-relief ratio I	68	64	64
14 Elevation/area ratio	66	60	60
15 Basin relief II	61	58	60
16 Ruggedness ratio/Lewis slope	68	52	58
17 Relief ratio IV	47	47	46
18 Total relief	37	36	37
19 Concavity	24	20	20

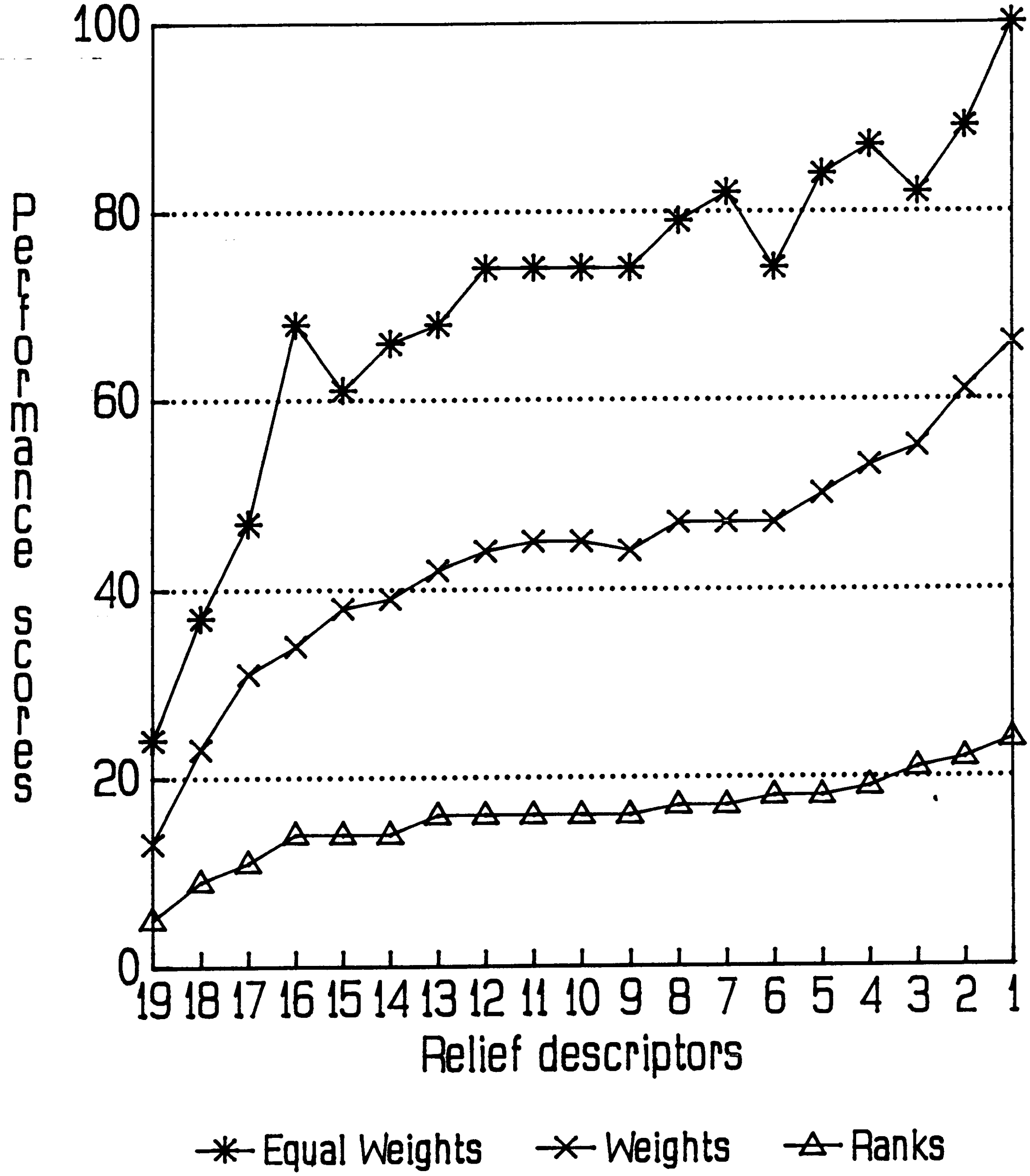


Figure 7. Scaled plots of performance scores of relief descriptors under 3 weighting schemes

There are many instances of its use in the literature. Local relief is easy to measure, calculate, and requires only 2 inputs.

Several researchers reported that local relief was an important variable for determining flood response (Onesti and Miller 1974, Patton and Baker 1976, Abrahams 1984). Patton and Baker (1976) claimed that local relief and drainage density were the most discriminating variables in flood prediction. As basin relief increases, valley slope (gradient) and stream gradient increase, and the time of runoff concentration declines, with a corresponding increase in the flood peak (Patton and Baker, 1976). As such, basin relief may be thought of as influencing sediment discharge (Maxwell 1960, Onesti and Miller 1974). Local relief was highly correlated with drainage density and relief ratio (Abrahams 1984). The correlation with relief ratio is expected, because local relief is part of that descriptor, but the relation to drainage density is not immediately clear. Drainage density is an index to valley spacing or landscape dissection, and so is likely to be more independent of local relief than the relief ratio. Mark (1983) found that basin relief measured from 1:24,000 USGS topographic maps was significantly correlated with field measures of main stream length, total channel length, main stream relief, and total channel relief. Cherkauer (1972) demonstrated that basin relief was 1 of the controlling or predictive factors for channel slope in ephemeral stream systems. Though local relief analysis shows only major differences in relief, it is a practical analysis, because it is easier to prepare than slope maps and relief does differ from locale to locale (Zakrezewska 1967).

Nir (1957) criticized the use of local relief, suggesting that it did not account for the vertical distance from the erosional base. Identical local relief values from different areas may not be of equal importance, because the absolute altitude or base level may differ.

Relief ratio I (Schumm 1956) was the second relief measure selected. This measure is basin or local relief divided by the maximum basin length. This variable has often been used in hydrologic and geomorphologic studies to express basin relief or steepness (Gregory and Walling 1973, Kabir and Orsborn 1982). It is a simple ratio to compute, and often easier to obtain than slope (Strahler 1957, Gardiner 1975). It has been used as a surrogate for local (or basin) slope in hydrologic assessments, because it is closely related to channel and valley-side slopes (Strahler 1957, Ebisemiju 1979, Abrahams 1980). Gardiner (1976) used the relief ratio to estimate average slope in scenery assessment. Gardiner (1982b) warned that values of this measure could be affected by an extreme elevation.

The relief ratio measures the effects of gravity on a drainage system (Ebisemiju 1979). It is an index of the forces affecting infiltration capacity and sediment yield in a basin (Maxwell, 1960, Ebisemiju 1979). Morisawa (1962) reported that this relief ratio was positively (and significantly) correlated with peak discharge and the rainfall-runoff ratio in the Appalachian plateau. In her study, it was 1 of the factors responsible for peak runoff intensity and was independent of the other 2 significant topographic factors. This ratio is highly correlated with drainage density, relative relief, channel slope, and basin or local relief and should not be used in regression analysis with those factors (Gardiner 1975, Abrahams 1984). Park (1978) found that it did not account for any significant allometric variation in streams across regions.

Maxwell's (1960) relief ratio (*relief ratio II*) is a modification of the original relief ratio. It is as useful as the first, and shares the same faults. It differs from relief ratio I in that relief is measured along the length of the drainage basin and then divided by basin length.

The third-highest ranked variable was the *elevation-relief ratio* of Wood and Snell (1960). I evaluated this variable as both a relief and a texture descriptor. Its components are elevational inputs, it quantifies the vertical scale of a feature, and it can be considered a relief descriptor. Yet, it has been mathematically proven to provide a good approximation of the hypsometric integral, an important texture descriptor (Pike and Wilson 1971, Mark 1975a, Gardiner 1981).

The elevation-relief ratio is an easily interpreted index of the distribution of uplands to lowlands (Gardner 1972). As a measure of the distribution of elevation in a drainage basin, it has been used for physiographic classification and for measuring the stage of land surface development (Gardiner 1975, Mark 1975a). It is highly correlated with ground slope (Abrahams 1984). Several authors cautioned against relying on this index alone (Pike and Wilson 1971, Gardner 1972, Beasom et al. 1983).

There was little in the literature about *main channel relief.* The high score may be attributed to the ease of measuring the few necessary inputs (no contour crenulation decision rules are necessary) and the ease of calculation. Gardiner (1975) found it to be an important factor for estimating main channel slope. He considered it comparable to mesh or stream relief for first order streams. In eastern Kentucky, main channel relief was significantly and positively correlated with several other morphometric variables including basin area, stream, mesh, and basin lengths, as well as basin and mesh relief Mark (1983). It was significantly negatively correlated with stream and mesh slope.

Available relief was among the top 7 relief descriptors, because of the mechanics of measuring, calculating, and the limited inputs that are required for this measure. It measures the height of the landscape above the valley floor, that is available for erosion (removal) or dissection by stream channels (Zakrezewska 1967, Drummond and Dennis, 1968, Mark 1975a).

The *dissection index* (Nir 1957) is a relief measure that incorporates an "absolute altitude" or base level. Zakrezewska (1967) saw it as an improvement over local relief. It is an expression of the sharpness of relief. Both Nir (1957) and Zakrezewska (1967) have suggested using the dissection index to classify or define regions. They saw this index as a quantitative alternative to phrases like "high mountains". The inputs are few and easily measured, the calculation is not difficult.

The next 2 descriptors selected were *mesh* and *stream relief.* Mark (1983) found that mesh relief, the difference in elevation from a stream outlet to its mesh source was significantly correlated with both main channel and total relief. Stream relief is more easily measured than mesh relief if the streams are not first order or exterior links. In a comparison of map to field analyses, Mark (1983) did not find any significant correlation between stream relief and field-measured variables. I found little in the literature to justify using either measure. Both indices ranked in the top 50% because they were easily calculated, and required only 2 inputs. However, there is subjectivity involved in locating the mesh source.

Morisawa (1962) used *average relief* in studies of basin relief in the Appalachian plateau. Chorley and Morgan (1962) used average relief to compare granitic mountains of Dartmoor, England and North Carolina. Like the other relief descriptors I have discussed, the necessary inputs are few, easily measured, and the descriptor is easily calculated.

Length and Linear Descriptors

I identified 24 descriptors of length or linearity that were associated with slopes, streams, or drainage basins. I excluded 2 features of profile analysis, elements and segments, they may be better left for a comprehensive effort aimed at classifying land surface features. I chose the top 11 linear descriptors for GEODES (Table 8).

The deviations from linearity in the unweighted curve (Fig. 8) are because of 2 descriptors, *basin length III* and *stream-length ratios*. Basin length III requires locating an axis that originates at the outlet, ends on the perimeter, and divides the basin into 2 equal areas. Stream-length ratios require a considerable number of inputs.

The linear measure with the highest score was *channel (stream) length*. Mueller (1979) considered channel length a fundamental property of fluvially eroded landscapes. Once the upstream extent of a channel has been located, the measurements and calculations are simple. Channel length has been used extensively by geographers, geologists, and hydrologists studying river profiles, network and channel geometry, and regional texture (Mueller 1979). Channel length is related to stream flow and stream slope (Morisawa 1962, Ruhe 1975). It is an expression of the water budget of a basin, because streams adjust their lengths over a range of sediment and discharge conditions (Blyth and Rodda 1973, Mueller 1979). Channel length is one of the factors determining water travel time in a drainage basin (Dingman 1979). Naiman et al. (1987) used it in the ecological characterization of streams.

Gardiner (1975) reported that channel length was correlated with drainage area, perimeter, and main channel length. Channel length distributions were normalized with log transformations (Maxwell 1960, Gardiner 1975). Maxwell (1960) used the lengths of first order

Table 8. Length descriptors and scaled performance scores

Descriptor	Equal Weights	Weighted	Ranked
1 Channel length	100	100	100
2 Total stream length	95	95	94
3 River sinuosity	80	79	78
4 Basin perimeter	83	76	74
5 Main channel length	83	76	74
6 Basin length II	75	72	70
7 Basin length I	75	70	68
8 Slope length	70	65	64
9 Mesh length	70	64	62
10 Length of overland flow	63	56	54
11 Hydraulic sinuosity	58	55	53
12 Stream-length ratio	50	49	49
13 Percent total stream length	60	50	48
14 Mean stream length	58	49	46
15 Basin length III	43	43	43
16 Relative perimeter	55	45	42
17 Mean slope of water divide	55	45	42
18 Basin diameter	48	41	41
19 Total channel length	48	41	39
20 Basin width	45	39	37
21 Mean height of water divide	50	40	36
22 Average length of overland flow	20	16	15

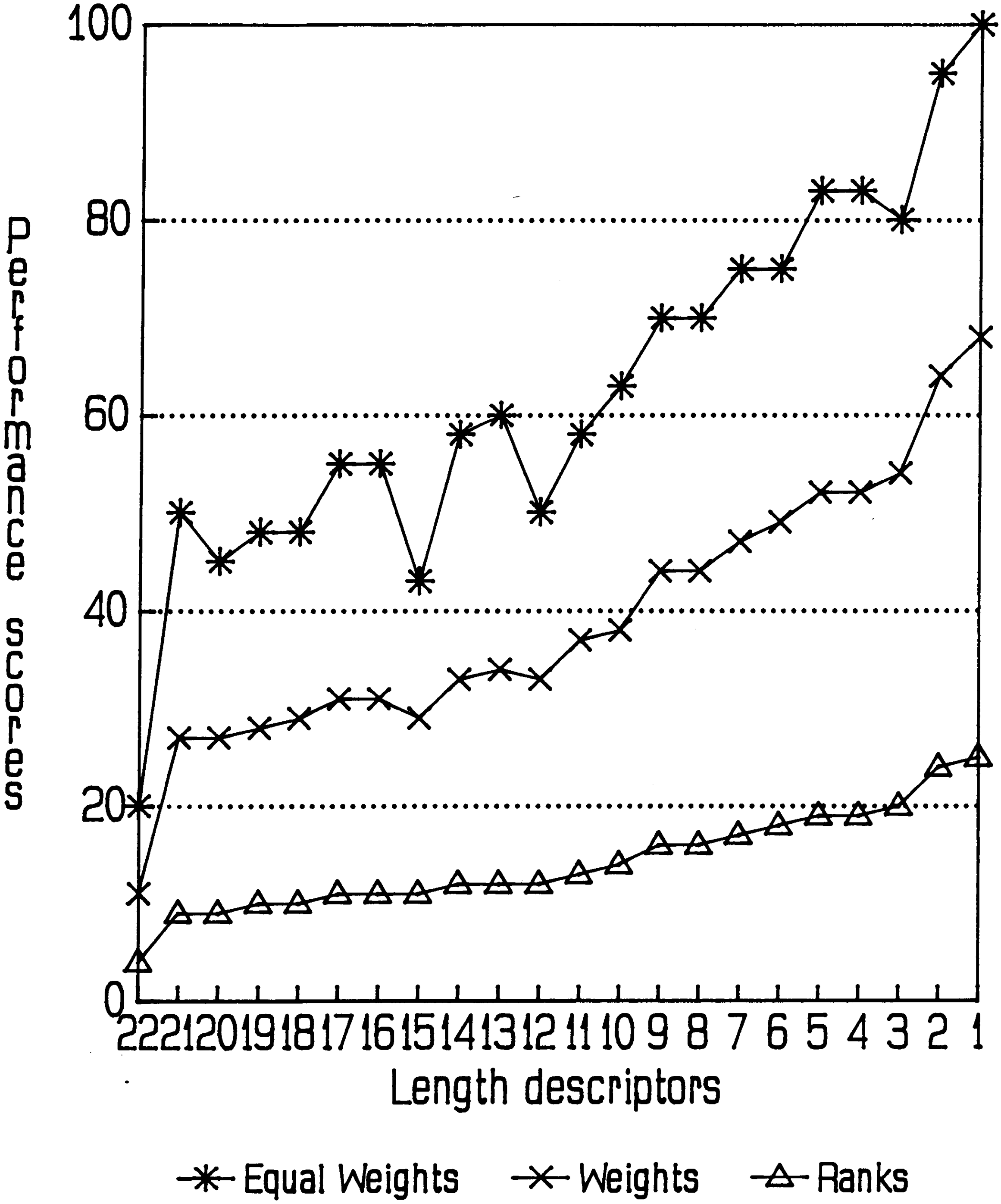


Figure 8. Scaled plots of performance scores of linear descriptors under 3 weighting schemes

channels to separate fourth-order watersheds. This variable has been incorporated into a variety of other indices.

Total stream length (cumulative length) is a necessary variable for calculating drainage density, length of overland flow, texture ratios, etc. It is a dynamic measure that changes with time, precipitation, and antecedent conditions (Blyth and Rodda 1973, Gregory and Gardiner 1975). It is related to the total precipitation that becomes streamflow, and is affected by soil type, geology, and basin storage (Kabir and Orsborn 1982). Total stream length exercises partial control over discharge and sediment yield (Lustig 1965, Ebisemiju 1979). Gregory and Gardiner (1975) used regression analysis of total stream length and basin area to characterize global regions in terms of mean precipitation. Total stream length was strongly correlated with basin area and main stream length (Ebisemiju 1979). It is a straightforward variable to measure and calculate, and the inputs needed are minimal. However, rules must be established for deciding what constitutes a stream source. This remains an unresolved and fundamental criterion for the use of this and other variables that depend on the location of the stream source.

Two measures of sinuosity were in the top half of the performance scores. Sinuosity is an important measure of channel pattern, reflecting stream debris load, stream discharge, energy relations, the homogeneity of the material a channel dissects, and the jointing or folding of the regolith (Gregory and Walling 1973, Welch 1978).

River sinuosity is a measure of channel adjustment to discharge and to sediment load (Leopold and Langbein 1966). Changes in runoff and sediment yield in a watershed affect both channel length and sinuosity (Mueller 1979). Rivers with uniform rates of discharge and large suspended sediment loads tend to be more sinuous than streams that carry a large coarse bedload and are subject to flashy flows (Mueller 1979, Knighton 1984). Increases in river sinuosity decrease average stream slope and stream power per unit length of channel (Beschta and Platts 1986). Onesti and Miller (1974) reported that sinuosity was significant in explaining variance in stream discharge (though it was less significant than slope or area).

Sinuosity was not significantly associated with other variables that explained variance in discharge.

Meanders are 1 form of stream slope adjustment, reducing stream gradient relative to the straight distance between 2 points by increasing channel length (Knighton 1984). Meanders have been defined as reaches with river sinuosity values greater than 1.5 (Ruhe 1975). Without other channel adjustments, high sinuosity values may reflect the presence of steep valley slopes (Knighton 1984). River sinuosity has been used for gross comparisons of aquatic habitat between streams or for reaches within a stream (Platts et al. 1983). It is easily calculated, requiring a few easily measured inputs, depending on where and how the endpoints are defined.

Hydraulic sinuosity may reflect the lithologic structure of a basin (Gregory and Walling 1973). Singh and Upadhyaya (1982) considered hydraulic sinuosity a significant tool for determining the stage of development of a basin, and for detecting factors that controlled river sinuosity. It is easily calculated, but Gregory and Walling (1973) warned that it may be difficult to separate the inputs of valley length and stream length.

Basin perimeter is a recommended morphometric measure that is often used in quantifying basin shape. It can be difficult to delimit a perimeter precisely on a map or in the field (Gardiner 1975, Gardiner, 1982b). However, it can be used to approximate planimetric area (Gardiner 1982b). Log transformations have resulted in normal distributions of basin perimeters in a region (Maxwell 1960, Gardiner 1973). It is a component of many texture and shape descriptors such as relief, circularity, and lemniscate ratios.

In a regional Indian study, basin perimeter was a significant variable in estimating the size, shape, and genetic aspects of basins (Singh and Upadhyaya 1982). In some studies, perimeter was strongly and positively correlated with basin area and basin length (Gardiner 1975, Singh and Upadhyaya 1982). Basin perimeter was a highly significant variable for explaining regional variation in channel form (Park 1978).

Main channel length is a highly recommended variable (Gardiner 1975). It is easier to measure from maps than channel length, because contour crenulation and other techniques for correcting for cartographic generalization are not necessary. It is positively correlated with basin area, perimeter, channel and basin length and negatively correlated with both main and channel slopes (Gardiner 1983, Mark 1983). It was used in regression analysis to estimate streamflow characteristics (Morisawa, 1962, Novitzki 1985, Wetzel and Bettandorf 1986). Potter (1953) found that peak flow was positively correlated with main channel length and developed a time factor (T-Factor) that incorporated main channel length. Park (1978) reported that it was significant in explaining channel form variations between regions.

There are many different formulations of drainage basin length. Gardiner (1975) considered it a necessary morphometric variable, and reported 10 different versions of it. In evaluating basin length, I considered 3 different versions of basin length (Table 4). Two were selected for inclusion in the descriptor system (*basin length I - II*). The best way to measure basin length has been disputed, but the consensus is that it is an important variable. Basin length affected concentration of runoff and was significant in explaining variations in channel form (Park 1978, Kabir and Orsborn 1982). All of these basin length measures are strongly correlated with channel length, basin area, perimeter, main channel length, and the number of first order streams in a basin (Gardiner 1975). Basin length is used to calculate hydraulic sinuosity, relief ratio II, shape factor, delta, the lemniscate k, and rotundity.

The best measure of basin length based on performance scores is *basin length II*. It is the longest axis in the basin from the outlet to the divide (Gregory and Walling 1973). Basin length II was used to characterize basins, especially in indices such as the relief ratios (Ruhe 1975, Gardiner 1981). Basin length may be hard to quantify when the drainage basin is elongated perpendicular to the basin mouth (Morisawa 1958). *Basin length I* is the stream length from the outlet to the highest point on the divide. It was incorporated in shape descriptors called form factors. *Basin length III* is more appealing theoretically and is a more precise descriptor than the other 2 measures of basin length (basin length I and II). It is also more difficult to calculate (Gardiner 1975). It is the axis from the basin mouth that divides the basin into 2 equal-sized areas.

Slope length has a broad range of applications. It is easily measured, and calculated. Gradient changes over a slope length affect vegetative and hydrologic properties of a site (Ruhe 1975). It is important in modeling overland flow, and a necessary parameter in the universal soil loss equation (Wishmeier and Smith 1965, Verstappen 1983, Megahan and King 1985). Munn and Vimmerstedt (1980) used this variable to predict site index. Gysel and Lyon (1980) reported important ecological effects due to slope length.

Mesh length was first used by Horton (1945). It is an accepted measure in North America, though it may overestimate true channel length and incorporate paleohydrological forms (Gardiner 1975, Mark 1983). In a field study in eastern Kentucky, Mark (1983) found that mesh length was a better predictor of true stream length than either map or contour crenulated lengths. Mesh length was positively and significantly correlated with field-measured main and total channel lengths and reliefs. It was also significant and negatively correlated with field-measured main and average slope. It is used in 1 formulation of the relief ratio.

The last linear descriptor selected is *length of overland flow*. This may be a questionable selection. Horton (1945) called it one of the most important independent variables in hydrologic and physiographic basin development. In fact, it is highly correlated with drainage density. Furthermore, the concept of Hortonian overland flow is much more limited in the scope of its application then when Horton envisioned it (Knighton 1984). Carlston (1963) showed that overland flow was primarily responsible for the lag time from precipitation to flood peak for basins of approximately 195-260 square kilometers (75-100 square miles) in area. Gardiner (1973) could not normalize distributions of this variable with any of 4 standard transformations.

Area Descriptors

Basin or drainage area is a basic topographic feature and a prerequisite for many texture and shape descriptors. Basin area is of hydrologic importance, particularly for base streamflow and peak discharge because it establishes a catchment size for precipitation (Strahler 1957, Morisawa 1962, Onesti and Miller 1974, Patton and Baker 1976, Paustian et al. 1984). Generally, as basin area increases, peak flows increase (Knighton, 1984). It is one of the most significant variables for explaining variance in sediment transport and yield (Strahler 1957, Lustig 1965, Gardiner 1982b). Anderson (1957) considered basin area as "the devil's own variable", because many morphometric variables such as channel length, perimeter, basin length, main channel length, main channel and total relief, main channel and total channel slope are significantly correlated with it (Gardiner 1975, Ebisemiju 1979, Mark 1983). It is not clear from the literature whether planimetric area or an estimate of surface drainage area was used.

I identified and evaluated 7 areal descriptors. I included the 4 descriptors with the highest weighted or ranked scores in GEODES (Table 9). For all 3 curves in Fig. 9, *planimetric area* was the highest scoring variable. Gardiner (1982b) noted that planimetric area is often used for scaling purposes. This variable is significantly correlated with bankful discharge and has been used to predict streamflow and flood peak discharge (Maxwell 1960, Patton and Baker, 1976, Knighton 1984, Novitzki 1985). Gottschalk (1957) used planimetric area to estimate stream sediment load and yield.

Surface drainage area is often calculated by applying mean slope to planimetric area. Zavoianu (1985) maintained that it was a significant factor when studying small, rugged areas. Doornkamp and King (1971) suggested that this variable could be used to correct for error when comparing basins with steep slopes to basins with more gentle slopes. Lustig (1965) reported that surface drainage area correlated well with basin sediment yield.

The *constant of channel maintenance I* (Schumm 1956) is approximated by the reciprocal of drainage density. This measure suggests that for a given set of environmental conditions, there is a minimal area required for channel initiation (Strahler 1957, Knighton, 1984). As the inverse of drainage density, it may suggest the relative size of landforms in a basin (Strahler 1957 1964). This was one of the few indices that was not significantly correlated with basin shape, so it could be used for regional regression analyses (Ebisemiju 1979). The constant of

Table 9. Area descriptors and scaled performance scores

Descriptor	Equal Weights	Weighted	Ranked
1 Planimetric area	100	100	100
2 Surface area	68	66	66
3 Constant of channel maintenance I	68	63	62
4 Drainage area ratio	74	64	61
5 Area-length association	61	55	54
6 Constant of channel maintenance II	68	55	50
7 Drainage area/stream order	26	23	22

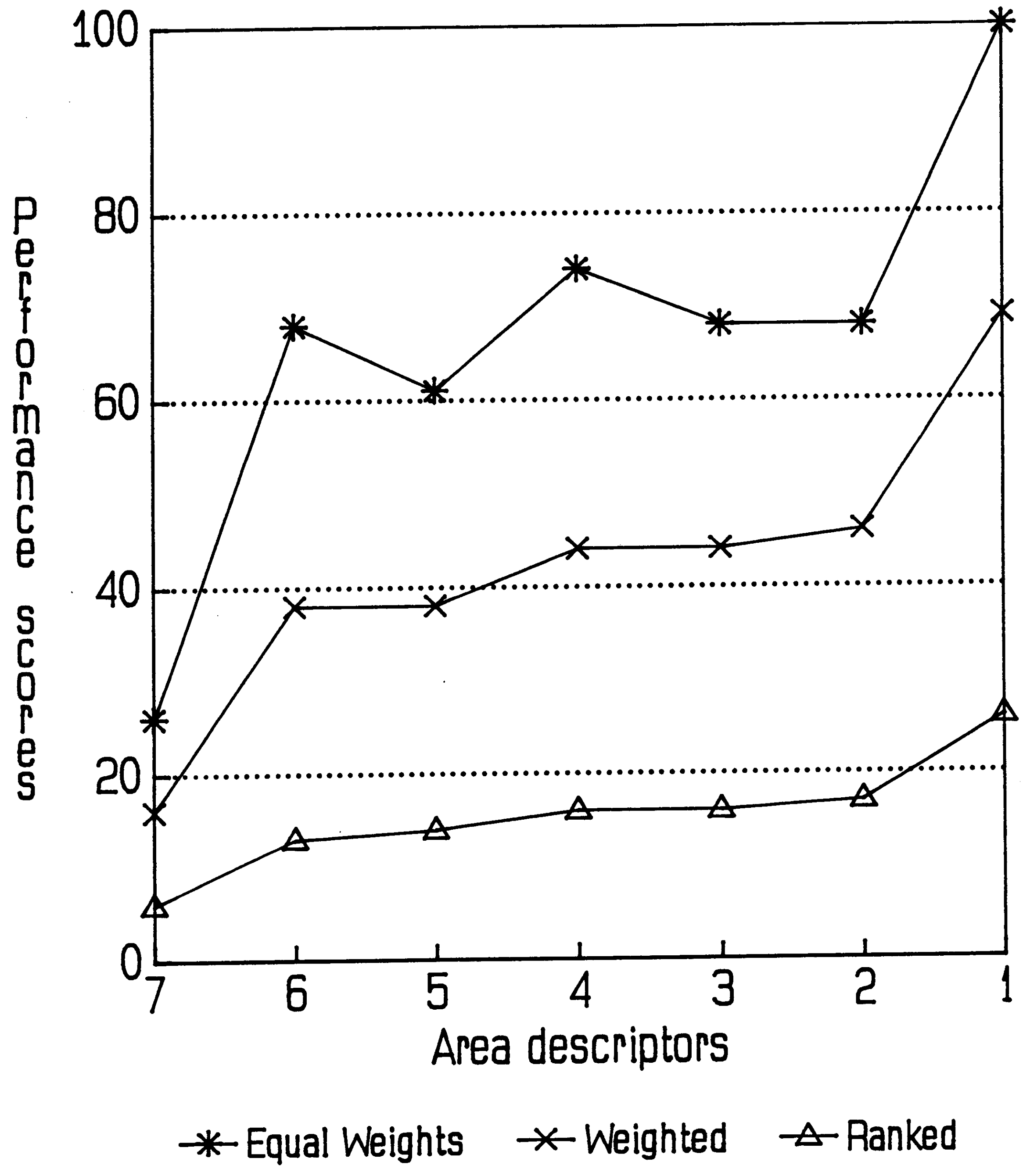


Figure 9. Scaled plots of performance scores of areal descriptors under 3 weighting schemes

channel maintenance is no more difficult to calculate than many of the other areal descriptors, but the inputs required are total channel length and basin area. Determining those inputs requires decisions on channel extent and basin slope.

The *drainage area ratio* is essentially a comparison of areas for different stream orders. This ratio is one of Schumm's (1956) additions to Horton's (1945) laws of basin composition, and was widely used to compare basins from different regions (Chorley and Morgan 1962, Morisawa 1962, Scheidegger 1968, Rodriguez-Iturbe and Valdes 1979, Valdes et al. 1979). Knighton (1984) suggested that the narrow range of values for this easily measured index are due either to an underlying regularity in basin composition, or a lack of sensitivity by its components.

Texture and Roughness Descriptors

Roughness refers to the irregularity of a topographic surface, while texture refers to the shortest significant wavelength of terrain roughness (Mark 1975a). This body of descriptors measures horizontal variations in topography. Many of these descriptors have not been fully explored in the literature. Several wildlife scientists have referred to the importance of ruggedness as a habitat characteristic and its role in habitat partitioning (Leslie and Douglas 1979, Geist and Petrocz 1977, Beasom et al. 1983).

Table 4 lists 19 texture and roughness descriptors that range from simple indices such as surface/planar area, to moment measures of profile and plan convexity distributions, to sophisticated and computationally demanding measures such as fourier or spectral analysis of elevation. I did not evaluate the 2 statistical measures of roughness. Two other descriptors (*depression density* and *mean solution depression density*) were not evaluated because they apply specifically to karst topography (Gardner 1972).

In Fig. 10, the deviations from linearity in the curve of equally weighted criteria is corrected in the other 2 curves by the greater emphasis on the literature value of these indices and a reduced emphasis on index calculation. From the 15 remaining texture descriptors, I selected 7 for inclusion in the terrain descriptor system (Table 10). The first 6 of those descriptors had the highest scores under all 3 weighting schemes. The seventh position could have been filled by either *cell length* or the *hypsometric integral*, however, *cell length* scored higher under the weighted and unweighted schemes than the *hypsometric integral*.

The first descriptor, *elevation-relief ratio II* (Wood and Snell 1960) was included because it has been used effectively as a substitute for another texture descriptor, the *hypsometric integral*. The hypsometric integral has been widely used for the physiographic classification of areas, calculation of basin volume, and measuring the degree of dissection of a landscape (Clarke 1966, Aronovici 1966, Mark 1975a). The hypsometric integral expresses the distribution of elevation in a basin and is not correlated with basin slope (Aronovici 1966, Gardiner 1975). It is time consuming to measure and to calculate (Pike and Wilson 1971, Gardiner 1975, Mark 1975a). Use of this elevation-relief ratio may obviate the need to incorporate the hypsometric integral in GEODES.

The elevation-relief ratio is a measure that applies to basins and arbitrarily bounded regions (Mark 1975a). It is probably the most useful, easily interpreted, and calculated index of uplands to lowlands (Gardner,1972, Gardiner,1981). Mathematically, it is identical to the hypsometric integral (Pike and Wilson 1971). Several researchers cautioned against using this descriptor by itself in analyses, because identical values may be obtained from dissimilar terrain (Pike and Wilson 1971, Gardner 1972, Gardiner 1981).

Ruggedness number was the next highest scoring descriptor. Zakrezewska (1967) noted that this descriptor combined relief, texture, and slope, and provided a precise measure of terrain texture. Later authors suggested that the ruggedness number summarized the interaction of relief and drainage density, combining an estimate of slope and proximity to water in a way that is useful in landscape assessment (Gardiner 1976, Patton and Baker 1976). It has been useful in regression analysis of mean and record floods, and may be valuable in identifying flash flood areas (Patton and Baker, 1976). Melton (1958a) believed that it provides information on the diastrophic history of a basin.

Table 10. Texture and roughness descriptors and scaled performance scores

Descriptor	Equal Weights	Weighted	Ranked
1 Elevation-relief II	100	100	100
2 Ruggedness number	85	90	90
3 Structural similarity	97	88	86
4 Avoidance factor	85	78	76
5 Surface/planar area	85	74	71
6 Valley spacing	79	69	67
7 Cell length	70	59	57
8 Hypsometric integral	58	57	57
9 Total terrain roughness	73	61	56
10 Composite terrain	70	56	51
11 Roughness index	55	49	48
12 Concavity index	55	46	43
13 Spectral analysis	52	44	42
14 Fourier analysis	52	44	42
15 Surface roughness	33	33	33

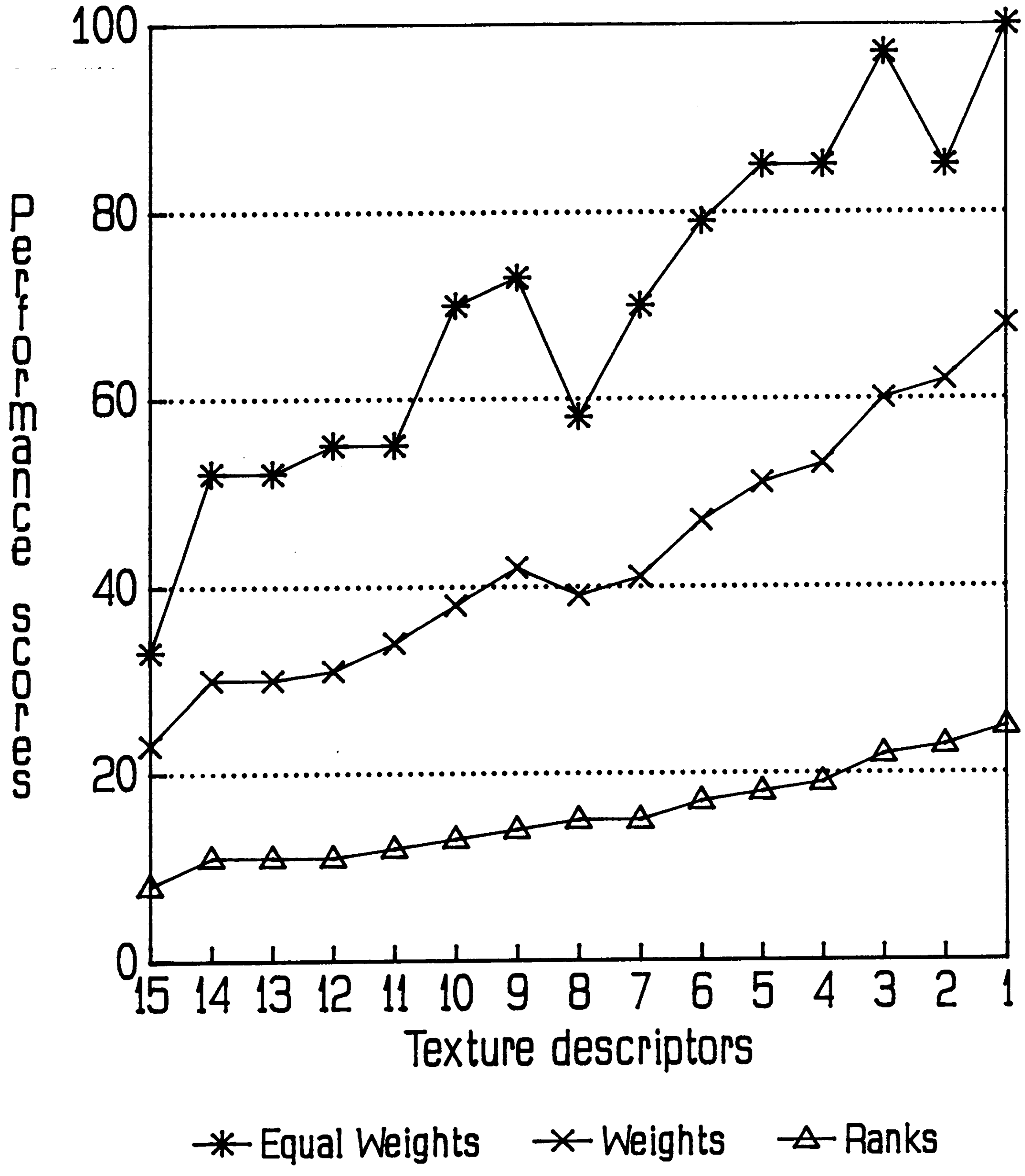


Figure 10. Scaled plots of performance scores of texture and roughness descriptors under 3 weighting schemes

In some studies, the ruggedness number was correlated with mean slope and maximum valley-side slope (Melton 1958a, Mark 1975a). It requires more complicated inputs (relief and drainage density) than some other texture descriptors, but those inputs are preferred measures from other descriptor groups. The utility of this measure may be limited, because a given value does not necessarily correspond to a unique textural region (Gregory and Walling 1973). Beasom et al. (1983) remarked that it failed to quantify uniquely the different conditions that make up rugged terrain. Gardiner (1973) was unable to normalize the distribution of this variable with any of 4 standard transformations. This variable did not account for any significant variation in allometric growth of streams in England (Park 1978).

Structural similarity is part of a battery of indices developed by Stone and Dugundi (1965) to quantify microrelief and microsurface roughness for the US Army. It indicates the tendency of relief features to be repeated in an area. I have not found other instances of its use in the literature, though it is an easy variable to calculate and requires only 2 easily measured inputs.

The *avoidance factor* was developed by Stone and Dugundi (1965) to quantify overall irregularity in terrain. Mitchell (1973) considered it a measure of the difficulty in travelling across a landscape, and thought it was inversely related to traversability. Stone and Dugundi (1965) believed it was the most informative and useful index they had developed. It is a simple index to calculate, but, I found no additional reports of its use.

Surface-planar area compares the surface area of a region to the planar area (Hobson 1972). It is based on the premise that surface area increases with terrain irregularity. Zavoianu (1985) considered it a general estimate of terrain texture. This index was correlated with surface geology (Hobson 1972). Small differences between areas have been used to distinguish rock types. Hobson (1972) recommended that this index be used with other roughness parameters.

Zakrezewska (1967) believed that *valley spacing* was applicable only to fluvial topography. Evans (1972) thought this variable might be an objective measure of surface texture. He questioned whether it was sufficient to characterize texture. Like many of the selected texture descriptors, it is a simple one to generate.

The last texture descriptor is *cell length* (Stone and Dugundi 1965). This descriptor was designed to measure the interval in which all "significant" features of a landscape were found. Where terrain is repetitious, its value is small. Like the other descriptors of Stone and Dugundi, I could not find other instances of its use.

Stream Ordering Systems

Drainage network composition is an important part of terrain pattern analysis, and a stream ordering system is the conceptual starting point. Ordering or separating basins hierarchically into orders, exterior and interior links, tributary sources, etc., has proven useful in studying biotic and abiotic processes within a basin, between basins, and across regions. Many ordering methods have been proposed. Many methods, e.g., Strahler (1952), Graf (1975), or Smart (1978), are modifications of or alternatives to systems that were already in use. I selected the 4 most prevalent ordering methods to evaluate: Strahler's (1952) alteration of Horton's (1945) system, Shreve's (1966) link magnitude system (as modified by Smart (1968 1978)); Scheidegger's (1966) system; and Graf's (1975) cumulative ordering system. Two systems were not chosen, Scheidegger's (1966), and Graf's (1975). Scheideggers's was rejected because it requires the use of non-integers and is difficult to use (Gardiner 1975, Dunkerly, 1977). Graf's system is hard to use with very large or intensely bifurcated basins. Some authors have maintained that functionally it is not very different from Shreve's (1966) system, and to date, not much has been published on it (Dunkerly 1977, Graf 1975).

I chose to concentrate on Strahler's ordering system, because it is most widely used outside the fields of geomorphology, geology, and hydrology. It is objective in application and completely hierarchical (Gardiner 1975). The organization of the data is simplistic. All basins of a specified order greater than 1 contain basins of lower orders up to the specified order.

Stream order is a description of the geographical position of a stream in the network (Onesti and Miller, 1974). This easily applied system is a rough index of basin dimensions, network discharge, and lithologic influence on a given stream (Strahler 1957, Gregory and Walling 1973, Onesti and Miller 1974, Patton and Baker 1976, Park 1978, Knighton 1984). It has been used to compare basins of different scale (but same order) and basins in different regions (Strahler 1957, Morisawa 1958 1962).

Recent ordering systems have sought to correct several problems with Strahler's ordering system. This system violates the associative and distributive laws of algebra (Smart, 1968, Knighton 1984). Lower order streams may enter higher order streams and increase the main stem flow, while stream order remains unchanged. As a result, order may be a poor measure of discharge (Graf 1975). The sequence that a given number of streams join affects mainstream order, while the volume of mainstream flow is unaffected. Werrity (1972) believed that this system is insensitive to lithology and structure.

Despite these identified problems, Strahler's ordering system is widely used in the biological sciences. Platts and others (1983) called it "a useful indicator of the physical and biological characteristics of a stream, providing general information on the species present, standing crop, and channel substrate". It has been used to predict fish and aquatic invertebrate population richness, species composition, and abundance (Platts 1979, Minshall et al. 1985, Naiman et al. 1987). Naiman et al. (1986) considered it an important variable in describing beaver habitat use. Trends in the ecological processes of primary production, respiration, and carbon cycling have been related to changes in Strahler stream order (Naiman et al. 1987). Water quality parameters (DO, pH, total alkalinity, and temperature) have correlated well with stream order (Jones 1978, Winger et al. 1987).

Shreve (1966) and Smart's model of network composition is based on the probabilistic-topologic approach, in which the Strahler stream segment is replaced by the link (an unbroken length of channel between successive nodes). This system has not been included in the descriptor system prototype because the data set used for development of GEODES consists of exterior links (Strahler order 1) and interior links of magnitude of less than 5 (Strahler order 2) and is too simple for an effective contrast with Strahler's system. Further development of GEODES would be required to accomodate fully the topologically distinct channel network system of Shreve and Smart. Their model resolved the violations of the laws of association and distribution by Strahler's ordering system. Their link magnitude system accounts for all exterior links in ordering a network, so that stream magnitude suggests the size of the drainage area (Smart 1968, Gardiner 1975, Abrahams 1984). This system is effective in a variety of lithologic, structural, and climatic regions and is more descriptive of the network's total discharge than Strahler's system (Werrity 1972, Gregory and Walling 1973). It has been used to predict the distribution and values of bifurcation, length, area ratios, and to predict previously empirical relations between stream frequency and drainage density (Smart 1968, Shreve 1975, Abrahams 1984).

The principal criticisms of this system are that it requires advanced mathematics, it does not account for overland flow to interior links, and that an ordered system may not necessarily be ordered in a stepwise, sequential manner (i.e., a 10-magnitude basin may or may not contain a 6-magnitude basin) (Gardiner 1975, Graf 1975, Shreve, 1975). Many attributes of link drainage networks such as link drainage areas, link slopes, and their relation to hydrologic processes remain to be explored (Knighton 1984). I have not found evidence of this system in use outside the fields of geology, geomorphology, or hydrology.

Four additional descriptors related to stream order were not evaluated. Two of them, *number of streams/area* and *number of streams/order/area* are components of other descriptors. The *bifurcation ratio* has been used in both Strahler and Shreve ordering systems to characterize networks, and to suggest the extent of dissection and may influence discharge efficiency (Strahler 1964, Gardiner 1975, Jones 1978, Ebisemiju 1979). Others have suggested that it has limited value (Gardiner 1982b, Knighton, 1984). *Conservancy of a drainage* is a measure that applies only to the Strahler ordering system, but may suggest the extent of dissection in that system.

Descriptors of Network Development

Ten measures of drainage network development were evaluated. I selected the top 5 for GEODES (Table 11). The curve of equally weighted criteria in Fig. 11 is relatively linear, though there are dips. These dips correspond to drainage density and relative density, and reflect the effort needed to measure the necessary inputs. Drainage density requires area and total stream length, a task that depends on locating stream sources. Relative density requires both drainage density and stream frequency as inputs.

Drainage density was the highest scoring network development descriptor. It is probably the most important descriptor of drainage network development. It is a common measure of network extent, easily comprehended, and simple to use. Several researchers recommended this measure for geomorphometric studies (Gregory and Walling 1973, Gardiner, 1975, Ebisemiju 1979, Gardiner 1982b). It is an expression of terrain dissection, the linear scale of landforms, and a component of many other indices (length of overland flow, valley spacing, relative density, etc.) (Gardiner 1975, Abrahams 1984). Caution should be exercised when using this descriptor in a morphometric study, because of the high correlation with basin relief, relief ratio, length of overland flow and other descriptors (Gardiner 1975, Patton and Baker 1976, Abrahams 1984). Values for this ratio depend on the map scale used (or aerial photo resolution), and on channel and perimeter definition (Gregory and Walling 1973, Mark 1975, Allen 1986). It is not correlated with stream order (Gardiner 1973, Gregory and Walling 1973).

Drainage density is a sensitive measure, providing a link between basin form and process, and reflecting temporal, topographic, lithologic, climatic, and vegetational forces, as well as human influence (Blyth and Rodda 1973, Gregory and Walling 1973, Gregory and Gardiner 1975, Abrahams 1984, Knighton 1984). So, it is likely to vary considerably from basin to basin (Abrahams 1980). Ebisemiju (1979) suggested that it might be the most important parameter affecting hydrologic response. Drainage density correlates with precipitation intensity and mean annual precipitation when adjusted to a given basin size (Mark 1975a,

Table 11. Drainage network extent descriptors and scaled performance scores

Descriptor	Equal Weights	Weighted	Ranked
1 Drainage density	93	100	100
2 Stream frequency	100	92	88
3 Microscopic link density	100	86	81
4 Channel length/basin perimeter	97	81	75
5 Relative density	80	77	74
6 Density of perennial drainages	87	73	68
7 Density of seasonal drainages	87	73	68
8 Density of temporary drainages	80	66	60
9 Langbein index	73	59	52
10 Macroscopic link density	60	54	51

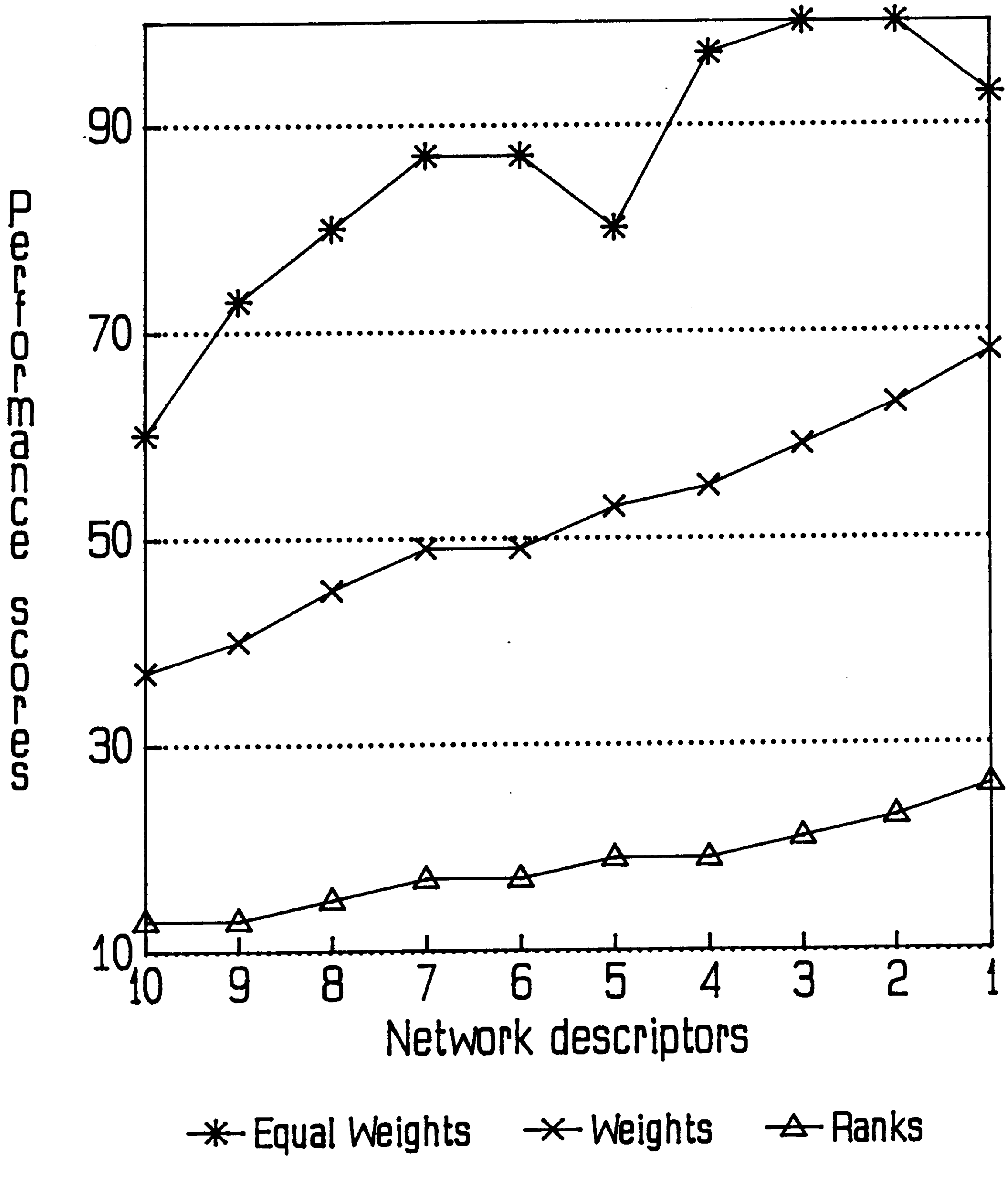


Figure 11. Scaled plots of performance scores of drainage network descriptors under 3 weighting schemes

Patton and Baker 1976, Gardiner, 1982a). It measures the efficiency of a basin in removing excess precipitation and is correlated with runoff, mean stream discharge and sediment yield, flood runoff, and infiltration capacity (Carlston 1963, Gregory and Gardiner 1975, Mark 1975a, Patton and Baker 1976, Abrahams 1984, Allen 1986). Flood runoff varies directly, while infiltration capacity varies inversely with drainage density (Carlston 1963, Patton and Baker 1976). Relief and drainage density are the 2 most distinguishing variables in flood prediction, and drainage density is largely unchanged by relief (Patton and Baker 1976, Abrahams 1984). It may be useful in landscape assessment because it provides some information on the proximity to water and on the dissection of the landscape (Gardiner 1976).

Stream frequency is an easily measured descriptor of network topology that is dependent on stream order and the stream ordering system used (Gregory and Walling 1973, Gardiner 1975, Abrahams 1984). It is a necessary component of relative density, a variable recommended for morphometric analyses by Gardiner (1975). In 4 geomorphometric studies of diverse regions, stream frequency was a significant factor (Gardiner 1975). It reflects network composition and has hydrologic value. More streams per unit area suggest that water is discharged from a basin more rapidly than in comparably sized basins with lower frequencies (Morisawa 1962). Frequency of first-order streams was one of the most significant topographic factors involved in peak runoff intensity in the Appalachian Plateau (Morisawa 1962). Care should be exercised when working with stream frequency and drainage density because they are significantly correlated (Patton and Baker 1976, Gardiner 1981).

Microscopic link density is the link analog of drainage density. It provides similar information as drainage density, but does not vary as widely from basin to basin (Abrahams 1980). It does influence the efficiency of network discharge (Ebisemiju 1979). Ground slope has some effect on microscopic link density in fluvial landscapes, but there is not a significant within-area correlation unless widespread overland flow occurs (Abrahams 1984). Knighton (1984) concluded that the significance of this variable has yet to be realized.

Channel length/basin perimeter was selected because it is easily measured and calculated. Melton (1958a) stated that it was a dimensionless measure of channel network development. Maxwell (1960) called the measure ambiguous because it is influenced by perimeter crenulations. I suspect that the value of the measure may lie with the fact that it does incorporate perimeter crenulations. That quality could make it a useful measure of the extent of drainage network development.

Relative density is a dimensionless measure of how completely drainages fill a basin outline for a given number of stream segments, and an indicator of basin maturity (Melton 1958a, Melton 1958b, Abrahams, 1984). This variable varies inversely with basin relief, ruggedness number, and valley-side slope (Abrahams 1984). It is correlated with any descriptor that incorporates drainage density, or stream frequency. It is also correlated with the hypsometric integral (Gardiner 1975, Abrahams 1984). According to Melton (1958a), it is independent of basin shape. He suggests that its value is in comparing basins with geometrically similar perimeters and networks. In areas with comparable drainage densities, basins with high relative densities have large valley heads or valley-side slopes (Church and Mark 1980, Abrahams 1984). Gardiner (1973) could not normalize distributions of this variable for first- or second-order streams.

Basin Shape Descriptors

Basin shape is an important characteristic in hydrology and geomorphology. Basin shape affects water concentration and flow by influencing the timing and intensity of runoff and discharge (Powell and Potter, 1953, Morisawa 1958, 1962, Knighton 1984). Basin shape indices have been used to predict flow intensity where hydrologic data are scarce (Verstappen 1983).

The shape indices I evaluated fit into 4 general classes:

1. Indices that use perimeter and area to quantify shape. This includes the various circularity and compactness indices. Austin (1984) noted that these are scale dependent measures and are sensitive to boundary irregularities.

2. Indices based on linear and areal measures such as the form factors, and rotundity. Most of the shape descriptors are in this group.
3. Lemniscate measures or measures incorporating area, length, and perimeter. These measures are scale dependent and sensitive to boundary irregularities (Austin 1984).
4. The final group of shape descriptors range from the relatively simple but difficult to measure radial shape index (Boyce and Clark 1964), to the symmetric difference metric (Lee and Sallee 1970) which is easy to measure, but more difficult to interpret, to the more complex to calculate and interpret fourier analysis of basin radials or the dual axis fourier analysis (Jarvis 1981, Griffith et al. 1986).

For many studies, simple shape indices have sufficed (Woodruff 1964, Gardiner 1975, Singh and Upadhyaya 1982). However, 2-dimensional indices do not reflect 3-dimensional shapes (Jarvis 1981, Griffith et al. 1986). Hobba and Robinson (1972) claimed that planar shape indices are inadequate for hydrologic prediction. The 2 major criticisms of simple shape indices are that they do not permit reconstruction of an object, and they are insensitive to variations in all but the measured dimensions (Hobba and Robinson 1972, Jarvis 1981, Austin 1984). Three-dimensional indices or models have been developed (Hobba and Robinson 1972, Jarvis 1981) but are hard to construct or demand an intensive effort to measure the necessary elements (Griffith et al. 1986). An alternative is to analyze basins with a battery of indices (Gardiner 1975, Griffith et al. 1986).

Through principal components analysis (PCA), the 3 major components of basin shape identified were elongation (represented by both *elongation I* and the *radial shape index*), compactness (represented by the *radial shape index*, *form factor II*, or *circularity I*), and the hourglass or concave component (represented by the *circularity ratio*) (Gardiner 1975, Griffith 1982, Griffith et al. 1986).

I selected the top 13 out of 25 descriptors evaluated (Table 12). All 13 rely on inputs such as area, length, and perimeter, that are much easier to derive from maps or Digital Elevation Models (DEMs) than other indices that require determining the centroid of an irregular shape.

The plots in Fig. 12 show little deviation from linearity. Some authors stress that no single shape descriptor is adequate for measuring basin shape (Griffith 1982, Griffith et al. 1986).

Circularity I (Miller 1953) was the highest scoring shape measure. *Circularity II* (Gravelius 1914) is the reciprocal of circularity I. The major difference is that circularity I was found more often in the literature than circularity II.

Circularity I is a measure of basin compactness (a circle is the most compact 2-dimensional shape) and was an important factor in a principal component analysis of shape variations (Griffith 1982). Both Griffith and others (1986) and Gardiner (1975) recommended using this index with the elongation ratio of Schumm (1956). It has been used to measure shoreline development (Håkanson 1974). It was one of several significant topographic factors in a regression analysis of peak runoff intensity (Morisawa 1958). This index has been used extensively to compare and contrast basins (Morisawa 1958, Sharma and Padmaja 1982, Singh and Upadhyaya 1982). McArthur and Ehrlich (1977) considered circularity and Schumm's elongation ratio to be better measures of basin form than the lemniscate ratio or lemniscate index (lemniscate k). Their findings suggest that this index is not good for distinguishing basins below a regional scale. Using this index, Jarvis (1976) found significant differences between basins of different orders, between regions, and between "formative" (tributaries that converge to create a higher order stream) and "excess" (tributaries that do not affect the mainstream order) basins.

Both circularity I and its reciprocal are very sensitive to perimeter crenulations (Morisawa 1958, Hobba and Robinson 1972, Whittington et al. 1972). These indices do not discriminate between a basin's departure from circularity because of its overall outline, and departures from circularity due to perimeter crenulations (Maxwell 1960). Strahler (1964) and Chorley et al. (1957) rejected this index because basins are not circular by nature, so a circle is not an appropriate shape for comparison. Bosch (1978) criticized the measure because it does not incorporate the basin diameter.

Circularity II has been extensively used outside the fields of hydrology, geology, or geomorphology. It is used in forestry and wildlife habitat management as a measure of habitat

Table 12. Basin shape descriptors and scaled performance scores

Descriptor	Equal Weights	Weighted	Ranked
1 Circularity I	100	100	100
2 Elongation I	97	93	93
3 Lemniscate index	97	90	89
4 Form factor II	97	90	89
5 Shape factor	89	78	76
6 Form factor I	89	78	76
7 Shape index II	89	78	76
8 Circularity II	83	75	73
9 Elongation II	86	74	71
10 Shape index I	86	74	71
11 Ogievsky	86	74	71
12 Circularity ratio	83	72	69
13 Delta	81	69	67
14 Cole's compactness	81	68	64
15 Zavoianu	81	68	64
16 Basin shape index	78	64	60
17 Hexagonality	75	63	60
18 Compactness coefficient I	75	63	60
19 Compactness coefficient II	75	63	60
20 Circularity III	64	59	58
21 Triangularity	72	59	56
22 Symmetric difference	64	55	52
23 Radial shape index	58	50	46
24 Fourier analysis	42	41	40
25 Lemniscate ratio	50	42	40

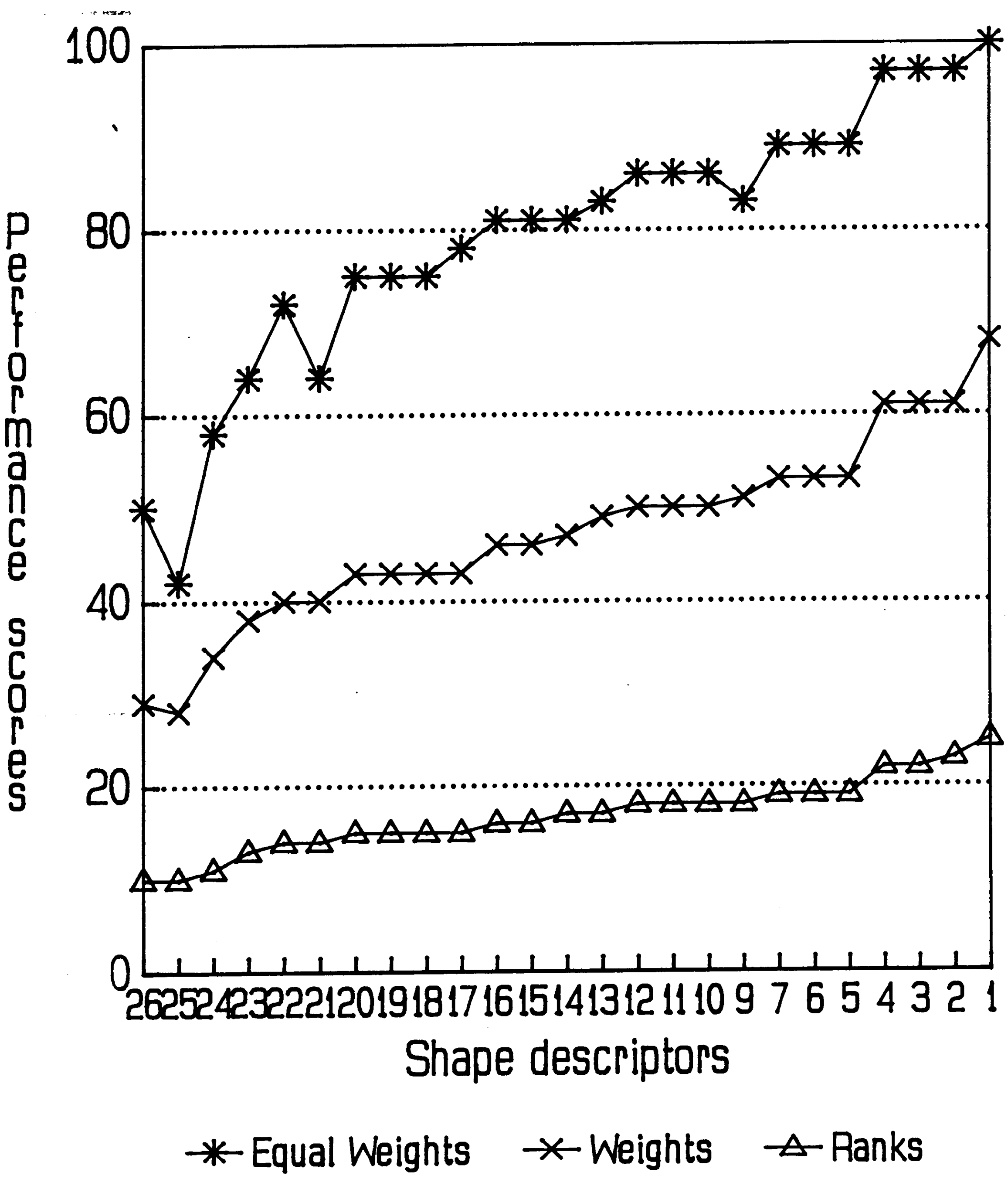


Figure 12. Scaled plots of performance scores of basin shape descriptors under 3 weighting schemes

availability for ecotonal species such as mule deer or elk (Patton 1975, Thomas et al. 1979, Hays et al. 1981). Marcot and Meretsky (1983) modified the measure to relate the amount of edge in an area to the perimeter of an ellipse, which may be more appropriate for species with edge requirements. Habitat shape is one factor that affects immigration rates, and variations in shape may incorporate heterogeneity into reserves or island habitats (Game 1980). It has been suggested that reserves should be as circular as possible to maximize "island" species richness (Diamond and May 1976), but several studies using this index have not borne out this hypothesis (Faeth and Kane 1978, Game 1980, Blouin and Connor 1985).

Two measures of basin elongation were selected, *elongation I* (Schumm 1956) and *elongation II* (Gardiner 1981). Both of these elliptic shape descriptors were significant measures of the elongation of a shape (Griffith 1982). Both are easily measured and calculated, and both are subject to Strahler's (1964) criticism (a circle is not an appropriate shape for comparison). There is no 1:1 correspondence between index and actual shape, so the shape cannot be recomposed from the index value (Griffith et al. 1986). Bosch (1978) believed it was inadequate because it did not include the perimeter in the formula.

McArthur and Ehrlich (1977) found Schumm's elongation ratio was sensitive in regional contrasts. Morisawa (1958) reported that it was a significant factor in a regression analysis of rainfall-runoff ratios. In a study of drainage basins in 4 US physiographic provinces, Woodruff (1964) reported that this ratio was the second most significant factor used.

The *lemniscate index* (lemniscate k) combines values for area, length, and perimeter (Gardiner 1975). It is easily calculated, and of the simple shape indices, it may be best for recomposing basin shapes and goodness-of-fit testing (Whittington et al. 1972, Jarvis 1976). This index compares basin shape to a lemniscate loop, a shape similar to a teardrop (Chorley et al. 1957). Hobba and Robinson (1972) criticized this index because it compares a basin to a non-existent or idealized shape. A major disadvantage of this index is its reliance on the lengths of major and minor axes of an ellipse (Whittington et al. 1972). Griffith (1982) found it to be a significantly non-normal variable. It has been used successfully to compare excess and formative basins (Jarvis 1976) and basins within and between regions (Chorley et al. 1957, Singh and Upadhyaya 1982). It was not a significant factor in explaining the variance in rainfall-runoff ratios (Morisawa 1958).

Three form factors, *form factor I, II,* and the *Ogievsky form factor*, were selected for use in GEODES. All are very simple indices. The only difference between form factor II and Ogievsky's form factor is in the definition of the indices' denominators, basin length. Form factor II had the highest score. Its distribution was significantly non-normal, and was considered sensitive to extreme points which affect the length of the axes but not the area (Whittington et al. 1972). Despite these drawbacks, it was the most significant factor in the compactness component of a PCA analysis of shape variation (Griffith, 1982). It was significantly and negatively correlated with compactness in that analysis. Form factor I is sensitive to some changes in shape, but not to small variations in shape, and it allows reconstruction of the basin if the basin approximates a regular polygon (Hobba and Robinson 1972).

Horton's *shape factor* and the *shape index I* scored in the top half of the shape descriptors because only 2 easily measured inputs were required. Morisawa (1958) found that neither index explained a significant amount of variation in the rainfall-runoff ratio. Blouin and Connor (1985) used Horton's shape factor in regressions relating reserve shape to species richness with limited success. They chose this index because it measured deviation from circularity and is insensitive to small scale irregularities. A log transformation normalized the distributions of this variable.

The *shape index* of Gibbs (1961) has been criticized for sensitivity to extreme points (Whittington et al. 1972). It requires easily measured inputs, is easily calculated and applied to convex 2-dimensional figures (Boots 1978). It was used to determine the degree that a measured area approximates a standard shape such as a hexagon, circle, etc., (Massam 1970, Haggett et al. 1977). It is not sensitive enough to distinguish between a square and a triangle (Massam 1970).

The *circularity ratio* is easily calculated and measured, and incorporates basin length and basin area. In a principal components analysis of shape variation, Griffith (1982) reported that it was the most significant factor in the third principal component, the hourglass component. He also reported that distributions of this variable were significantly non-normal.

The final shape descriptor has not been extensively reviewed in the literature. Smart and Surkan's (1967) *delta* was included because it is easily calculated from the available inputs. It is also a measure of the compactness of shape (Gardiner 1975).

GEODES

A microcomputer system (GEODES) was designed, developed, and programmed in RBASIC, REVELATION's programming language, to provide terrain descriptions in terms of elevation, slope, length, area, texture, and pattern. GEODES integrated programs and subroutines for raster and vector manipulation (written in RBASIC), the Map Analysis Package (MAP), and a FORTRAN program for converting vector data to raster format (hereinafter called rasterization). The complete system, including a modified version of MAP, REVELATION files, and the program for vector-to-raster conversion was developed on an IBM AT (1280 K RAM, math coprocessor, 20 megabyte hard disk) and demonstrated on an IBM PC (640 K RAM, math coprocessor, 20 megabyte hard disk). Data can be entered into the system either in file format (DOS or REVELATION files), or from the keyboard.

GEODES' functions are linked by a series of parallel menus. The main menu connects the system's components. Each option in the main menu directs the user to a different set of lower-level menus that are related to a specific task (e.g., converting vector data to raster format or descriptor calculation). Fig. 13 outlines the menu structure and options of GEODES.

Each lower level or secondary menu screen offers the user 3 common options: returning to the main menu; temporarily leaving the system to execute any desired DOS commands; and terminating a session (leaving the REVELATION Operating System for DOS). Each lower level menu offers the system user explanations of specific system functions and the opportunity to perform those functions. This structure provides the new user with step-by-step

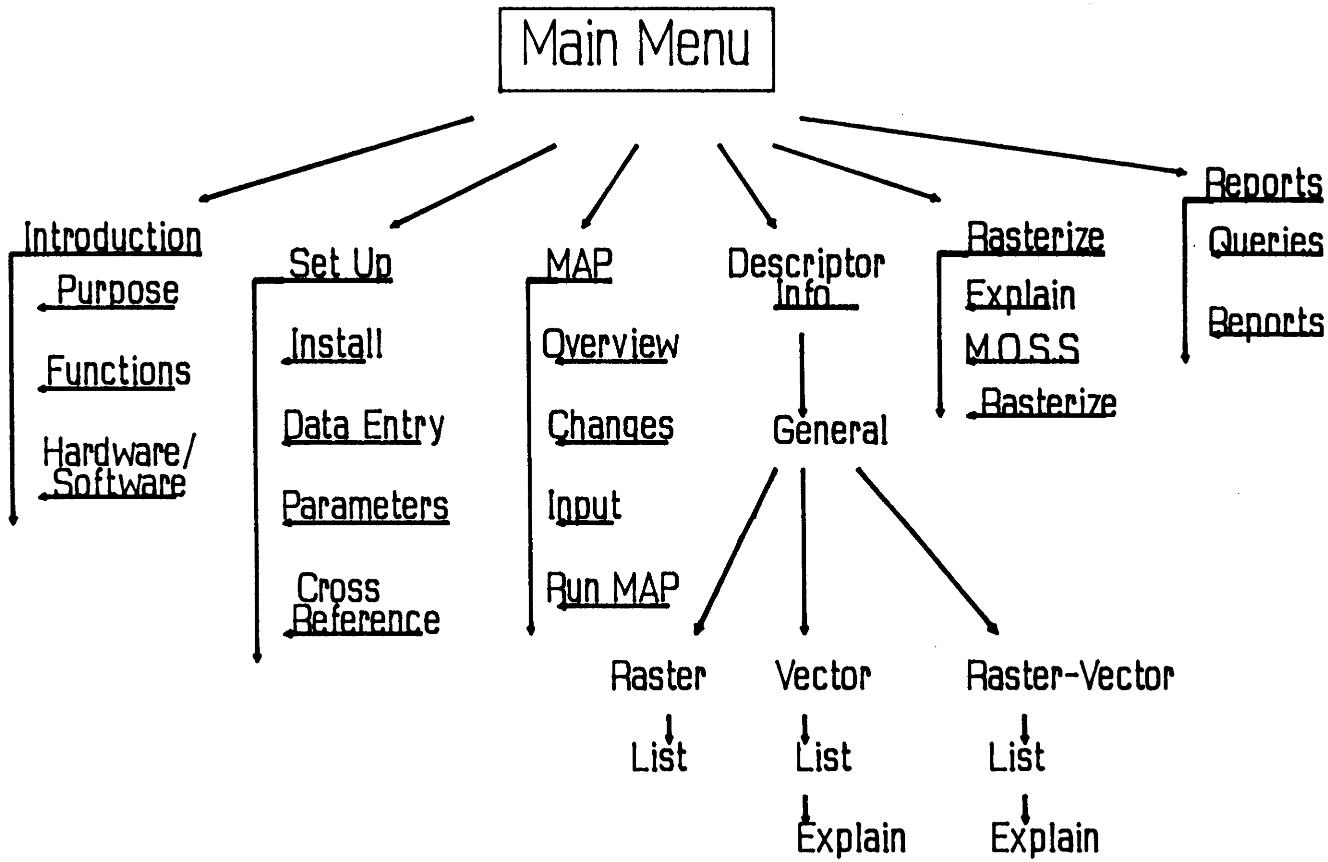


Figure 13. Menu structure and menu options in GEODES

explanations and examples of system operation, but does not require the experienced user to view these explanations.

The first option in the main menu is the *System Introduction*. This option explains the purpose of the system, the functions performed by GEODES, how GEODES processes data, and the hardware and software requirements of the system.

The *Set Up* option explains procedures used to install GEODES (including initializing raster and vector file parameters, creating paths between files, cross referencing files, and data entry from a keyboard). Entry screens for initializing parameters and manual data entry are accessed through this menu.

The third option of the main menu is the Map Analysis Package. An overview of MAP, data input, and MAP modifications required by GEODES (changes to Subroutine Slope and the DESCRIBE command) are discussed. One menu option operates MAP as well.

The *Descriptor Information* option of the main menu lists descriptors by the type of data processing required to generate them (e.g., raster, vector, and combined raster-vector descriptors). Descriptor explanations include a general formula for the descriptor and current or potential uses of each descriptor in the natural resource sciences.

The *Rasterization* option explains vector-to-raster conversion and the conversion protocol required by GEODES, converts REVELATION-based vector records to M.O.S.S. format (prerequisite to rasterization), and operates the rasterization (vector-to-raster conversion) routine.

The final menu option is *Descriptor Calculation*, the end product of the system. This option allows the user to list the available descriptors by data type, select specific descriptors to calculate (data base queries), or calculate all the descriptors for a specified data type (vector or raster-vector).

A total of 60 different descriptors were programmed into GEODES, including 4 elevation descriptors, 8 slope descriptors, 9 relief measures, 11 measures of length, 4 areal variables, 5 measures of texture, 13 shape descriptors, and 6 measures of network pattern. Table 13 lists

Table 13. Descriptors available in GEODES, by data type

Raster Descriptors	
Elevation and Relief	
Maximum Elevation	Minimum Elevation
Mean Elevation	Mean Slope
Elevation-Relief Ratio 1	Elevation-Relief Ratio 2
Vector Descriptors	
Length	
Mesh Length	Channel Length
Basin Perimeter	Total Stream Length
Main Stream Length	Basin Length 2
Parallel Basin Length	River Sinuosity
Hydraulic Sinuosity	Length of Overland Flow
Area and Texture	
Planimetric Area	Drainage Area Ratio
Constant of Channel Maintenance 1	Valley Spacing
Pattern and Shape	
Stream Order	Drainage Density
Stream Frequency	Relative Density
Channel Length/Basin Perimeter	Microscopic Link Density
Shape Factor	Shape Index 1
Shape Index 2	Circularity 1
Circularity 2	Circularity Ratio
Elongation 1	Elongation 2
Form Factor 2	Lemniscate Index
Ogievsky	
Raster-Vector Descriptors	
Elevation and Slope	
Minimum Elevation	Maximum Elevation
Mean Elevation	Minimum Slope
Maximum Slope	Mean Slope
Mesh Slope	Main Channel Slope
Limiting Angle	Slope Sine
Slope Tangent	Channel Gradient
Area and Length	
Surface Area	Surface Area/Planar Area
Basin Length 1	Hydraulic Sinuosity
Relief and Texture	
Relief Ratio 1	Relief Ratio 2
Elevation-Relief Ratio 2	Local Relief
Stream Relief	Average Relief
Main Channel Relief	Dissection Index
Ruggedness Number	Avoidance Factor
Mesh Relief	
Shape	
Delta	

the descriptors available in GEODES, grouped by the data type used to calculate these measures.

Several of the descriptors that were selected for inclusion in this terrain description system (see "Methods, Descriptor Selection") were not included in GEODES. *Slope position* was not included because of the difficulty of programming a routine to allow the user to pick specific points on the base map. Similarly, *cell length* was excluded because it would require the user to locate 1 or more transects on the study area. *Structural similarity* required the calculation of area for every watershed within a map or study area, a time and CPU intensive operation.

System Demonstration

The data sets used to develop GEODES were fairly large raster and vector data bases. Two smaller test data sets were used to refine descriptor calculation, make the system more user-friendly, and test the accuracy and precision of the calculations. Fig. 14 shows the data sets used for testing GEODES. Vector features representing hypothetical watersheds and streams were overlayed on the gridded (or raster) data base of elevations. Vector coordinates were entered from the keyboard, raster and vector parameters were initialized, and cross references were established. Fig. 15 presents the overlays of rasterized vector features (mesh source, stream, and basin) for test data set 1. A comparison of the original vector boundary of test data set 1 (Fig. 14) and the rasterized boundary in Fig. 15 suggests that information and accuracy were lost in the vector-to-raster conversion process. The resulting rasterized overlay generalizes boundary information more than the vector format. Report forms and descriptor queries were produced for both test data sets. Table 14 presents the descriptor values GEODES calculated for test data sets 1 and 2 (hereinafter called TD1 and TD2).

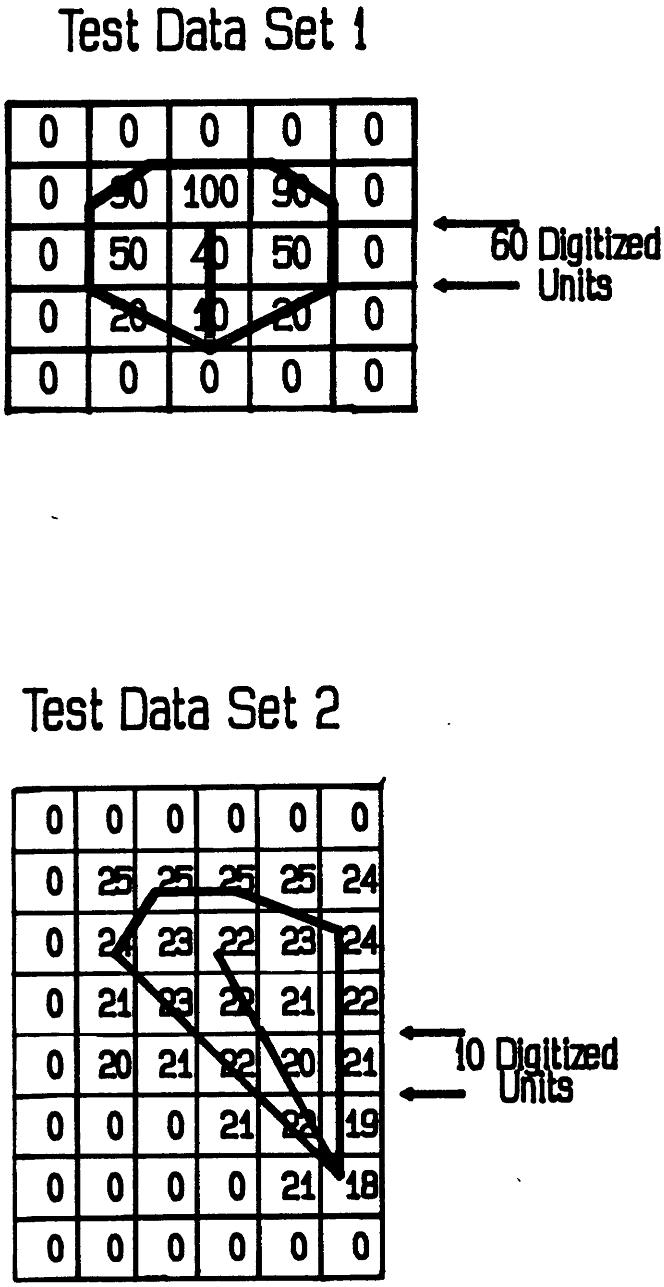


Figure 14. Two test data sets used to test and refine GEODES. Vector boundaries and hypothetical streams are overlayed on the raster data sets. Cell values are elevations. Cell lengths are measured in digitized units.

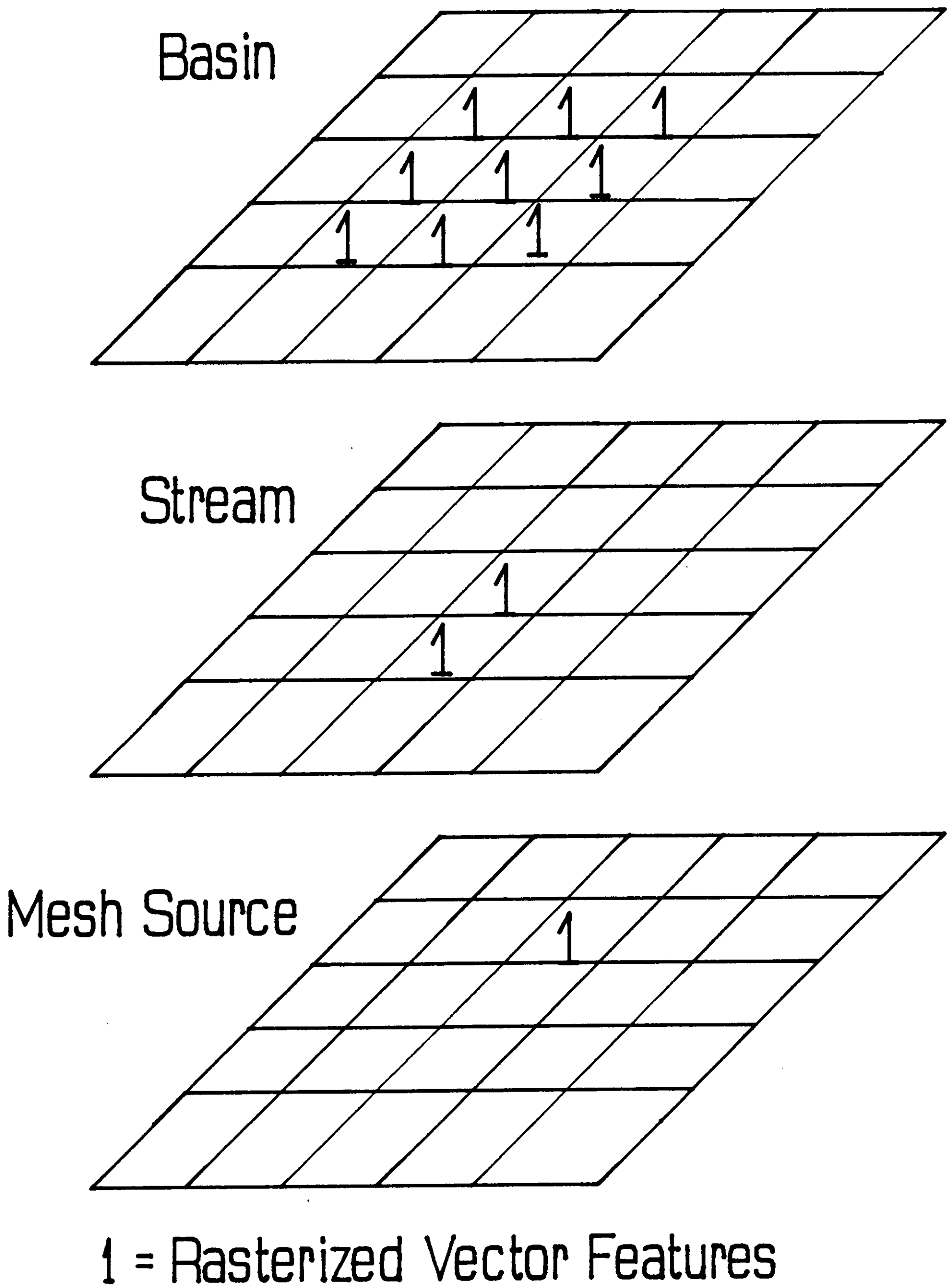


Figure 15. Rasterized vector overlays for the test data sets.

Test data sets

Channel length, total stream length, and *main stream length* were equal for each test data set. *Basin length 1* was equal to *parallel basin length* for TD1, so both the vector and raster-vector measures of hydraulic sinuosity were equal. This is consistent with the data sets shown in Fig. 14, because the longest axis in TD1 was also parallel to the hypothetical stream.

Drainage density was larger for TD2 than TD1. TD1 was a much larger basin. The *constant of channel maintenance I* was equal to *valley spacing* for each test data set.

The shape indices *shape factor, shape index 1, shape index 2, circularity 1,* and *circularity 2* suggested that test data set 1 was more circular than TD2. The value of *elongation 2* indicated that TD2 was more elongated than TD1. These results were confirmed by an examination of the digitized data sets (Fig. 14). The values for the *lemniscate index* implied that TD2 was more teardrop or petaloid in shape than TD1. *Ogievsky* index values indicated that TD1 was more square-shaped than TD2.

Test data set 1 had the larger range of elevations (and larger slope values and slope range), so it had larger relief values. TD1 was more highly dissected than TD2 according to the *dissection index*. However, it was only slightly more rugged than TD2 based on values of the *ruggedness number*. This may have been because of the much larger *drainage density* value for TD2. TD1 did have a higher value for the *avoidance factor*, suggesting that travel across this hypothetical basin could be more difficult than in TD2.

Havens drainage basins

Once the process of refining descriptor calculation was complete, descriptors were generated using the Havens Wildlife Management Area data sets. All available raster-based descriptors were calculated for the entire study area (Table 15). The available vector and raster-vector descriptors were calculated for 3 first order and 3 second order watersheds in

Table 14. Values calculated by GEODES for test data sets 1 and 2

Descriptors	Test Data 1		Test Data 2	
Raster Descriptors				
Minimum Elevation	10	units	18	units
Maximum Elevation	100	units	25	units
Mean Elevation	52	units	22	units
Mean Slope	43	percent	13	percent
Available Relief	90	units	7	units
Elevation-Relief Ratio 1	0.5333		0.4286	
Elevation-Relief Ratio 2	0.4667		0.5714	
Vector Descriptors				
Length				
Mesh Length	148	units	59	units
Channel Length	99	"	45	"
Basin Perimeter	470	"	185	"
Total Stream Length	99	"	45	"
Main Stream Length	99	"	45	"
Basin Length 2	148	"	58	"
Parallel Basin Length	148	"	45	"
River Sinuosity	1		1	
Hydraulic Sinuosity	0.6689		0.7759	
Length of Overland Flow	79	units	6	units
Area				
Planimetric Area	15554.5 sq.	units	560 sq.	units
Drainage Area Ratio	1		1	
Constant of Channel Maintenance 1	157	units	12	units
Texture and Pattern				
Valley Spacing	157	units	12	units
Stream Order	1		1	
Drainage Density	6.3647	units/unit^2	80.3571	units/unit^2
Stream Frequency	64.2901	str./unit^2	1785.7143	str./unit^2
Relative Density	1.5870		0.2765	
Channel Length/Basin Perimeter	0.2106		0.2432	
Microscopic Link Density	0.6301		3.6161	
Shape				
Shape Factor	1.4082		6.0071	
Shape Index 1	1.4082		3.6161	
Shape Index 2	0.9040		0.2119	
Circularity 1	0.9406		0.4534	
Circularity 2	1.0631		2.2053	
Circularity Ratio	$3.4 * 10^{-3}$		$1.9 * 10^{-5}$	
Elongation 1	0.9509		0.5934	
Elongation 2	0.1051		12.4444	
Form Factor 2	0.1051		0.0097	
Lemniscate Index	1.1060		4.718	
Ogievsky	1.1266		0.2618	

Table 14. Values calculated by GEODES for test data sets 1 and 2 (cont.).

Descriptors	Test Data 1		Test Data 2	
Raster-Vector Descriptors				
Elevation				
Minimum Basin Elevation	10	units	18	units
Maximum Basin Elevation	100	"	25	"
Mean Basin Elevation	52	"	22	"
Slope				
Minimum Basin Slope	32	percent	2	percent
Maximum Basin Slope	77	"	27	"
Mean Basin Slope	43	"	14	"
Mesh Slope	61	"	12	"
Main Channel Slope	too few points to estimate		0.0296	
Limiting Angle	32 - 77		2 - 27	
Slope Sine	multi valued		multi valued	
Slope Tangent	multi valued		multi valued	
Channel Gradient	0.303		0.0889	
Area				
Surface Area	21,268	sq.units	577	sq.units
Surface Area/Planar Area	1.3673		1.0306	
Length				
Basin Length 1	148	units	68	units
Hydraulic Sinuosity	0.6689		0.6618	
Relief and Texture				
Relief Ratio 1	0.6081		0.1556	
Relief Ratio 2	0.6081		0.5413	
Elevation-Relief Ratio 2	0.4667		0.5714	
Local Relief	90	units	7	units
Stream Relief	30	"	4	"
Average Change in Relief	1.4286	"	0.4375	"
Main Channel Relief	30	"	4	"
Dissection Index	0.9000		0.2800	
Ruggedness Number	0.5712		0.5625	
Avoidance Factor	0.6429		0.1094	
Mesh Relief	90	units	7	units
Shape				
Delta	0.9468		2.2927	

this study area. Fig. 16 shows the basins that were described. Basins were selected that were visually distinctive or appeared to differ in shape, width, or length from one another. The purpose of this demonstration was not statistical analysis, but to suggest the range of descriptor values in this study area.

First-order watersheds

Table 16 lists results of descriptor calculation for 3 first-order watersheds. This list is divided into vector descriptors and raster-vector descriptors.

Vector descriptors

Like the test data sets, values for *total stream length, main stream length,* and *channel length* are identical within a basin. *Basin length 2,* by definition, is the longest basin length measure, though for 2 of the sample basins, *mesh length* was as long. *Parallel basin length,* was smaller than the other basin length measures because it was measured parallel to the mainstem stream, and not necessarily along the longest basin axis. *River sinuosity* values for these sample watersheds were only slightly greater than 1.0, confirming a visual impression that these streams were not sinuous. *Hydraulic sinuosity 2* incorporates *basin length 1* in the denominator, so values were more variable than for *river sinuosity*. Values for *hydraulic sinuosity 2* were close to 1.0 for 2 of the sample first-order basins. The value for basin 101 was less than 1.0 because the channel length was much shorter than the basin axis.

Drainage area ratio compares the area of a given basin to the average area of the lower order basins within it. No values were reported because there were no lower order basins identified in these first-order basins.

Drainage density ranged from 3.4 to 4.8 km/km^2 (5.5 to 7.7 mi/mi^2). Basin 169 had the highest density, basin 136 had the lowest. These values were slightly larger than values

Table 15. Raster descriptor values for Havens data set

Descriptors		
Minimum Elevation	378	meters
Maximum Elevation	994	meters
Mean Elevation	646	meters
Minimum Slope	2	percent
Maximum Slope	153	"
Mean Slope	32	"
Available Relief	616	meters
Elevation-Relief Ratio 1	0.5649	
Elevation-Relief Ratio 2	0.4351	

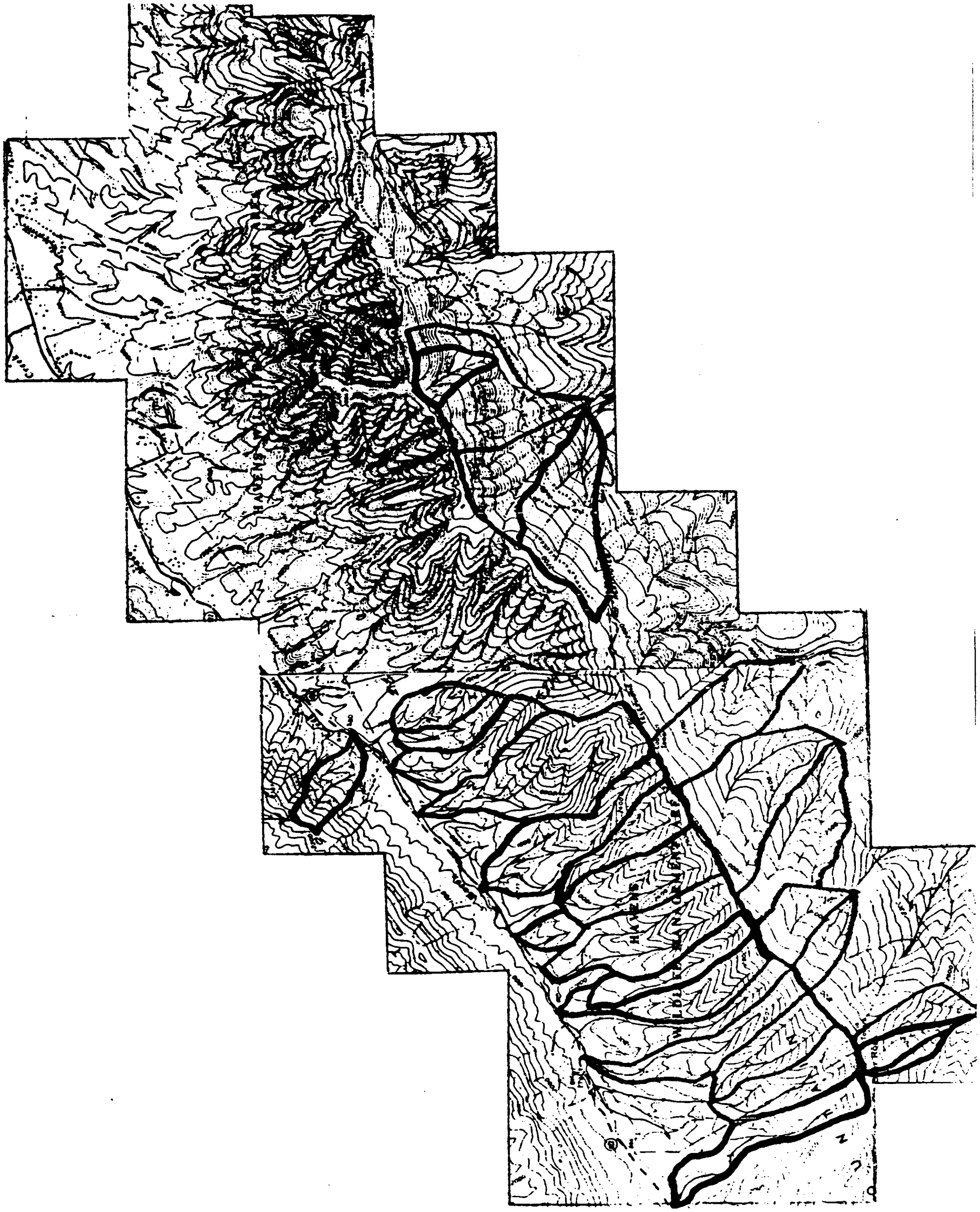


Figure 16. Selected digitized watersheds from the Havens Wildlife Management Area.

reported for basins in the Appalachian Plateau (3 to 4 mi/mi^2 for densely vegetated basins, on resistant sandstone, in a region of gentle topography) (Strahler 1964). The larger values for Havens watersheds may be due to the rugged topography of this area.

Stream frequency and *microscopic link density* varied proportionately with *planimetric area*. *Relative density* varied inversely with basin area. These results were expected, because basin area is a component of each of these descriptors. *Channel length/basin perimeter* also varied proportionately with basin area.

Griffith (1982) reported that *shape factor* values (he called this descriptor an elongation ratio) close to 1.0 suggested circular shapes, while values greater than 1.0 suggested ellipsoid shapes. Basin 136 was the most circular of these first-order basins, with a value of 2.48 compared to the more attenuated shapes of basins 101 and 169 (values of 9.72 and 7.98 respectively). Most of the other shape indices confirmed the departure of basins 101 and 169 from standard shapes (circles or squares).

According to Griffith (1982), small values of the *circularity ratio* suggest convex shapes (with 0 as the lower limit), while larger values indicate concave shapes. Values for this index range from 0.12 for basin 101 to 3.37 for basin 169, but the basins do not appear particularly concave or convex.

Circularity 1, *circularity 2*, and *elongation 1* are measures of compactness (Patton 1975, Jarvis 1976, Marcot and Meretsky 1983). A value of 1.0 denotes a circular shape. Values of *circularity 1*, *elongation 1*, and *elongation 2* declined as a basin elongated. Basin 136 was more compact than either basin 101 or basin 169.

Low values of the *lemniscate index* suggest a non-lemniscate (or non-petaloid) shape (Chorley et al. 1957, Jarvis 1976). Basin 136 did not have a lemniscate shape, while basin 101 and 169 approached the petaloid form (values of 7.64 and 6.27 respectively).

The *Ogievsky* index compares basin shape to a square of comparable perimeter (Zavoianu 1985). Values of 1.0 indicate a square shape. Basin 136 had a value of 0.947, and appeared relatively square. The other 2 basins had much lower values and did not appear square.

Table 16. Descriptor values for selected first order basins.

Descriptors	Basin 101		Basin 136		Basin 169	
Vector Descriptors						
Length						
Mesh Length	717	meters	682	meters	1565	meters
Channel Length	211	"	643	"	1458	"
Basin Perimeter	1501	"	1800	"	3314	"
Total Stream Length	211	"	643	"	1458	"
Main Stream Length	211	"	643	"	1458	"
Basin Length 2	717	"	690	"	1565	"
Parallel Basin Length	373	"	677	"	1521	"
River Sinuosity	1.0102		1.0261		1.0346	
Hydraulic Sinuosity 2	0.2943		0.9319		0.9316	
Length of Overland Flow	125	meters	149	meters	105	meters
Area						
Planimetric Area	52,871	m^2	191,759	m^2	306,792	m^2
Drainage Area Ratio	—		—		—	
Constant of Channel Maintenance 1	251	meters	298	meters	210	meters
Texture						
Valley Spacing	251	"	298	"	210	"
Network Pattern						
Stream Order	1		1		1	
Drainage Density	3.9908	km/km^2	3.3532	km/km^2	4.7524	km/km^2
Stream Frequency	18.914	streams/km^2	5.2149	streams/km^2	3.2595	streams/km^2
Relative Density	1.1876		0.4638		0.1443	
Channel Length/Basin Perimeter	0.1406		0.3572		0.4400	
Microscopic Link Density	0.8421		2.1561		6.9290	
Shape						
Shape Factor	9.7235		2.4828		7.9833	
Shape Index 1	2.6315		2.3901		7.5407	
Shape Index 2	0.1309		0.5127		0.1595	
Circularity 1	0.5431		0.8624		0.5925	
Circularity 2	1.8415		1.1596		1.6878	
Circularity Ratio	0.1191		0.6212		3.3691	
Elongation 1	0.6956		0.7299		0.4109	
Elongation 2	0.1417		0.2832		0.2017	
Form Factor 2	0.0737		0.2779		0.1960	
Lemniscate Index	7.6368		1.9500		6.2701	
Ogievsky	0.3756		0.9470		0.4470	

Table 16. Descriptor values for selected first order basins (cont.).

Descriptors	Basin 101		Basin 136		Basin 169	
Raster-Vector Descriptors						
Elevation						
Minimum Basin Elevation	695	meters	738	meters	555	meters
Maximum Basin Elevation	875	"	878	"	920	"
Mean Basin Elevation	779	"	817	"	693	"
Slope						
Minimum Basin Slope	31	percent	18	percent	13	percent
Maximum Basin Slope	66	"	56	"	74	"
Mean Basin Slope	46	"	32	"	38	"
Mesh Slope	30	"	20	"	26	"
Main Channel Slope	0.2654		0.1638		0.1948	
Limiting Angle	31 - 66		18 - 56		13 - 74	
Slope Sine	multi	valued	multi	valued	multi	valued
Slope Tangent	multi	valued	multi	valued	multi	valued
Channel Gradient	0.0853		0.21		0.2586	
Area						
Surface Area	76,111	m^2	226,118	m^2	389,325	m^2
Surface Area/Planar Area	1.4396		1.1792		1.2690	
Length						
Basin Length 1	695	meters	637	meters	1506	meters
Hydraulic Sinuosity 1	0.3036		1.0094		0.9681	
Relief and Texture						
Relief Ratio 1	0.4826		0.2068		0.2400	
Relief Ratio 2	0.2276		0.1994		0.2702	
Elevation-Relief Ratio 2	0.4667		0.5643		0.3781	
Local Relief	180	meters	140	meters	365	meters
Stream Relief	18	"	135	"	377	"
Average Change in Relief	37.6667	m/ha	5.5455	m/ha	1.9667	m/ha
Main Channel Relief	42	meters	135	meters	377	meters
Dissection Index	0.2057		0.1595		0.3967	
Ruggedness Number	0.7184		0.4694		1.7346	
Avoidance Factor	3.1833		2.1073		7.2997	
Mesh Relief	213	meters	135	meters	408	meters
Shape						
Delta	2.4117		1.1606		2.1694	

Raster-vector descriptors

Channel gradient was slightly greater than *main channel slope* for basins 136 and 169. *Main channel slope* was greater than *channel gradient* for basin 101. These differences may reflect differences in the processes used to calculate these descriptors, or they may be because of the small size of basin 101 and the small number of elevational (raster) values associated with it. There was an order of magnitude difference in resolution of the raster and vector data.

Slope sine and *slope tangent* generated multiple valued fields (arrays). These descriptors were merely the tangent or sine of all slope values in a specified basin. The arrays were not reported in Table 16 but can be listed or accessed for use.

Surface area/planar area ratios ranged from 1.18 to 1.44. Hobson (1972) used this measure as an index to surface roughness. Basin 101 could be considered "rougher" than the other 2 basins.

Hydraulic sinuosity 1 values (calculated using basin length measured from basin outlet to highest elevation on the divide) ranged from 0.30 to 1.01. Basin 101 had the lowest value because of the short *channel length*.

Basin 169 was the largest, longest, first-order basin sampled, and had the largest *local relief* and *mesh relief* values (basin 136 had the lowest values). Basin 101 had the largest value for the *relief ratio 1* (0.48) and basin 136 had the lowest (0.21). However, values for *relief ratio 2* suggested that basin 169 had the greatest relief along the basin length that relief was measured. The discrepancy between these 2 ratios is because the denominator of the *relief ratio 1* is *parallel basin length*, a measure that is shorter relative to the major axis for basin 101 than for the other basins. *Stream relief* was equal to *main channel relief* for basins 136 and 169, but not for basin 101. This difference may be due to the small size of basin 101, scalar differences between raster and vector data, or the different procedures used to calculate each descriptor.

The texture/ruggedness descriptors *dissection index, ruggedness number,* and *avoidance factor* suggested that basin 169 was the most dissected or most rugged basin (highest value) and basin 136 was the least dissected.

Delta, the only raster-vector shape descriptor, indicated that basins 101 and 169 were more attenuated than basin 136.

Second-order watersheds

Table 17 lists the values of vector and raster-vector descriptors for 3 sample second-order watersheds. No mesh source descriptors (i.e., *mesh length, mesh slope,* or *mesh relief*) were included because each second-order basin contains 2 or more first-order basins and 2 or more mesh sources.

Vector descriptors.

Basin 201 was the smallest and basin 225 was the largest of the sample second-order basins in terms of *basin perimeter, main stream length, parallel basin length,* and *basin length 2.* Basin 208 had the largest values for *channel length, river sinuosity, hydraulic sinuosity, planimetric area* and *drainage area ratio* (followed by basin 225). It appeared to be more sinuous than the other 2 basins because it had 1 more first-order stream (an "excess" stream) than the other 2 basins. The *drainage area ratio* suggested either that the first-order watersheds of basin 208 were proportionately smaller than the component basins for watersheds 201 and 225, or that basin 208 had a larger area that was not part of first-order basins than the other 2 basins.

As *drainage density* increases, the size of individual basins decrease (Strahler 1957). Basin 201, the smallest basin had a density of 5.1 km/km^2 (8.2 mi/mi^2), while the largest basin, 208 has the lowest density (2.9 km/km^2 or 4.7 mi/mi^2). These values were slightly greater than those reported for the Appalachian Plateau (Strahler 1964). *Valley spacing* values were

Table 17. Descriptor values for selected second order basins.

Descriptors	Basin 201		208		225	
Vector Descriptors						
Length						
Mesh Length	—		—		—	
Channel Length	1007	meters	2130	meters	1996	meters
Basin Perimeter	2230	"	3968	"	4196	"
Total Stream Length	1007	"	2130	"	1996	"
Main Stream Length	257	"	680	"	965	"
Basin Length 2	981	"	1696	"	1888	"
Parallel Basin Length	281	"	436	"	819	"
River Sinuosity	1.0208		1.8913		1.0748	
Hydraulic Sinuosity 2	1.0265		1.2559		1.0572	
Length of Overland Flow	98	meters	171	meters	112	meters
Area						
Planimetric Area	197,731	m^2	729,452.5	m^2	446,065.5	m^2
Drainage Area Ratio	2.202		4.1485		3.6376	
Constant of Channel Maintenance 1	196	meters	342	meters	223	meters
Texture						
Valley Spacing	196	"	342	"	223	"
Network Pattern						
Stream Order	2		2		2	
Drainage Density	5.0928	km/km^2	2.92	km/km^2	4.4747	km/km^2
Stream Frequency	15.1721	$streams/km^2$	5.4836	$streams/km^2$	6.7255	$streams/km^2$
Relative Density	0.5850		0.6431		0.3359	
Channel Length/Basin Perimeter	0.4516		0.5368		0.4757	
Microscopic Link Density	5.1284		6.2196		8.9315	
Shape						
Shape Factor	4.8670		3.9433		7.9911	
Shape Index 1	0.3993		0.2606		1.5037	
Shape Index 2	0.2616		0.3228		0.1593	
Circularity 1	0.7069		0.7630		0.5642	
Circularity 2	1.4147		1.3106		1.7723	
Circularity Ratio	0.9837		11.4851		7.8536	
Elongation 1	1.7856		2.2104		0.9202	
Elongation 2	0.7037		1.6731		0.5446	
Form Factor 2	0.2016		0.4301		0.2363	
Lemniscate Index	3.8225		3.097		6.2762	
Ogievsky	0.6362		0.7413		0.4054	

Table 17. Descriptor values for selected second order basins (cont.).

Descriptors	Basin 201		208		225	
Raster-Vector Descriptors						
Elevation						
Minimum Basin Elevation	634	meters	555	meters	555	meters
Maximum Basin Elevation	945	"	847	"	975	"
Mean Basin Elevation	817	"	740	"	718	"
Slope						
Minimum Basin Slope	31	percent	9	percent	9	percent
Maximum Basin Slope	66	"	42	"	153	"
Mean Basin Slope	41	"	26	"	34	"
Mesh Slope	--	"	--	"	--	"
Main Channel Slope	0.3320		0.2039		0.1009	
Limiting Angle	31 - 66		9 - 42		9 - 153	
Slope Sine	multi	valued	multi	valued	multi	valued
Slope Tangent	multi	valued	multi	valued	multi	valued
Channel Gradient	0.0636		0.0371		0.0486	
Area						
Surface Area	261,996	m^2	811,590	m^2	538,052	m^2
Surface Area/Planar Area	1.3250		1.1126		1.2062	
Length						
Basin Length 1	981	meters	1232	meters	1861	meters
Hydraulic Sinuosity 1	1.0265		1.7289		1.0725	
Relief and Texture						
Relief Ratio 1	1.1068		0.6697		0.5263	
Relief Ratio 2	0.0107		0.055		0.1489	
Elevation-Relief Ratio 2	0.5884		0.6336		0.3881	
Local Relief	311	meters	292	meters	420	meters
Stream Relief	64		79		97	
Average Change in Relief	15.6250	m/ha	3.3500	m/ha	6.0882	m/ha
Main Channel Relief	61		110		85	
Dissection Index	0.3291		0.3447		0.4308	
Ruggedness Number	1.5839		0.8526		1.8794	
Avoidance Factor	5.4688		1.1055		8.7671	
Mesh Relief	--		--		--	
Shape						
Delta	1.7602		1.1509		2.2232	

greatest for basin 208 and least for basin 201. There was more distance between valleys and more area was required to maintain a length of channel for either basin 208 or 225 than for basin 201.

Stream frequency ranged from 5.4 to 15.2 streams/km^2, with the greatest stream frequency in the smallest basin. *Relative density* ranged from 0.34 to 0.64 with no apparent trend. The lowest values of *channel length/basin perimeter* were associated with the smallest basin (201). *Microscopic link density* ranged from 5.1 for basin 201 to 8.9 for basin 225.

None of the sample watersheds seemed circular. *Shape factor, circularity 1, circularity 2,* and *shape index* values suggested that basin 208 was the most circular and basin 225 was the least circular. *Form factor 2* values were much less than the $\pi/4$ value generated by circular shapes.

Based on values of *elongation 1* and *elongation 2*, basin 225 was the most elongated basin, basin 208 was the least elongated. *Lemniscate index* values for all 3 basins were too large for any basin to be considered lemniscate. The *Ogievsky* index values indicated that these basins were not close to square.

Raster-vector descriptors

Basin 201 had the largest values for *minimum basin slope* and *mean basin slope*, while basin 225 had the greatest range of slopes (*limiting angle*). *Main channel slope* varied from 10% for basin 225 to 33% for basin 201. *Main channel slope* values were greater than *channel gradient* values for all 3 basins.

Like the vector-based measures of sinuosity, values of *hydraulic sinuosity 1* indicated that basin 208 was more sinuous than the other 2 basins.

Basin 225 had the greatest range in *local relief* and the largest *relief ratio 2* because it was a longer basin that encompassed a wider range of relief than the other basins. Basin 208 had the smallest range. Basin 201 had the largest *relief ratio 1* value because of a very small value for *parallel basin length* in the denominator. The relative proportion of uplands to lowlands, measured by *elevation-relief ratio 2*, was greatest for basin 208 and least for 225. Values ranged between 0.4 and 0.6.

Stream relief and *main channel relief* were not similar in this small sample. However, both descriptors were of the same order of magnitude. The *average change in relief* was greatest for the smallest basin (201) and least for the largest basin (208). This was not surprising because there were many fewer data points associated with the smaller watershed, though it had a relatively large range in relief (311 m).

The texture measures, *dissection index, ruggedness number,* and *avoidance factor* were all strongly correlated with local relief. Generally, the highest values were for the basin with the greatest range in relief, basin 225.

Like the vector-based shape descriptors, *delta* values suggested that basin 208 is more circular than basins 201 or 225.

First- and second-order basins.

Mesh slope, main channel slope, and *channel gradient* were less than *mean basin slope* for both first- and second-order basins. *Mean basin slope* and *main channel Slope* were strongly correlated for first order basins ($R = 0.99$, $n = 3$) but not for second-order basins ($R = 0.52$, $n = 3$). *Main channel slope* and *channel gradient* were more highly correlated for first-order basins ($R = 0.84$) than for second-order basins ($R = 0.61$).

Values of both hydraulic sinuosity indices (*hydraulic sinuosity 1* and *2*) were similar for a given first- or second-order basin. *Total stream length* is equal to *channel length* for first- and second-order basins.

Planimetric area and *channel length/basin perimeter* were strongly correlated ($R = 0.98$, $n = 3$) for both first- and second-order basins. This is not surprising, because *planimetric area* is calculated from *basin perimeter*. *Surface area/planimetric area* ratios did not vary as widely for second-order basins as for first-order basins.

The shape indices *circularity 1, circularity 2, shape factor, shape index 2,* and *delta* all measure basin circularity. These indices are in agreement for the sample watersheds.

Stream relief and *main channel relief* values for first-order basins were strongly correlated (R = 0.99). Values for second-order reaches were poorly correlated (R = 0.44). As might be expected, relief ratios were greater for second-order basins.

Drainage density values were more variable for second than first order basins, while *relative density* values were more constant. *Microscopic link density* was generally greater for second-order basins. Values for the *constant of channel maintenance I* and *valley spacing* were identical for a basin. The *length of overland flow* was 1/2 the *valley spacing.*

Discussion

Evaluation of project objectives

I conducted a literature review of the major relations between geomorphic components and wildlife habitats of mountainous land management areas in the Ridge and Valley province of Virginia. This review began with an examination of the major geomorphic processes operating in this physiographic region: physical weathering, chemical weathering, and fluvial processes. I examined the major factors controlling the intensity of these processes: lithology, climate, and vegetation.

Geomorphology focuses primarily on the dynamic processes responsible for the development and evolution of landforms and landscapes. Many of these processes operate on time scales far longer than the life spans of the animals that inhabit these landscapes. For most wildlife species, as human resources, terrain structure changes so slowly that it may be treated as constant. Therefore, much of this review focused on a subset of geomorphology, the analysis of terrain or landform structure.

Landform structure, climate, and vegetation are strongly interrelated. Different configurations of one affect the forms and processes of the others. No review of geomorphic-wildlife habitat relations would be complete without an examination of the role of terrain structure on local and regional patterns of climate and vegetation. Terrain structure shapes climate through effects on temperature, precipitation, windflow, and solar radiation. Through these climatic effects and through soil-moisture effects, terrain structure influences the distribution and community composition of vegetation. These factors may be considered indirect effects of terrain structure on wildlife.

The second part of this literature review examined more direct relationships between wildlife species and land surface shape. I examined the role of land surface shape in the distribution of species, species movements, energetics, phenologies, food habits, and as a component of cover. I also reviewed the little-studied role of wildlife as agents of geomorphic change.

I sought literature that connected terrain parameters and wildlife species in the Ridge and Valley Physiographic Province. Many of the best examples were drawn from other regions, particularly places like the Rocky Mountains, where wildlife species are more apparently adapted to rugged terrain, and terrain structure (especially relief) is a more obvious habitat component.

It has not been easy to locate information on terrain components of wildlife habitat. References to terrain structure are often buried in habitat analyses. Terms like topography, relief, terrain, slope, or aspect, are not usually keywords in the wildlife literature, making the search for relevant literature difficult. Many habitat studies use only general measures of terrain attributes such as percent slope or compass orientation (aspect) (e.g., Pack et al. 1980, Gaudette and Stauffer 1988). The use of more specific terrain measures may improve the ability of researchers to explain wildlife habitat use. Several major questions remain for future exploration. How does an organism perceive its environment? With more precise or discriminating measures of terrain structure (or any other habitat attribute) can researchers or managers perceive the environment as a given species might, or will geomorphic measures only cloud their understanding of habitat use by a species?

The second objective was to determine the inputs necessary to quantify geomorphic components efficiently and effectively. For this project, inputs were both the individual components of descriptors (i.e., elevation or slope) and the actual measures used to quantify terrain of mountainous land management areas.

The Literature Review section titled "Geomorphology in the Ridge and Valley Province" identified the fundamental characteristics of terrain: elevation, slope, aspect, and their derivatives. At the next larger scale, landforms, I examined the characterization of 2 specific landscape features, streams and drainage basins. I identified the major structural attributes of these features and the landscapes these features are part of: elevation, slope, aspect (or slope orientation), length, area, relief, texture, and pattern.

Over 120 terrain descriptors that had been used to measure 1 or more of these structural attributes were found in the literature. This was an unwieldy number of measures to use for quantifying land surface shape. I sought to reduce the number of descriptors to a manageable number, without compromising the ability to describe potentially important aspects of wildlife habitat. I sought the best descriptors for each category of structural attributes. I hoped to present descriptors that might be useful in pattern recognition and a variety of other applications. I eliminated redundant descriptors and statistically-based measures.

I used an objective-weighting procedure (Churchman and Ackoff 1954, Giles 1978) to select these descriptors. There are 3 major advantages to this decision-making procedure. The procedure is formalized and the decision is elevated above a "guesstimate" (Giles 1978). Secondly, the decision-making process is expressed openly; all of the steps are in plain view. Finally, numerical values are assigned to often subjective concepts, allowing quantitative comparison of these concepts. In this objective-weighting process, the utility of each descriptor, as reported in the literature, and the ease of calculating a given descriptor were most important. I suspect that if another researcher were to use the same procedure with the same criteria, the results would be substantially the same.

For each group of descriptors (e.g., slope descriptors), I chose to include the measures in the top 50% in GEODES. A smaller percentage might have served just as well. In several instances (slope, relief, and texture), descriptors at the lower end of the range, were included in GEODES, though their utility was questionable, or their scores were similar to descriptors that were not included. In retrospect, 35% would have been a better range.

Several interesting and potentially useful descriptors were not included in GEODES, because examples of their use were not found beyond the initial literature citation, or because of the difficulty in calculating these descriptors. Examples of the former category include: Bosch's (1978) *circularity index* that compares a basin's area to the product of its major axis and its perimeter (incorporating measures of area, diameter, and circumference in one index); Lee and Sallee's (1970) *symmetric difference metric* that compares a shape to a reference shape; Cole's (1964) *compactness index* comparing a shape to the smallest circle to enclose that shape; Potter's (1953) *T-Factor* attempts to express the time needed for water to travel a stream length; the *transport efficiency factor* (Lustig 1965) and the *ruggedness ratio* (Melton 1965). Descriptors that were not included because of the difficulty in calculating them included: *hypsometric integral, dual axis fourier analysis, surface roughness,* and the *radial shape index* of Boyce and Clark (as cited in Gardiner 1975).

No index, simple or complex, can account for all of the dimensions of land surface shape. Instead, I sought descriptors that quantify one or more dimensions of a structural component of land surface form (i.e., compactness or elongation components of shape). Measures of these structural components taken together may **effectively** quantify an area's landforms. Ultimately, multivariate analyses may be necessary to describe land surfaces.

Efficiency is a difficult concept to treat. In this project, an efficient measure refers to the number of inputs necessary for a descriptor, the ability to express the unique nature of a feature, and correlations between measures and natural phenomena. For the number of necessary inputs needed to compute a descriptor, the selected measures are efficient measures. All of the descriptors currently available in GEODES can be generated from minimal inputs of elevation, horizontal distance, and linear features (points, lines, and polygons).

Several researchers suggested that efficient descriptors are those that express the unique nature of the feature being quantified, allowing that feature to be reconstructed through decomposition of the descriptor (Jarvis 1976, McArthur and Ehrlich 1977). Some authors have objected to simple indices because they are insensitive to variations in all but the pre-selected dimensions (Hobba and Robinson 1972). These are strong arguments, particularly in complex fields like shape or pattern analysis. Others have suggested that the most effective way to quantify a structural component, such as shape or texture, is through a battery of indices (Stone and Dugundi 1965, Griffith et al. 1986). The descriptors provided in GEODES may provide the raw material for such a multivariate approach.

An efficient index should be highly correlated with a measurable phenomenon such as sediment discharge, particularly in the natural resource sciences. Indices that are easily understood and interpreted are more likely to be used than those that require substantial training or expertise. A *Dual Axis Fourier Analysis* may be better at expressing the shape of a feature than simple indices of elongation, compactness, or concavity, but a battery of simple indices may effectively depict a feature, and be easily interpreted (Griffith et al. 1986).

The third objective was to develop new programs or to locate and modify existing programs that present geomorphic information for use by natural resource professionals. GEODES, the GEOmorphic DEscription System integrated 2 existing software systems and many existing programs and subroutines for spatial data manipulation.

This system relied on REVELATION's file structure and its facilities for program and menu development, and information exchange between files. REVELATION is a flexible system. The data base and fields within the data base are easily changed. The programming language is more flexible than programming languages like FORTRAN or BASIC. Program modules are easily created, altered, or eliminated. GEODES is subject to the limitations of REVELATION, notably the initial difficulty of learning to use REVELATION, and the difficulty of using REVELATION to manipulate large matrices.

GEODES supplements the capabilities of MAP by quantifying specific features within a MAP overlay. It allows the user to summarize or reduce the information in an overlay to a form that can be more easily manipulated in statistical analyses.

GEODES uses several programs written by others at VPI & SU for manipulating vector data, and for converting vector data to raster format. Many new programs were written to generate terrain descriptors from raster data (from MAP overlays), vector data, or both (an opportunistic attempt to develop the best descriptors from the available data).

In its present form, GEODES offers the resource manager or agency decision maker an opportunity to become familiar with the analysis of land surface shape.

The final objective of this project was to suggest applications of geomorphic-based information to wildlife research and management. The Literature Review section "Geomorphology in Environmental Sciences" discussed some of the applications of geomorphic parameters to soil science, hydrology, forestry, engineering, and fisheries. This section demonstrates the utility of some elements of terrain analysis to environmental sciences and implies possible applications to wildlife habitat practices. Techniques used for silvicultural or hydrologic management may be applied directly to wildlife habitat management.

Potential applications of geomorphology and geomorphic measures to wildlife research and management will be discussed later in this section.

System Limitations

REVELATION is suited to the design and development of applications software. Its dictionary structure and features, such as file translation and cross referencing, allow the designer to modify applications rapidly. However, REVELATION is slow when manipulating matrices the size of the data set used for GEODES development (8800 elements) because it must use dynamic rather than dimensioned arrays for matrices of that size. The tradeoff is processing speed. Processing speed or efficiency in generating map-wide descriptors was increased by calculating these descriptors from DOS files that were created with the MAP commands DESCRIBE and WRITE, rather than converting MAP overlays to arrays in REVELATION. Descriptors that require raster data associated with a specific vector feature (stream, mesh source, or basin) also require conversion of at least a portion of a MAP overlay to a dynamic string array. This weakness in data processing could be remedied by system calls to compiled external subroutines written in C, Pascal, FORTRAN, or another language more suited to manipulating large arrays. It would then be easier to adapt many of the "local" descriptors of texture and relief (i.e., drainage density) to "regional" or map-wide description. This might encourage the use of techniques like Fourier Analysis that require intensive manipulation of numeric data.

GEODES may be more suited to providing a detailed examination of an area than to a so-called "quick and dirty" examination for 2 reasons. First, it requires time and effort to compile the necessary raster and vector data sets and to set the system up (rasterize vector data and establish cross references). Secondly, the data processing efficiency of GEODES increases as the number of descriptors increases, because frequently used component descriptors (e.g., channel length) are stored in "pure" fields for quick access. The ability of GEODES to generate rough, but rapid analyses of data could be improved. For example, if only raster data are available, it is possible to provide the user with an approximation of area by multiplying the number of grid cells within a specified feature by the area of a grid cell.

The last major limitation of this system is its vector data format requirement. Vector data must be stored in the 3 field format of key (or record id), attributes, and XY coordinates.

GEODES could be improved by converting from the REVELATION operating system to AREV (Advanced REVelation). This software package would reduce the number of menus a user would meet. It incorporates the concept of expert level, so that the more experienced the user is, the fewer the prompts and explanations are necessary.

Evaluation of GEODES descriptors

Three considerations for evaluating the measures presented in GEODES are:

1. The structural attributes best suited to each type of data processing (raster, vector, or raster-vector).
2. Potential sources of error in descriptor calculation.
3. Reducing the number of descriptors available in GEODES.

Structural attributes

In GEODES, raster-based descriptors are used as measures of elevation, slope, relief, and texture. The raster format stores information on a cell's interior (implying the boundaries), and is suited to storage of elevation, slope, and aspect (Berry 1987b). Raster data are easily manipulated algebraically and processing often consists of summations, averages, etc. (Peuquet 1977, Burroughs 1986). This type of operation is suited to rapid, map-wide, or regional data processing.

Vector-based descriptors are primarily measures of length, area, pattern, and shape. In contrast to raster data, vector data stores information on boundaries and implies polygon interiors (Berry 1987b). Vector format data allow spatially directed searches. GEODES can locate a specific feature within a map, based on that feature's attributes. In the system demonstration, vector-based descriptors were more precise than raster or raster-vector descriptors because of the greater resolution of vector data. The digitizing program reported vector coordinates to the nearest meter, though given the scale of the maps used (1:24,000) these coordinates are not likely to be more accurate than to the nearest 20 to 30 meters. This is still more accurate than the raster data set. Each raster data point applied to a 100m by 100m cell.

Raster-vector descriptors are primarily raster-based measures of elevation, slope, relief, and texture applied to vector-defined features (i.e., basins or streams). A few descriptors of area, length, and shape were developed that relied equally on raster and vector inputs.

Sources of error

The principle source of error in raster-based descriptors and a major source of error in raster-vector descriptors is the size of the grid cell. By its nature, a raster representation or grid cell misses detail. As grid cell length increases, the level of resolution and precision decrease (O'Neill and Mark 1985, Bailey 1988). The problem is one of making the grid cell small enough to represent accurately terrain without storing unnecessary information. Increased precision is gained at the expense of increased data collection, storage, and processing. Grid cell size can be important in mountainous or deeply dissected terrain where large cells may misrepresent smaller surface features such as first-order watersheds (Mark 1975b, Mark 1983, O'Neill and Mark 1985). Mark (1975b) estimated that the average error in relief measures using regular grids was:

$$0.4 \times \text{cell length} \times \tan \alpha$$

$$\text{where: } \alpha = \text{average slope}$$

Based on this equation, relief error for the Havens data set could average 25 meters, or approximately 4% of the *available relief* for the map.

The major source of error in vector-data representation is overlaying 2 or more digitized networks, such as streams, basins, and mesh sources (Burroughs 1986). This error is closely related to the accuracy of the digitizing process, and the nature of the digitized factor (discrete or continuous). I sought to minimize this type of error by digitizing all of a basin's features at once, and then plotting the digitized coordinates to check for poor registration.

The greatest potential for error is with the group of raster-vector descriptors. Descriptors that combine both data types are subject to the errors characteristic of each, and to new sources of error. Miller and Goldberg (1984) pointed to misalignment of raster and vector data sets as a major difficulty. This problem is due to the differences in scale and simplification of the 2 data types. Rasterization of vector data generalizes the vector representation of boundaries, resulting in a loss of detail, which may be compounded by overlaying several of these rasterized vector features. I tried to control this error by minimizing program calls to multiple rasterized vector overlays, and by using vector descriptors rather than raster format descriptors for input as often as possible.

The equation for average error in relief (discussed above) can be used to demonstrate the error potential of raster-vector descriptors. In contrast to map-wide relief, the sample first-order watersheds could have relief error terms of 25 to 41 meters, or as much as 23% of the reported *local relief* values for those basins. The second-order basins in the system demonstration could have average relief errors of 20 to 35 meters, or 12% of the reported *local relief* values.

The final source of error is numerical or computational errors. This is perhaps the most difficult type of error to control. This category includes errors due to insufficient precision, rounding, and inaccurate computation (Burroughs 1986). Map Analysis Package output is in integer format, which could lead to potentially serious errors, especially with measures of slope. I attempted to control these errors with test data sets, checking results by hand, and reporting ratios (indices) to 4 decimal places.

Reducing the number of descriptors

After examining the descriptor results for the 2 test data sets and the sample drainage basins from the Havens Wildlife Management Area, I suspect that some of GEODES' descriptors could be eliminated without compromising the ability of the system to describe structural components of a landscape. This group of descriptors includes: duplicates of other measures, descriptors that yield similar results, and descriptors that yield questionable results. Eliminating some of these descriptors could reduce the potential for confusion among users, and reduce some of the ambiguity inherent in shape analyses.

Some duplication of measures was evident when converting general equations to routines for extraction of descriptors from the raster and vector data bases. These duplicates can be eliminated from the system. *Valley spacing* and the *constant of channel maintenance I* generate the same value consistently, and 1 or the other can be eliminated. Based on the ease of data input, computational effort, ease of description, and the meaning of the descriptors, I recommend that both *true slope* and *total stream length* be dropped from GEODES. When characterizing a stream or an entire basin, *maximum slope* is equivalent to *true slope. True slope*, as it is defined in GEODES, is misleading, referring to the maximum slope angle along a given slope segment, not the entire basin. As programmed in GEODES, *channel length* is equivalent to *total stream length*.

There are several related measures that do not generate the same values but suggest similar results. Eliminating some of these from GEODES could reduce confusion over the interpretation of results. The best example of this is the array of shape descriptors that are currently in the system.

Griffith et al. (1986) reported 3 principal components to a city's shape: compactness, elongation, and concavity. GEODES has at least 5 measures of compactness: *form factor II, circularity I, circularity II, shape factor,* and *delta*. Griffith (1982) recommended 2 of these descriptors to measure compactness, *form factor II* and *circularity I*. At the least, I suggest dropping the *shape factor* and *delta* from GEODES. *Circularity II* might be kept in the system, not because of its value in quantifying shapes, but because it has been widely used in forest and wildlife management and could serve as a standard or reference measure (see Patton 1975, Thomas et al. 1979, Marcot and Meretsky 1983).

Similarly, there are 2 measures of elongation in GEODES, *elongation I* and *elongation II*. According to Griffith (1982), both variables were significant in measuring elongation. However, the first measure was sensitive to regional basin contrasts (McArthur and Ehrlich 1977) and was useful in regressions of rainfall to runoff ratios (Morisawa 1958). So, if one of these measures is to be dropped, let it be *elongation II*.

There are 2 measures of *hydraulic sinuosity, (I and II)*. The results from the system demonstration are similar for both variables, so one measure could be dropped from GEODES. I recommend keeping *hydraulic sinuosity I*, because it uses a more consistent measure of basin length (the longest basin length) than *hydraulic sinuosity II* (basin length parallel to the mainstream channel).

There is a group of descriptors that are either of questionable value or give inconsistent results (based on the system demonstration) and could be dropped from GEODES. *Slope sine* and *slope tangent* were chosen through the selection process detailed in the Methods, but the actual utility of these measures is questionable. These measures are merely transformations of slope values and do not summarize any aspect of terrain.

Main channel slope could be dropped from GEODES. Values for this descriptor are more difficult to calculate and are generally larger than values for *channel gradient*. Similarly, *main channel relief* could be dropped in favor of *stream relief*. These main channel descriptors are generated by combining vector measures (i.e., length of main channel) with raster values (elevation or slope) at 2 different measurement scales. For the system demonstration, grid cells were 100 meters on a side, while vectors were measured to the nearest meter, a difference of 2 orders of magnitude. Both main channel descriptors required calls to 2 different rasterized vector overlays (mesh source and stream), increasing the error potential. *Channel gradient* and *stream relief* were extracted from rasterized vector data, so the scale problem was resolved (all inputs were on similar scales), though some loss of detail could be expected.

Relief ratio I could be excluded from GEODES. The denominator of this measure is the basin length parallel to the main stem, instead of along the principal basin axis. In the system demonstration, this measure suggested that basin 201 was more rugged than it actually was relative to the other second-order basins.

Conclusion

The descriptor selection process reduced the number of descriptors to a more manageable number (see Methods and Results). I identified many uses and potential uses of these descriptors in the Results section titled "Descriptor selection". I hesitate to shorten the list of descriptors that are currently available in GEODES without performing an extensive analysis of landforms. Many of the recommendations for reducing the number of descriptors are tentative and based on a necessarily small sample. Some of these reductions might be unnecessary with greater raster data resolution. Seen in light of general systems theory, the list of available descriptors is short enough to allow managerial use and still provides for yet unspecified applications. Furthermore, the major objective of developing a system to quantify land surface form has been achieved.

Another version of GEODES could be developed that excludes the descriptors mentioned above, along with descriptors that are highly correlated with simple measures of specific terrain attributes (i.e. *mesh length* vs. *channel length*). As an alternative, a version of GEODES could be developed using only those descriptors that placed in the top 35% of each descriptor group, based on their performance scores. Either refinement could make the next version of GEODES a more practical system for the natural resource professional.

GIS and Wildlife Resource Management

Applications

Geographic Information Systems are being applied with increasing frequency to wildlife resource management problems. GIS are used primarily as planning tools. Recent applications of GIS to natural resource management include: natural resource inventory (usually vector-based systems), wildlife habitat assessments, risk assessment, and quantitative modeling or simulation of management consequences (Berry 1987b, Berry and

Sailor 1987, Coulson et al. 1987, Currier and Ziewitz 1985, Goulter and Forrest 1987, Scott et al. 1987).

These applications involve searches for coincidence between variables or overlays (Coulson et al. 1987). Different environmental factors (physical, biological, socio-economic, etc.) are processed to isolate and clarify relations between these factors. This technology offers the potential of better insights to natural resource decision makers (Goulter and Forrest 1987).

In wildlife management, GIS have been used to assess the quantity, quality, and juxtaposition of habitats, and to explore habitat utilization by such diverse species as wild turkey, white-tailed deer, and sandhill cranes (*Grus canadensis*) (Currier and Ziewitz 1985, Donovan et al. 1987, Fales 1969, Fies 1983, Hoar 1980, Jones 1976, Tomlin et al. 1983).

The ability of a GIS to process and overlay data layers rapidly has lent itself to quantitative modeling and simulation. This has encouraged development of models of abiotic processes, such as river basin management or storm runoff prediction (Berry and Sailor 1987, Goulter and Forrest 1987) and biotic processes like vegetative succession (Currier and Ziewitz 1985).

GIS have been used to model habitat changes for populations, species, or communities and to identify needs for ecosystem protection. Recent examples include identification of critical areas for native forest birds in Hawaii, or grizzly bears (*Ursus arctos horribilis*) in the greater Yellowstone ecosystem (Scott et al. 1987, Winn and Barber 1985). Some researchers have coupled GIS technology with concepts of habitat suitability to measure wildlife habitat quality and simulate changes in management strategies (Currier and Ziewitz 1985, Davis and DeLain 1986, Donovan et al. 1987, Winn and Barber 1985).

Some limitations

Some of the limitations of GIS technology have been mentioned in the discussion of raster and vector data formats. These problems include inaccuracy, generalization, precision, and the lack of boundary correspondence between factor maps (Bailey 1988, Berry 1987b). The resource professional should be aware of additional limitations on the use of GIS or automated overlay analyses.

Three important limitations of GIS in wildlife management include: availability of suitable data, assumptions of ecological significance, and familiarity or expertise. Bailey (1988) asserted that some factors such as the degree of landscape dissection (an important factor in estimating sediment losses from an area) are generally not available in map form and may not be practical to develop. Interpreting the results of automated processing of overlays requires familiarity or expertise with the system (Coulson et al. 1987). Bailey (1988) warned against the assumption that significant ecologic units can be captured through the manipulation of overlays. He suggested that clusters of cells based on the attribute similarities are not necessarily ecologically significant units, only portions of those units. He implied that habitat heterogeneity was not accounted for in these clusters.

Alternatives

One alternative to the development of "ecologically significant units" through automated processing of overlays is to select a biologically meaningful factor (such as climate or landform) and to use it to partition a landscape for analysis or planning purposes (Bailey 1988:). The DBMS of GEODES allows the user to partition a landscape based on a specific landform feature (e.g., vector-defined watershed boundaries). These vector features can be used as "cookie cutters" to associate additional data layers with landscape features (watersheds).

An information management system integrating a DBMS with a GIS could make a useful automated system for environmental assessment (Asherin and Drewien 1985). GEODES is such a system, and is able to export data to other operating systems, generate data summaries, and process directed data base inquiries.

Morphometric applications to wildlife

The scope of this project suggests at least 2 types of applications to wildlife research and management: applications of specific descriptors and applications of GEODES, an automated system for quantitative description of land surface shape. Actual applications are limited only by the user's imagination. In the following sections, I have discussed some areas where land surface shape descriptors may be used to increase managerial control and understanding.

Descriptor applications

Many site-specific, GIS related models of abiotic factors have been developed for natural resource management including temperature (Anderson 1981), insolation (Lawrence 1976), wind (Francis 1980, Ryan 1983), and precipitation (Wajda, in progress). These models may improve the ability of wildlife professionals to predict the distribution of plant and animal species, determine factors limiting populations, and increase understanding of wildlife-habitat relationships. These models assimilate general topographic variables such as elevation, or slope and aspect class intervals. I suspect that the performance of many of these models could be improved with more specific terrain measures.

Anderson's (1981) site-specific temperature models are good examples of this point. Temperature estimates could probably be improved with the incorporation of relief and texture measures. Topographic shading was one of the factors that Anderson felt was needed in these models. *Valley spacing* (the distance between parallel streams) and *local relief* could be used to approximate topographic shading in his models.

Fies (1983) developed a system for forest cover type classification based on topographic attributes. This system demonstrated a classification accuracy of 57 to 79%. This accuracy is remarkable because it was based on 4 topographic variables alone: elevation, slope, aspect, and topographic shape (valley, saddle, ridge, etc.). I suspect the accuracy of his system could be improved with one of two additional measures. The *ruggedness number* would add a measure of slope steepness, slope length, and proximity to water to his system. The *length of overland flow* could be used by the system to measure a site's proximity to water.

Proximity to environmental water is an important habitat factor for many wildlife species including wild turkey poults, pileated woodpeckers, moles, and shrews (Conner 1973, Pack et al. 1980, Prescott 1979). Many of the descriptors reported in this thesis were developed to characterize water resources. A logical application of these measures would be to characterize observed relations between water and wildlife. *Drainage density*, the ratio of stream length to area, may be an important variable for predicting beaver abundance and distribution from remote sensing data (Cotton, in progress). *Relief ratios* express basin steepness and hint at the type of water movement that predominates in a given landscape (wash, stream flow, throughflow, etc.). *Channel gradient* and *stream order* have been used to measure and predict the habitats selected by beaver (Naiman et al. 1986). Shape indices can provide general indications of basin flow regimes (Knighton 1984).

One group of descriptors, shape indices, may be applied to wildlife management without consideration of the actual land surface shape. Many of these descriptors could be used to examine patch or island habitats (such as reserves or silvicultural treatments). Patch shape or habitat geometry influences immigration and emmigration and thus may affect population stability, cycles, and the local probability of species extinction (Diamond and May 1976, Game 1980, Buechner 1987, Stamps et al. 1987). Bunnell and Johnson (1974) demonstrated the importance of habitat geometry in the establishment and maintenance of populations of pikas in the Pacific Northwest. In simulation studies, patch shape rather than size may be the major factor affecting net species movements (Buechner 1987). Patch shape suggests the extent of the exposure of the patch interior to the exterior. Small or elongated regions may mean that more of the interior is exposed to exterior agents. Increased exposure could mean an increase in edge-adapted species, or a decline in species that are dependent on an undisturbed internal habitat (Schonewald-Cox and Bayless 1986, Buechner 1987).

Conservation of threatened or endemic species may be more difficult in elongated reserves, because, all else being equal, they are more permeable to immigration and emmigration than more compact reserves (Stamps et al. 1987). Examples of this include the loss of black bears (*Ursus americanus*) at the edges of Shenandoah and Great Smoky Mountains National Parks (hunting, poaching, dispersal, habitat destruction, etc.) and the invasion of Great Smoky Mountains National Park by wild boars (*Sus scrofa*) (Buechner 1987). Both parks are attenuated, increasing the opportunity for exchanges between the interior and exterior of the parks (Buechner 1987).

The descriptors that have been reported in patch shape analyses are either perimeter-to-area ratios (and the inverse) or *circularity II* (Blouin and Conner 1985, Buechner 1987, Faeth and Kane 1978, Game 1980, Schonewald-Cox and Bayless 1986, Stamps et al. 1987). The principle criticism of these indices is that they are overly sensitive to perimeter crenulations (Morisawa 1958, Hobba and Robbinson 1972). An alternative would be to use a battery of indices that would measure the principle components of shape: compactness, elongation, and convexity (Griffith 1982, Griffith et al. 1986). A battery of descriptors that quantify these dimensions might consist of: *form factor II, elongation I,* and the *circularity ratio* (Griffith et al. 1986). These indices could be useful in examining faunal changes on smaller islands such as U. S. Forest Service group selection cuts as well.

Gradients in terrain attributes of slope, relief, and texture may affect the movements of wildlife species across boundaries and landscapes. Many of the descriptors identified in this thesis could be used to measure the energetic cost of travelling across terrain. Beyond the simple measures of slope and aspect, other potentially suitable measures include: *limiting angle* (the range of slopes a life form may occur in), *relief ratios* (overall habitat steepness), *avoidance factor* (difficulty in traversing a habitat), *ruggedness ratio* (maximum relief along a traverse), and *cell length* (the distance in which all relief features are encountered).

A logical follow-up to this research would be to assimilate the geomorphic-based descriptors identified in this thesis into a wildlife habitat classification system based on terrain characteristics. Such a system might integrate the topographic forms (saddle, ridge, valley, etc.) identified by Grender (1976) with geomorphically-based descriptors to identify ecologically significant, 3 dimensional landform elements.

Application of GEODES

Bailey (1988) noted that many potentially useful factors, such as the extent of landscape dissection are not generally available to geographic information systems. This is due to the cost of developing overlays of these factors. GEODES can make available for spatial analysis the kind of factors Bailey discussed, such as *Drainage density*. By integrating raster- and vector-based processing, many of these factors are available on either a map-wide, or feature-by-feature basis.

A system such as GEODES may be quite useful for examining habitat selection and habitat partitioning among wildlife species. I suspect that the application of measures of terrain components of habitat could improve our understanding of the ecological relations and distributions of many species, particularly cryptic species like amphibians, reptiles, and small mammals. The significance of general terrain attributes (such as elevation, slope and aspect) have been reported for several salamander species (Howard and Wallace 1985, Buhlmann et al., in press). One potential study that could improve understanding of wildlife habitat selection, and test the utility of GEODES, would be to explore further the relationship between salamanders of the Ridge and Valley province and terrain attributes. This study could make extensive use of GEODES in the search for factors that explain the distribution and abundance of sympatric species.

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Appendix A.

Map Analysis Package Modifications

This source code contains modifications to the Map Analysis Package that enables it to calculate slope and aspect for irregularly shaped overlays and to use data sets with missing data points.

```
SUBROUTINE SLOPE (JC,JR,OPTION,CWIDTH,IA,IB)
C**********************************************************************
C THIS SUBROUTINE WAS WRITTEN BY DANA TOMLIN, AND MODIFIED BY STEVEN
C MARTIN (VPI & SU). IT CALCULATES MAXIMUM
C SLOPE, AVERAGE SLOPE, ASPECT IN COMPASS DIRECTIONS, AND ASPECT IN
C DEGREES, DEPENDING ON THE USER'S OPTION. OPTION 0 IS AVERAGE SLOPE,
C OPTION 1 IS MAXIMUM SLOPE, OPTION 2 IS ASPECT IN DEGREES, OPTION 3
C IS ASPECT IN COMPASS POINTS.
C**********************************************************************
COMMON/SAM/NP,NI,NCL,NC,NR,NMAPS,NBPM,NBUF,NWIDE,NCPB
INTEGER*2 IA(JC,JR), IB(JC,JR)
INTEGER EL(9), OPTION, CWIDTH, COUNT(9), TOTAL
REAL SLOP(4)
IF(OPTION.LT.0.OR.OPTION.GT.3) OPTION = 0
IF(CWIDTH.LE.0) CWIDTH = NWIDE
C*****************************************************
C PROCESS THE MATRIX, COLUMN BY COLUMN FOR EACH ROW
C*****************************************************
DO 100 L = 1,NR
  DO 100 K = 1,NC
    LTOP = L-1
    LBOT = L+1
    KLEFT = K-1
    KRIGHT = K+1
    N = 0
```

```
      TOTAL = 0
C*********************************************************************
C SET THE WINDOW FOR PROCESSING (9 POINTS, OR 8 NEIGHBORS & THE CELL OF
C    INTEREST)
C*********************************************************************
     DO 200 LL = LTOP,LBOT
       DO 200 KK = KLEFT,KRIGHT
         N = N+1
         COUNT(N) = 0
C**********************
C  CHECK FOR BOUNDARIES
C**********************
         IF(LL.LE.0.OR.LL.GT.NR.OR.KK.LE.0.OR.KK.GT.NC) GO TO 210
C*********************************************
C STORE THE POINT'S ELEVATION IN A WORKING PSN
C*********************************************
         EL(N) = IA(KK,LL)
         GO TO 200
 210      EL(N) = -99
 200 CONTINUE
     DO 220 N = 1,9
C*********************************************************************
C  COUNT THE # OF ZEROS (MISSING ELEVATIONS) FOR THE CELL AND ITS
C  NEIGHBORS
C*********************************************************************
       IF (EL(N).EQ.0) COUNT(N) = 1
       TOTAL = TOTAL + COUNT(N)
C****************************************
C SEPARATE BOUNDARIES FROM INTERIOR CELLS
C****************************************
       IF(EL(N).NE.-99) GO TO 220
       NN = 10-N
       IF(EL(NN).EQ.0) THEN
          EL(N) = 0
          COUNT(N) =1
          GO TO 220
       ENDIF
C******************************
C FIND A VALUE FOR BOUNDARY CELLS
C******************************
       IF(EL(NN).EQ.-99) EL(NN) = EL(5)
       EL(N) =(EL(5)*2) - EL(NN)
 220 CONTINUE
      IF(OPTION.NE.1) GO TO 290
C****************************
C   CALCULATE MAXIMUM SLOPE
C****************************
 230  NN = -1
      SLOP(1) = 0.0
      SLOP(2) = 1.0
C*********************************************************************
C IF THE CELL OF INTEREST IS 0 (MISSING DATA) THEN GO TO THE NEXT CELL
C*********************************************************************
      IF(EL(5).EQ.0) GO TO 100
      DO 240 N = 1,9
        NN = -NN
        SLOP(2) = SLOP(2) + (0.4142*NN)
C*******************************************************************
C IF THE ELEVATION IS MISSING (0 IN THIS CASE), MOVE TO THE NEXT PSN
C*******************************************************************
        IF (EL(N).EQ.0) GO TO 240
        SLOP(3) = (EL(5)-EL(N)) / (CWIDTH*SLOP(2))
        SLOP(4) = 1.0
        IF(SLOP(3).LT.0) SLOP(4) = -1.0
        IF(SLOP(3)*SLOP(4).GT.SLOP(1)) SLOP(1)=SLOP(3)*SLOP(4)
 240  CONTINUE
    IB(K,L) = (SLOP(1)*100.0)
    IF(OPTION.GT.1) GO TO 500
    GO TO 100
C************************
C CALCULATE AVERAGE SLOPE
C************************
```

```
 290 SOUTH = 0.0
     WEST = 0.0
C*****************************************************************
C IF THE # OF 0'S IN A ROUND WAS GREATER THAN 0, CALCULATION OF AVE.
C SLOPE IS COMPLICATED
C*****************************************************************
     IF (TOTAL.GT.0) THEN
C***************************************************
C IF THE CELL'S VALUE IS 0 THEN LOOK AT THE NEXT CELL
C***************************************************
       IF (EL(5).EQ.0) GO TO 100
C*****************************************************
C TEST IF THERE IS A VALUE IN A CELL AND ONLY 1 NEIGHBOR
C*****************************************************
       IF(TOTAL.EQ.7) GO TO 230
C******************************************************************
C OTHERWISE, IF 2 OR MORE OF ITS NEIGHBORS ARE 0, THEN IT'S ROOK'S CASE
C******************************************************************
       CALL TWOPT(N,EL,CWIDTH,WEST,SOUTH)
       GO TO 350
     ELSE
   DO 300 N = 1,4
      NN = 10-N
      IF( (EL(N)-EL(5)) * (EL(5)-EL(NN)) .GE.0) GO TO 310
      SLOP(N) = 0.0
      EL(N) = 0
   GO TO 300
 310  SLOP(N) = (EL(N)-EL(NN)+0.0) / (CWIDTH*2.0)
      EL(N) = 1
 300  CONTINUE
     ENDIF
     IF(EL(1)+EL(2)+EL(3).EQ.0.OR.EL(1)+EL(4)+EL(3).EQ.0)GO TO 400
     SOUTH = (SLOP(1)+SLOP(2)+SLOP(3)) / (EL(1)+EL(2)+EL(3))
     WEST = (SLOP(1)+SLOP(4)-SLOP(3)) / (EL(1)+EL(4)+EL(3))
 350 IF(OPTION.GT.1) GO TO 500
C**********************************************
C CALCULATE AVE. SLOPE FROM X & Y COMPONENTS
C**********************************************
     IB(K,L) = (100.0*SQRT(SOUTH**2+WEST**2)) + 0.5
     GO TO 100
 400 IF(OPTION.GT.0) GO TO 500
     IB(K,L) = 0
     GO TO 100
 500 IF(SOUTH.NE.0.0.OR.WEST.NE.0.0) GO TO 600
     IB(K,L) = 0
     GO TO 100
C****************************
C CALCULATE ASPECT IN DEGREES
C****************************
 600 KK = 2
     RADIAN = ATAN2(WEST,SOUTH)
     IF(RADIAN.GE.0.0) KK = 0
     IB(K,L) =180.0-((RADIAN+(KK*3.141593)) * 57.295773)
     IF(IB(K,L).LT.0) IB(K,L) = IB(K,L)+360
 700 IF(OPTION.EQ.2) GO TO 100
C**********************************************
C CALCULATE ASPECT IN TERMS OF COMPASS DIRECTIONS
C**********************************************
     IF(IB(K,L).GT.337.AND.IB(K,L).LE.360) IB(K,L) = 0
     IB(K,L) = ((IB(K,L)+22.5) / 45.0) + 1
 100 CONTINUE
RETURN
END

     SUBROUTINE TWOPT (N,EL,CWIDTH,SUMX,SUMY)
C*************************************************************
C WRITTEN BY STEVEN MARTIN, DEPT.FIW, VPI & SU
C
C THIS SUBROUTINE CALCULATES THE X AND Y COMPONENTS OF SLOPE
C WITHIN A RASTER DATABASE. IT USES A MODIFICATION OF THE
C TWO-POINT ALGORITHM FOR SLOPE COMPUTATION DESCRIBED BY
C O'NEILL AND MARK (1987). THIS IS THE ROOK'S CASE OR 4 CONNECTED,
```

```
C 2 ORTHOGONAL NEIGHBORS ALGORITHM. THIS ROUTINE IS USED BY THE
C MAIN SLOPE SUBROUTINE WHEN THERE IS AN OUT OF BOUNDS DATA POINT,
C SUCH AS 0. IT COULD BE USED TO COPE WITH MISSING VALUES IN THE
C DATABASE.
C
C VARIABLES INCLUDE:   N - A POSITIONAL MARKER
C                   EL - AN ARRAY CONTAINING NEIGHBOR ELEVATIONS,
C                      USED IN CALCULATING A CELL'S SLOPE.
C                   CWIDTH - CELL WIDTH
C                   SUMX - THE SUM OF THE X SLOPE COMPONENTS
C                   SUMY - THE SUM OF THE Y SLOPE COMPONENTS
C                   COUNTER - A COUNTER
C                   XSLOPE AND YSLOPE ARE ARRAYS, EACH ELEMENT
C                     CONTAINS AN X OR Y COMPONENT OF 1 ROOK'S
C                     CASE CONTRAST.
C*********************************************************************
COMMON/SAM/NP,NI,NCL,NC,NR,NMAPS,NBPM,NBUF,NWIDE,NCPB
INTEGER EL(9), CWIDTH, COUNTER
REAL XSLOPE(4),YSLOPE(4),SUMX,SUMY
    COUNTER  = 0
C*****************************************************************
C IF THE SECOND POSITION IS NOT 0, THEN CHECK THE 4 & 6 POSITIONS.
C*****************************************************************
    IF(EL(2).NE.0) THEN
C*******************************************************
C IF PSN 4 IS NOT 0, CALCULATE THE X & Y SLOPE COMPONENTS
C USING ELEVATIONS IN PSNS 2,4, &5
C*******************************************************
        IF(EL(4).NE.0) THEN
           COUNTER = COUNTER + 1
           XSLOPE(COUNTER) = ABS((EL(5) - EL(2) + 0.0)/(CWIDTH*2.0))
           YSLOPE(COUNTER) = ABS((EL(5) - EL(4) + 0.0)/(CWIDTH*2.0))
        ENDIF
C*******************************************************
C IF PSN 6 IS NOT 0, CALCULATE THE X & Y SLOPE COMPONENTS
C USING ELEVATIONS IN PSNS 6,2, &5
C*******************************************************
        IF(EL(6).NE.0) THEN
           COUNTER = COUNTER + 1
           XSLOPE(COUNTER) = ABS((EL(5) - EL(2) + 0.0)/(CWIDTH*2.0))
           YSLOPE(COUNTER) = ABS((EL(6) - EL(5) + 0.0)/(CWIDTH*2.0))
        ENDIF
    ENDIF
C*****************************************************************
C IF THE EIGHTH POSITION IS NOT 0, THEN CHECK THE 4 & 6 POSITIONS.
C*****************************************************************
    IF(EL(8).NE.0) THEN
C*****************************************************************
C IF PSN 4 IS NOT 0, CALCULATE THE X & Y SLOPE COMPONENTS
C USING ELEVATIONS IN PSNS 8,4, &5
C*****************************************************************
         IF(EL(4).NE.0) THEN
            COUNTER = COUNTER + 1
            XSLOPE(COUNTER) = ABS((EL(8) - EL(5) + 0.0)/(CWIDTH*2.0))
            YSLOPE(COUNTER) = ABS((EL(5) - EL(4) + 0.0)/(CWIDTH*2.0))
         ENDIF
C*******************************************************
C IF PSN 6 IS NOT 0, CALCULATE THE X & Y SLOPE COMPONENTS
C USING ELEVATIONS IN PSNS 8,6, &5
C*******************************************************
         IF(EL(6).NE.0) THEN
            COUNTER = COUNTER + 1
            XSLOPE(COUNTER) = ABS((EL(8) - EL(5) + 0.0)/(CWIDTH*2.0))
            YSLOPE(COUNTER) = ABS((EL(6) - EL(5) + 0.0)/(CWIDTH*2.0))
         ENDIF
    ENDIF
C*****************************************************
C SUM THE X SLOPE COMPONENTS AND THE Y SLOPE COMPONENTS
C*****************************************************
    DO 20 I = 1,COUNTER
        SUMX = SUMX + XSLOPE(I)
        SUMY = SUMY + YSLOPE(I)
```

```
 20 CONTINUE
   SUMX = SUMX/COUNTER
   SUMY = SUMY/COUNTER
RETURN
END
```

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