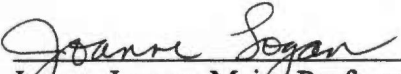
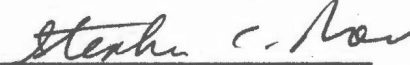
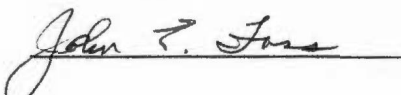


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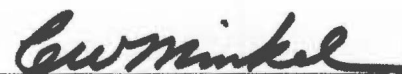
I am submitting herewith a thesis written by Thomas Bryan Coffey entitled "Using GIS to Analyze the Precipitation Regime of the Great Smoky Mountains National Park, TN/NC". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Plant and Soil Science.


Joanne Logan, Major Professor

We have read this thesis and
recommend its acceptance:

Accepted for the Graduate Council:


Associate Vice Chancellor and
Dean of the Graduate School

**Using GIS to Analyze the Precipitation Regime of the
Great Smoky Mountains National Park, TN/NC**

A Thesis

presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Thomas Bryan Coffey

May 1995

DEDICATION

This thesis is dedicated to my parents, Ray and Arlene Coffey, who have provided the financial, but more importantly the moral and the emotional support throughout the duration of my graduate career. Their guidance has contributed greatly to my perseverance and success.

For my wife and best friend,

Lynn

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Abstract

Studies or research conducted in remote areas of the Great Smoky Mountains National Park (GSMNP) involving the use of precipitation data, have often resolved to utilizing the precipitation data from weather stations located in more easily accessible areas or from nearby towns and cities. This study was conducted to determine an accurate annual average precipitation value for the GSMNP and to develop an average annual precipitation database (coverage) for the park as a whole. Precipitation data from 51 weather stations in and around the GSMNP were placed into the geographic information system (GIS), ARC/INFO, and three methods were implemented to meet the desired objectives. These methods included: 1) constructing a THIESSEN polygon coverage from the precipitation station locations, 2) employing the use of a Triangulated Irregular Network (TIN) of the precipitation stations to create a precipitation coverage, and 3) establishing a linear relationship between the terrain data (elevation, slope and aspect) and the precipitation data obtained at the station locations and implementing this linear equation within the GIS to construct the precipitation coverage. The THIESSEN method determined the annual average precipitation to be 1542.5 mm with a maximum value of 2105.9 mm and a minimum value of 1194.8 mm; however, this database had an unrealistically small number of different precipitation values. The TIN method estimated the annual average precipitation to be 1532.1 mm with a maximum value of 2099.3 mm and a minimum value of 1217.9 mm. Again, the database obtained had only a limited number of precipitation data. The linear model developed from the statistical method showed a significant ($R\text{-square} = .80$, $p = 0.05$) relationship between the terrain data and

the precipitation data, indicating that changes in terrain influence precipitation amounts (Shanks, 1954). The linear equation estimated the average annual precipitation of the GSMNP to be 1575.1 mm with a maximum value of 2013.5 mm and a minimum value of 1217.7 mm. The statistical method seemed to develop the best representation of the precipitation of the park as it determined a larger variety (2,292,296 values) of precipitation values which were based on the various changes of the complex terrain within the study area. The precipitation database obtained from the statistical method could aid researchers and other interested persons in their studies of the GSMNP.

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Review of Literature

Description of the Study Area

Background

The Great Smoky Mountains National Park (GSMNP) lies on the border of Tennessee and North Carolina. It is bounded by the Pigeon River along its eastern side and the Little Tennessee River along its western side (Murless and Stallings 1973). It occupies portions of Blount, Sevier and Cocke counties in Tennessee and Swain and Haywood counties in North Carolina. The park is located between 35°25' and 35°47' N latitude and 83°02' and 84°01' W longitude. The boundary of the park encompasses an area¹ of 2063.1 square kilometers. Of this area, over 85% (Campbell, 1960) has been influenced by human activity. The remaining 15%, or nearly 200,000 acres, has never been commercially logged (National Park Service, 1981; Pyle, 1985) and has been described as virgin forest (Broome, 1965).

The park was established on June 15, 1934 through the acquisition of land by the United States Government beginning in 1926. This acquired land belonged to 18 timber and pulpwood companies and contained 1,200 farm tracts of various sizes and more than 5,000 lots and summer homes (Campbell, 1960).

Topography

The GSMNP is located in the Unaka Range of the Blue Ridge physiographic province in the Southern Appalachian Mountains (Cain, 1937; Fenneman, 1938). The Great Smokies are a central part of the master chain of the Southern Appalachians

¹Determined from a digitized 1:125,000 scale boundary of the GSMNP provided by the National Park Service (NPS).

(Peattie, 1943). The mountains in the park contain some of the highest peaks in Eastern North America. The main crest of the mountain chain stands above 1524 meters for 58 of its 114 kilometers in length (National Park Service, 1981) and is the major drainage divide in the park (McMaster and Hubbard, 1970). Clingmans Dome is the highest peak in the park at 2,025 meters. There are 15 other peaks that rise above 1,828 meters in elevation (National Park Service, 1981). The slopes of the mountains form most of the area for the GSMNP. It has been estimated that more than 90% of the surface area has slopes greater than 10° (Whittaker, 1956). The mountains extend in a general direction from southwest to northeast, but individual ridges often lie at nearly right-angles to the general direction of the chain and have no general direction (Donley and Mitchell, 1939). They are high, very rugged and densely forested (Peattie, 1943). Most of the peaks are dome-shaped with steep sidewalls descending into narrow valleys (King and Stupka, 1950). The valleys are V-shaped and deep with rather steep but evenly-sloping sides (Cain, 1937). The mountains and valleys of the GSMNP have been carved with large amounts of water erosion (Peattie, 1943).

The Blue Ridge is the dividing line between the east-flowing and west-flowing rivers in the Eastern United States, but the drainage of the GSMNP is completely westward into the Tennessee River (Cain, 1937; Murless and Stallings, 1973). The drainage system is characterized by a dense network of small streams flowing through steeply-sloping channels to the Tennessee River or its tributaries (McMaster and Hubbard, 1970) and has been classified into two patterns. A dendritic drainage pattern is most characteristic of the slopes of the mountains facing east and a trellis drainage pattern for

the mountains facing west (Houk, 1993). Peattie (1943) describes the drainage system of the GSMNP as the most abundant and elaborate on the continent due to the heavy rainfall that descends upon these highlands. Whittaker (1956) reports that almost all the mountain surface is covered by a mantle of soil and vegetation. Probably no portion of North America has a more intricate physiography than the Southern Appalachians (Peattie, 1943).

Geology

The rocks that underlie the main crest of the GSMNP are highly resistant to erosion (Wolfe, 1967) and have maintained high relief in spite of their age (Whittaker, 1956). These sedimentary rocks were constructed during the Late Precambrian period. The Ocoee Series of this period forms most of the rocks of the GSMNP and adjacent foothills. This series has been complexly folded and faulted by varying degrees of heat and pressure which in turn has attributed to the basic form of the mountains (Cain, 1937; King et al., 1968).

The Ocoee Series includes several differing parts: the Snowbird Group, the Walden Creek Group and the Great Smoky Group. These Groups are distributed at various locations in the park. The Snowbird Group occurs in the middle, in the foothills just north of the mountains. The Walden Creek Group occurs in the northwest, in the part of the foothills nearest the Appalachian Valley. The Great Smoky Group, which forms the main bulk of the Great Smoky Mountains, is most widespread toward the southeast, where it forms the main mass of the mountains. This group extends the entire length of the park. The Great Smoky Group runs from near the Pigeon River in the east to beyond

the Little Tennessee River in the west (King et al., 1968). Each Group of the Ocoee Series consists of multiple interbedded formations. Since the Great Smoky Group occupies the main mass of the GSMNP, it will be the only group to receive attention here.

The Great Smoky Group is a thick mass of clastic sedimentary rocks, pebble conglomerate, coarse to fine sandstone, and silty or argillaceous rocks. These rocks are divided into four intertonguing formations: the Elkmont Sandstone (fine-grained), the Thunderhead Sandstone (coarse-grained), the Anakeesta Formation (dark, silty argillaceous rocks) and an unnamed sandstone. The Elkmont and Thunderhead Sandstones are somber gray and thick bedded and are composed principally of quartz and potassic feldspar grains with some quantities of plagioclase feldspar, granite and quartzite. These are found in the middle to lower portions of the park. The Anakeesta Formation incorporates portions of dark silty and argillaceous rocks, which contain little free carbon and iron sulfides, that are altered to slate, phyllite, or schist. This formation is found in the higher parts of the Great Smoky Mountains (King et al., 1968).

Soils

Examination of the county soil maps² indicate that the most common soils for the GSMNP are the Ramsey soils. These include the Ramsey slaty silt loam, steep phase, the Ramsey slaty silt loam, very steep phase, and the Ramsey stony fine sandy loam, very steep phase. The Ramsey soils have low to moderate fertility and are of medium to strong acidity. These soils are shallow, occur on steep slopes (35 to 50+ percent) and therefore hold little water for plant use. The Ramsey soils are best suited for forestry. Other soils

² Blount, Sevier and Cocke counties TN. Haywood County, NC. Swain County, NC not available.

noted are the Allen-Hayter soils that occupy Cades Cove and the Jefferson, Barbourville and Hamblen soils that fill the larger stream and creek beds (U.S. Soil Conservation Service, 1953). It has been determined that soil pH decreases with elevation and varies with vegetation type (Cain, 1931; Golden, 1974; MacKenzie, 1993).

Inceptisols, Ultisols and Spodosols cover the Unaka Mountains. Springer and Elder (1980) describe these soils in the following manner.

“Generally, the soils on the upper parts of the mountains are about 1 to 3 feet deep over rock, are loamy, and contain varied amounts of rock fragments. On the talus or lower parts of the slopes, which may amount to one-half or more of the entire mountainside, the soils are about 3 to 7 feet deep over rock, are loamy and perhaps stony, and support highly productive woodlands. Soils generally are darker, deeper, and more productive on north-facing slopes than on south-facing slopes. The valleys contain a variety of soils, most of them deep, well drained, loamy and productive.”

In classifying these soils according to their annual average temperatures, these soils have been placed in the thermic (greater than 15°C) category, the mesic (between 15°C and 8.33°C) category and the frigid (less than 8.33°C) category. Frigid soils are found only on the mountain tops above 1524 meters. Soils found on the north-facing slopes may be mesic and on the south-facing slopes may be thermic (Springer and Elder, 1980).

Vegetation

For its size, the GSMNP contains one of the most diverse populations of vegetation in the world. This population consists of 130+ species of trees and approximately 1300 species of flowering plants (King and Stupka, 1950; Whittaker, 1956; Bogucki, 1970; Houk, 1993). The park also contains a variety of species of mosses, ferns,

liverworts, lichens, and fungi. Jennison (1939), Wolfe (1967) and Frome (1986) report that the GSMNP has more species of trees than the entire continent of Europe. Whittaker (1956) states that the Great Smoky Mountains of Tennessee and North Carolina support vegetation which is particularly rich in species and varied in community types. Whittaker (1956) also concludes that the vegetation of the GSMNP is a complex mix of coniferous and deciduous forest. Houk (1993) reports more than 80 percent of the park's land is classified as part of the complex Eastern Deciduous Forest Ecosystem. The Great Smokies contain the nation's largest and finest remaining virgin forest of mixed hardwoods as well as the largest and finest forest of virgin red spruce (Campbell, 1960). The vegetation of the GSMNP is a tall three-tiered forest with a mantling carpet of moss and herbs upon the ground (Peattie, 1943).

The diversity of topography and the great range in elevation contribute to the abundant amounts of precipitation and wide range of relatively mild temperatures. This in turn contributes to the rich variety of vegetation within the GSMNP (Braun, 1950; Whittaker, 1956). The span of elevation ranging from 256 meters at the mouth of Abrams Creek to 2025 meters at Clingmans Dome has divided the park into three distinct life zones: the Carolinian, the Alleghenian Transition, and the Canadian (NPS, 1981). These life zones are occupied by the species of flora that can survive and dwell there. Even though the range in elevation of the park is dramatic, the mountains are not high enough to support a present-day, climatic treeline (Harmon et al., 1983; MacKenzie, 1993).

Climatic diversity is also another contributor to the wide variety of vegetation in the Great Smoky Mountains (Bogucki, 1970). The GSMNP receives abundant rainfall

throughout the year with the higher elevations receiving nearly twice the amount of precipitation as the nearby lowlands. The evidence of temperature differences within the park are also visible in the vegetation patterns. In the spruce-fir forest, temperatures average 5.6°C to 8.3°C lower than those at the base of the mountains during the growing season (Shanks, 1954). This lower temperature is ideal for the existence of spruce-fir in the higher elevations. Cain (1937) reports that large vegetational belts are a reflection of the broad climatic belts. This idea of climatic diversity is due to the southern latitudinal location of the GSMNP and the grand range of elevation.

Communities within the GSMNP are defined by the predominant tree species (Houk, 1993). Whittaker (1956) has classified the vegetation of the GSMNP into 14 major mature vegetation types (Harmon et al., 1983) based on elevation and site moisture. MacKenzie's (1993) methods determined that 12 vegetation types occurred in the Thunderhead Mountain area. MacKenzie (1993) then concluded that these vegetation types were representative of a synthesis of Great Smoky Mountains National Park vegetation described by others (Miller, 1938; Whittaker, 1956; Golden, 1981; Eager, 1984a; Callaway et al., 1987). These 12 vegetation types derived by MacKenzie (1993) are Cove Hardwood, Northern Hardwood, Hemlock-Hardwood, Mixed Mesic Hardwood, Mesic Oak, Xeric Oak, Oak-Pine, Pine, Tulip Poplar, Treeless, Heath Bald and Grape Thicket.

Heath Balds occur at elevations of 900 to 2000 meters and are usually found on ridge tops and convex slopes (MacKenzie, 1993). Whittaker (1956) describes the Heath Balds as being dominated with species of evergreen shrubs. The Grape Thickets occur at

the low to mid elevations and are composed of a number of thicket forming *Vitis* species (MacKenzie 1993). The remaining ten vegetation types have been described by Eager (1984a) and are reproduced in table 1 from MacKenzie (1993). The distribution of vegetation within the GSMNP is represented in figure 1.

Another vegetation type of the GMNSP recognized but not described by MacKenzie (1993) is the Spruce-Fir forest. This forest community is found at the highest elevations in the park. The Spruce-Fir forest begins at about 1450 meters in elevation with *Picea rubens* (red spruce) being the dominant species. This species forms mixtures with *Abies fraseri* (Fraser fir) to about 1890 meters in elevation, where *A. fraseri* becomes predominant (Golden, 1974). Pauley (1989) states yellow birch (*Betula lutea*) is a frequent associate of the Spruce-Fir forest.

Climate

In describing the climate of the Southern Appalachians of which the GSMNP is a part, Henry (1911) claims that the climate of westward facing slopes of this region is rather closely related to the great continental type of climate of the middle latitudes (found between the Mississippi River Valley and the foothills of the Rocky Mountains). The continental type of climate has cold winters and hot summers. The eastward facing (Atlantic) slopes have a modified continental type climate (U.S.D.A, 1941) that is somewhat less severe, being often influenced by the warm southerly winds in the winter and the cool oceanic winds in the summer.

Although the climate of the GSMNP and the Southern Appalachians is similar to that of the continental type, it does possess distinctive characteristics, such as lower

Table 1. Vegetation of the GSMNP

Vegetation type	Description
Cove Hardwood	Major Species include <i>Tilia heterophylla</i> , <i>Halesia carolina</i> , <i>Acer saccharum</i> , <i>Acer rubrum</i> , <i>Aesculus octandra</i> , <i>Fagus grandifolia</i> , <i>Magnolia acuminata</i> , <i>Betula lenta</i> and <i>Tsuga canadensis</i> . Cove Hardwood forest generally do not have a single dominant species. This type typically occurs in coves, draws and ravines from 450 to 1200 meters.
Northern Hardwood	Major species include <i>Fagus grandifolia</i> and <i>Betula lutea</i> . Minor species include <i>Acer rubrum</i> , <i>A. saccharum</i> and <i>Quercus rubra</i> . This type generally occurs at elevations above 1075 m.
Hemlock-Hardwood	This type is dominated by hemlock (< 50% of stems) but any of the Cove Hardwood species may be found as minor species. This type is considered a subdivision of the Cove Hardwood type and is found in similar sites.
Mixed-Mesic Hardwood	This type has no clear dominant but may contain <i>Quercus</i> , <i>Liriodendron tulipifera</i> , <i>Pinus</i> , <i>Acer rubrum</i> , <i>Juglans nigra</i> , <i>Liquidambar styraciflua</i> , <i>Platanus occidentalis</i> , <i>Carya</i> , <i>Robinia pseudoacacia</i> , <i>Ulmus</i> , and others. This type is found mainly where farming occurred or in recently logged (approx. 70 years ago) areas. Elevation is typically < 750 m.
Mesic Oak	Major species include <i>Quercus rubra</i> , <i>Q. prinus</i> and <i>Q. alba</i> . At higher elevations (> 1050 m) this type occurs on ridges and south facing slopes. At lower elevations, this type occurs on ridges and side slopes.
Xeric Oak	Major species include <i>Quercus coccinea</i> , <i>Q. prinus</i> , <i>Nyssa sylvatica</i> , <i>Oxydendron arboreum</i> and <i>Robinia psuedoacacia</i> . This type typically occurs on ridges and side slopes below 1050 m.
Oak-Pine	This type contains an even mixture of oak and pine. It typically occurs on ridges and south facing slopes at middle and lower elevations.
Pine	Major species include <i>Pinus rigida</i> , <i>P. pungens</i> and <i>P. echinata</i> . <i>Pinus strobus</i> and <i>P. virginiana</i> are minor species of this type. This type has the same site characteristics as the Oak-Pine type.
Tulip poplar	This type is dominated by <i>Liriodendron tulipifera</i> . The type occurs in coves and valleys at elevations from 300 to 1050 m and is typical of areas that had been logged or farmed prior to the establishment of the park.
Treeless	The Treeless vegetation type in the Thunderhead Mtn. test study area represents what Eager (1984a) refers to as a Grassy Bald. The grassy bald within GSMNP are dominated by grasses with only minor occurrences of trees. Grassy balds are generally found on the mountain tops above 1525 m and appear to be anthropogenic communities (Harmon et al. 1983).

From MacKenzie, 1993.

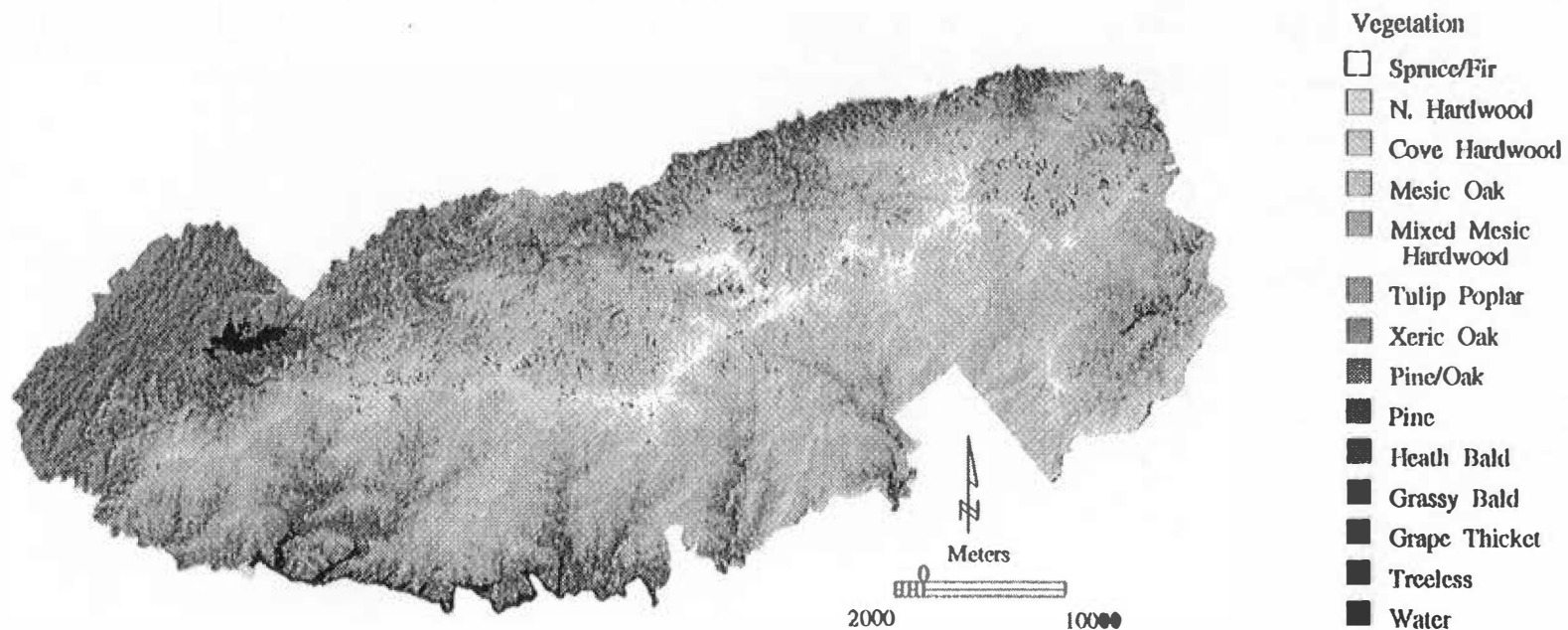


Figure 1. Vegetation of the GSMNP. MacKenzie, M. 1993. The vegetation of the Great Smoky Mountains National Park: past, present and future.

summer and winter temperatures, greater rainfall and snowfall, a drier atmosphere, higher wind velocity and a greater intensity of direct solar rays. These characteristics are due for the most part to the greater altitude of the Appalachian region as compared with surrounding regions (Henry, 1911).

Cain (1937) describes the climate and soils of the GSMNP in the following manner:

“In the Smokies, the higher altitudes have more rainfall, more frequent rains, more fogs and cloudiness, cooler temperatures, smaller temperature ranges, a shorter growing season, more acid soils, more sterile soils due to the washing out of soluble substances than do the lower regions.”

Shanks (1954) used the Thornthwaite's climate classification method (1948) to classify the climate at four stations located at different elevations in the GSMNP. Meteorological data from the years 1946-1950 were taken at stations located at elevations of 445 meters, 1158 meters, 1524 meters, and 1920 meters and analyzed. The 445 m station was classified as humid mesothermal, whereas the 1158 m and the 1524 m stations were classified as perhumid mesothermal. The classification of the 1920 m station was beyond the perhumid microthermal category. Another significant finding of Shanks (1954) is that mountain climates above an altitude of 610-760 meters are extremely humid; they fall into the rain forest or perhumid class. Shanks (1954) also concludes that precipitation exceeds evapotranspiration at the higher elevations. Golden (1974) attributes the considerable climatic variation of the GSMNP to the effects related to elevational change. The climate of the spruce-fir zone of the GSMNP is comparable to

the climate of the spruce-fir zone of the White Mountains of Vermont (Oosting and Billings, 1951).

Stephens (1969) analyzed hourly temperature and relative humidity data and daily precipitation and cloud cover data from the period of 1947-1950. The data were collected at the same elevations as in Shanks' (1954) study. Stephens' (1969) findings indicate that percent cloud cover generally increased with elevation, but decreased during the warmer part of the year. He also notes that temperature decreases and precipitation increases with increasing elevation. Relative humidity increases with altitude, although the relative humidity at the 1920 m station was reduced probably by higher wind movement. The distribution of relative humidity had a greater range during the colder months than in summer. Vapor pressure deficit decreased with increasing elevation (Stephens, 1969).

The effects of local climate or microclimate are particularly pronounced in areas of rugged terrain (Hicks, 1979). Therefore, microclimatic variations can be accounted for in the GSMNP. Southerly-facing slopes appear to be drier and warmer as compared to their northerly-facing counterparts. Solar radiation seems to be the driving force behind these variations. Exposed areas such as peaks and ridges receive more solar radiation and tend to be drier and warmer, whereas valleys, coves, gaps, and sheltered areas, seem to be wetter and cooler. Hicks (1979) states that sheltering valley walls reduce radiation input into coves. Furthermore, microclimatic variations can also be seen in the different vegetation zones. Hicks (1979) also determined that the less complete canopy of the heath vegetation, as compared to the canopy of a cove forest community, allows more radiation to penetrate into the community and increase the local temperature. Altitude,

slope, exposure, and other topographic factors radically influence the environment as well (Cain, 1937). Dickson (1959) estimated that extreme microclimatic effects began to occur at an elevation of 1524 meters.

Temperature

Henry (1911) states that the temperatures of the Southern Appalachian region are generally proportional to the altitude, but they decrease at various lapse rates. Conrad and Pollack (1950) defines the temperature lapse rate as the amount of temperature change per given elevational change. Shanks (1954) determined that the average annual temperature will decrease at a lapse rate of 1.24°C per increase in 304.8 meters of elevation within the GSMNP. Dickson (1959) found that the annual temperature lapse rate and the temperature lapse rates for the months of January and July were 1.56°C , 1.16°C and 1.89°C per 304.8 meters, respectively. The increase in lapse rate in the summer in the Smokies reflects a more pronounced temperature gradient attributable to greater radiation income (Hicks, 1979). Stephens (1969) indicates that February was consistently the coldest month and July was the hottest. The temperature at Gatlinburg, TN (the 445 m station) averages 13.6°C annually. The higher elevations average $5.6\text{-}8.4^{\circ}\text{C}$ cooler than the base of the mountains during the growing season (Shanks, 1954).

Stephens (1969) calculated a temperature lapse rate for each month of the year to determine if they varied either seasonally or altitudinally. Using the 445 m stations as a base, Stephens (1969) calculated lapse rates from this station to the other stations in his study. He determined that the lapse rate based on monthly mean temperatures decreased with an altitudinal range. The largest temperature lapse rate occurred between the 445 m

station and the 1158 m station. The smallest temperature lapse rate occurred between the 445 m station and the 1920 m station. This indicates that the temperature-altitude relationship was not linear and that the lapse rates did not show consistent decrease with increase in elevational range (Stephens, 1969). As elevation increases (in the Rocky Mountains), the lapse rate becomes smaller (Daubenmire, 1956). Stephens (1969) determined that the same type of relationship exists for the GSMNP.

Precipitation

Donley and Mitchell (1939), Smallshaw (1953), Shanks (1954), Dickson (1959), Bogucki (1972) and Hicks (1979) determined that precipitation amounts increase with elevation in the Southern Appalachians including the GSMNP. Stephens (1969) found similar results except for the two highest stations (1524 m and 1920 m) in his study. From November through March the 1524 m station had greater precipitation amounts than the 1920 m station. During the rest of the year, the 1920 m exhibited greater amounts of precipitation (Stephens, 1969). This indicates a seasonal distribution of precipitation. Differences in average annual precipitation of more than 635 mm between a rain gauge in a valley and one on a peak less than 16.1 kilometers away are not uncommon (McMaster and Hubbard, 1970). Shanks (1954) summarizes the precipitation regime of the Great Smoky Mountains National Park in the following manner:

“In summary it might be said that the precipitation at the base of the mountains is not far different from that of the adjacent valley area, but that it increases sharply with altitude, and has increase 50% by the time the lower limit of the spruce-fir zone is reached, at 4500 to 5000 feet.”

Precipitation ranges from an annual average of 1410 mm in Gatlinburg, TN to 2160 mm near the peak of Clingmans Dome (Stephens, 1969). Precipitation in the park averages 1626 mm annually (figure 2), which amounts to 3.36 billion cubic meters of water (McMaster and Hubbard, 1970). The rainfall amounts at the higher elevations are near rain forest proportions (Houk, 1993). Precipitation is fairly evenly distributed throughout the year although maximums and minimums occur. April-May and September-October can be dry periods (Houk, 1993). At elevations of 1158 m, 1524 m and 1920 m, January is the wettest month. August is the wettest month at the 445 m station. The month of lowest precipitation totals is September for the 445 m and 1158 m stations, April for the 1524 m station and October for the 1920 m station (Stephens, 1969). Bogucki (1972) determined that intense rainfalls are more prevalent during the summer half of the year (April through September).

Circulation Patterns

The weather and climate of any particular area are greatly influenced by the types of airmasses that frequent the region. Maritime tropical and continental tropical are the types of airmasses that affect the area of the Southern Appalachians. These warm, moist, unstable airmasses originate as a result of evaporation in their source region³ and begin to move with the prevailing circulation currents. The continental tropical airmasses that affect the GSMNP originate over the southern plains, whereas the maritime tropical airmasses originate over the Gulf of Mexico and southern Atlantic Ocean. During the spring, fall and winter, cyclonic storms move across the region from a southwesterly to a

³ The area where an air mass acquires its characteristic properties of temperature and moisture. (Lutgens and Tarbuck, 1992).

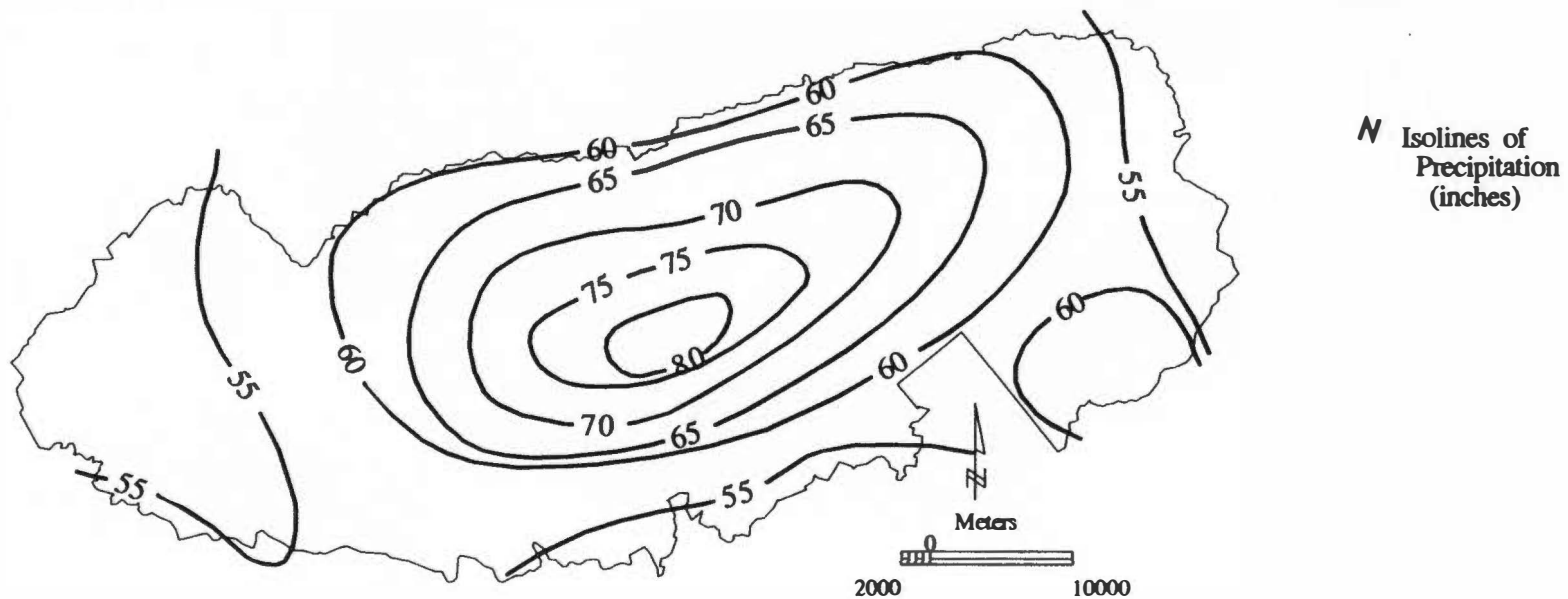


Figure 2. Precipitation of the GSMNP. McMaster, W.M. and E.F. Hubbard, 1970. Water resources of the Great Smoky Mountains National Park, Tennessee and North Carolina.

northeasterly direction pulling these airmasses along with them and bring about changes in the local weather. However, in the summer season these cyclonic disturbances move across so far to the north that their influences upon the weather of the southern Appalachian is almost inappreciable (Henry, 1911). It is during this season that an anticyclonic⁴ weather system sits off of the southern Atlantic coast influencing the weather of the Southern Appalachians.

Precipitation Processes

Precipitation in the mountains can take place as the result of three distinct processes. Each process can occur at different times of the year and the precipitation amounts that result depend on the nature and severity of the process. The usual division of the three types of processes are the convective, cyclonic and orographic precipitation processes. They result according to the primary mode of uplift of the air (Barry and Chorley, 1982).

Cyclonic Precipitation

Cyclones are defined as an area of low atmospheric pressure characterized by rotating and converging winds and ascending air. Mass convergence in the area of low pressure and forceful lifting of air along the frontal zones initiates cloud development and frequently abundant precipitation (Lutgens and Tarbuck, 1992). These systems are normally associated with the approach and passing of weather systems - warm fronts and cold fronts. Cyclones move across the United States in a northeasterly direction. Figure 3 shows the area of origin and the movement of these cyclonic systems. The rainfall that

⁴ An area of high atmospheric pressure characterized by diverging and rotating winds and subsiding air aloft, clockwise air flow. (Lutgens and Tarbuck, 1992).

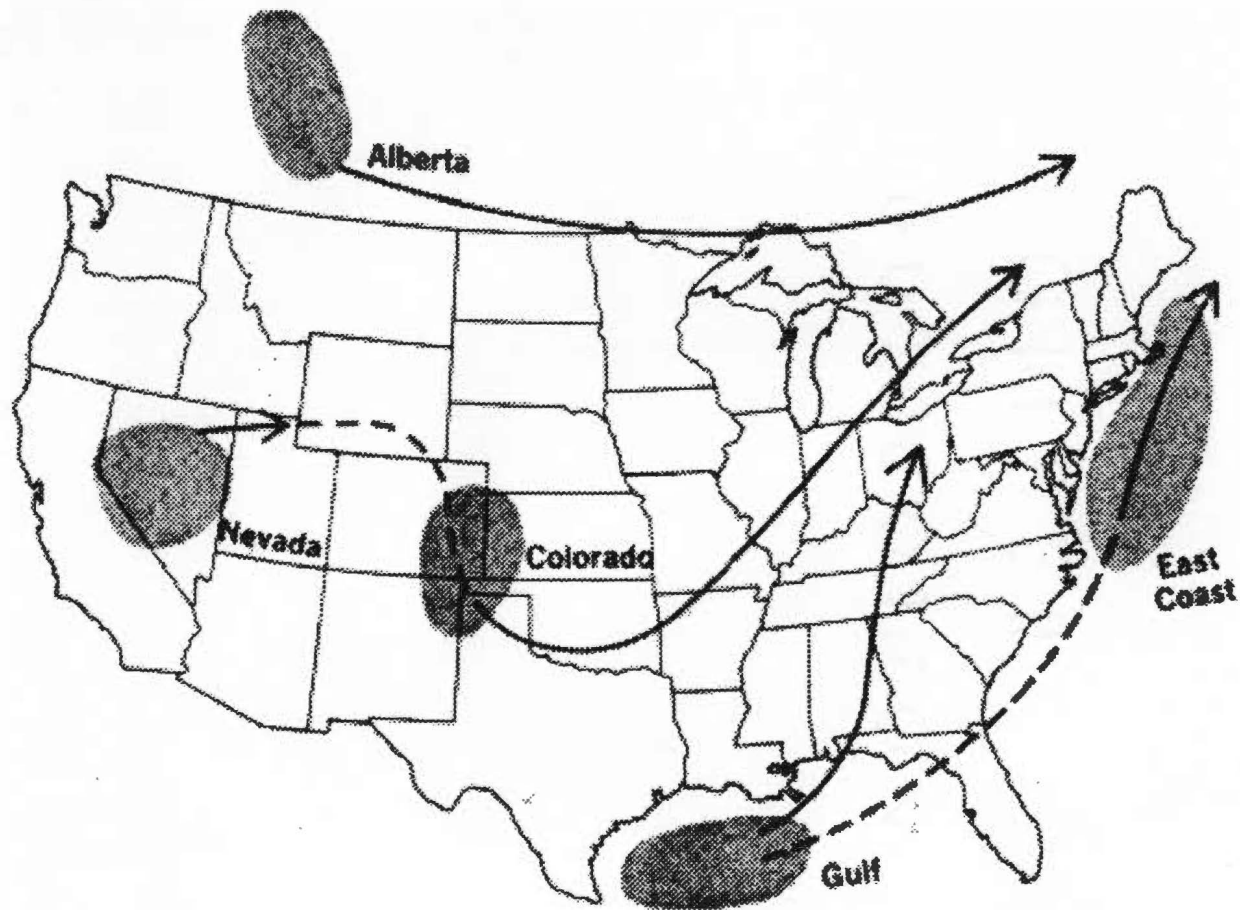


Figure 3. Major cyclogenetic areas and common cyclone tracks in North America. Cyclones which develop over Nevada are usually weak and disorganized, but they often intensify after moving into the Colorado cyclogenetic area (Trewartha, 1980).

results from cyclones usually last for periods of hours to days. The precipitation belt in the forward sector of the cyclonic storm can affect a locality in its path for 6 to 12 hours, whereas, the belt in the rear gives a shorter period of thunderstorm-type precipitation (Barry and Chorley, 1982). In the GSMNP this type of precipitation occurs during the winter months and is of long duration (Bogucki, 1970).

Convective Precipitation

Convection is defined by Rosenberg et al. (1983) as mass motions of fluid (air, in this case) resulting in the transport and mixing of the properties of that fluid. Free convection is the motion caused only by density differences within the fluid. Still air in contact with a warm surface, for example, is heated and rises because of its increased buoyancy. Strong summer heating of the Great Valley floor and other low lying areas around the GSMNP will cause this process to occur. The unstable air begins to ascend up the slopes of the mountains into the cooler air associated with the lower layers of the troposphere. This unstable air begins to cool adiabatically and precipitation occurs. The type of precipitation associated with convective heating is usually torrential in nature. It is of short duration, one-half to one hour, and takes place mostly in the span of the summer months (Bogucki, 1970). For the GSMNP, Bogucki (1970) determined that the months of June, July and August contained the highest average number of thunderstorms and most intense precipitation during the course of the year.

Orographic Precipitation

When horizontally moving air encounters higher land (a range of mountains, for example), some of the air is forced to rise as it passes over the higher land. The resulting

precipitation is called orographic precipitation (Trewartha and Horn, 1980). As the air rises, it cools at the dry adiabatic lapse rate of about $1^{\circ}\text{C}/100\text{m}$. The air is chilled to a temperature at which the water vapor condenses. These water droplets grow larger and begin to fall out as precipitation (Rosenberg et al., 1983). Barry and Chorley (1982) explain orographic precipitation in the following manner:

“Orography, dependent on the alignment and size of the barrier, may (i) trigger conditional or convective instability by giving an initial upward motion or differential heating of the mountain slopes, (ii) increase cyclonic precipitation by retarding the rate of movement of the depression system, (iii) cause convergence and uplift through the funneling effects of valleys on airstreams. In mid-latitude areas where precipitation is predominantly of cyclonic origin, orographic effects tend to increase both frequency and intensity of winter precipitation, whereas during summer and in continental climates with a higher condensation level the main effect of relief is the occasional triggering of intense thunderstorm-type precipitation. The orographic influence occurs only in the proximity of high ground in the case of a stable atmosphere.”

Windward vs. Leeward Slopes

The side of the higher land facing the direction from which the wind is coming is called the windward side, while the opposite side is called the leeward side (Trewartha and Horn, 1980). Many of the rainiest places in the world are located on windward slopes. These rainy places are situated such that the mountains act as a barrier to the general circulation (Lutgens and Tarbuck, 1992). Air rising up and over a windward slope cools and the water vapor in the air mass condenses. Precipitation results and continues to fall as long as this process persists. As this air mass begins to descend down the leeward side of the mountain, much of the moisture has been lost. The air warms and is no longer saturated (Rosenberg et al., 1983) and condensation becomes less likely (Lutgens and

Tar buck, 1992). Thus, the windward slope of a mountain range tends to be cooler and wetter, whereas the leeward side is warmer and drier.

Precipitation/Topography Investigations

An even distribution of precipitation gauges in a mountain range is uncommon. Because of the nature of the rugged mountain terrain, the severity of the elements and the expense associated with maintaining automatic recording precipitation gauges, many precipitation records are made with manual recording rain gauges. Some mountainous areas have access roads and trails to the peaks of the mountains for tourist and recreational purposes. Manual precipitation gauges can be easily placed and measurements can be made in these areas because of convenience and easy access. Precipitation gauges can also be placed at lower elevations because of the convenience of towns and communities located near the base of the mountains. Therefore, the rainfall that has occurred at the base and the peaks can be determined. However, many of the intermediate elevations of the mountain ranges are without precipitation records because they are inaccessible. This has led to the need to investigate the distribution of precipitation over broad areas such as mountain ranges.

Precipitation in mountain areas is as nearly unmeasureable as any physical phenomenon (Anderson, 1972). Therefore, many investigations regard the distribution of precipitation in mountainous areas have assumed that precipitation amounts increase with increasing elevations. For example, Donley and Mitchell (1939) subdivided the precipitation records for the Southern Appalachians into four rainfall-zones whose

boundaries are dependent upon the principal direction of moisture travel and the topography of the area. These researchers then applied the straight-line equation of

$$R' = R + K(A/100)$$

which was developed by J. B. Lippincott in 1899. The variables R' and R indicate the average rainfall in inches at the higher and lower points respectively, A is the difference in altitude in feet and K is a constant for each zone. The coefficient K varies in each zone and generally decreases in the principal direction of moisture travel. Applying Lippincott's equation to their data and plotting the results, Donley and Mitchell (1939) concluded that a definite relation exists between the rainfall and elevations that is peculiar to each of these zones.

In studying the precipitation of the GSMNP, Smallshaw (1953) plotted annual precipitation totals against elevation for the period of 1946-1950. Smallshaw's results clearly show a decided increase in precipitation with an increase in elevation. During the five year period an average of 787.4 mm more rain fell at Newfound Gap than at Gatlinburg, or about 228.6 mm of precipitation for each 304.8 m of elevation.

Spreen (1947), Dickson (1958), Linsley (1958) and Schermerhorn (1967) also indicate that precipitation is related to increases in elevation. These investigators suggest that precipitation may be related to other topographical features as well. Slope, exposure and orientation were calculated into their models and determined to contribute significantly to the precipitation variations in mountainous areas.

Spren (1947) analyzed the site factors (topographic features) of elevation, slope exposure and orientation, for each precipitation station in his study. Regression analysis was calculated between precipitation and elevation. The linear equation of

$$P = 0.62E - 0.88$$

was developed where P is precipitation in inches and E is elevation in feet. The correlation coefficient, r , was +0.55, indicating that only 30% of the variation in precipitation was attributable to elevation. Spren then used exposure, slope, orientation and elevation values against the precipitation totals in a multiple statistical test. The multiple correlation coefficient, R , was computed to be 0.94, indicating that about 88% of the original variance was attributable to the four topographic parameters. Dickson (1958), Linsley (1958) and Schermerhorn (1967) utilized the general techniques that were employed by Spren (1947).

Geographic Information Systems

Definition

Many individuals attempt to define a Geographic Information System in their own way. Carter (1989) gives a rather universal and broad definition of Geographic Information Systems (GIS). He states that a GIS is an integrated (computer) system used to capture, store, manage, analyze, and display information relative to concerns of a geographic nature. Crawford (1990) offers a similar interpretation by stating that a GIS has the ability to collect, store, retrieve, analyze and display spatial data. Burrough (1989) defines a GIS as a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world for a particular set of

purposes. Parker (1989) states a GIS is an information technology which stores, analyzes, and display both spatial and non-spatial data. GIS technology was developed to store and analyze diverse information specific to geographic locations (Scarborough, 1991). A GIS is an internally referenced, automated, spatial information systems designed for data management, mapping and analysis (Berry, 1987). To summarize, the main purpose of a GIS is to process spatial information (Berry, 1988) and to manipulate geographic data in digital form (ESRI, 1989). Dangermond (1986) places the functionality of a GIS into five categories: data entry, data analysis, data manipulation, data base query and data display and report generation.

Spatial Data

The most important element of a GIS is the geographic or spatial data. A GIS would not exist without the idea of being able to process spatial data. Parker (1988) defines spatial data as data which represent objects that have physical dimensions; they take up space. In a GIS, spatial data occurs in three forms: points, lines and polygons (Parker 1988). These spatial features have cartographic {x,y} coordinates that are used to place the features in a spatial plane. Point features in a GIS are represented by a single pair of {x,y} coordinates. A point might represent a well or a meteorological station. Line features contain a series of {x,y} coordinate pairs. One pair of coordinates representing the starting point (from-node) and another pair representing the stopping point (to-node) of a line. Each existing pair of coordinates (vertices) between the starting and stopping points represent a change in direction for that line. A line could represent a road or a stream feature. Polygon features are similar to line features as they contain a

series of {x,y} coordinate pairs. Polygon features are different from line features in that the starting and stopping coordinate pairs usually contain the same {x,y} coordinate pair. They encompass the surrounding area and gives the polygon its shape. Polygons could spatially represent a soil cover type or a forest cover type. These spatial features are placed in a GIS in digital format.

Once the geographic features have been established, attributes or characteristics can then be assigned to the features by use of the systems data base management program. These attributes will distinguish each feature from another. When performing the analysis or display of certain criteria, the attributes are the items that are used to decide which parameters fit the specific needs. Only the spatial features that are in question will then be displayed. This is the true power of a GIS.

Objectives of the study

The primary objective of this study is to estimate an average annual precipitation value for the GSMNP. Using a GIS, three different methodologies will be implemented in order to meet this goal. The method which best represents the average annual precipitation for the park will be determined. A secondary goal will result from the determination of the first objective. A precipitation database (coverage) of the park will be created in determining the best representation of the average annual precipitation value. This precipitation coverage can be used for other studies in the GSMNP. An example of the use of this coverage is given.

Methods

Data Collection

Digital Elevation Models

The terrain data used in this study were obtained from the United States Geological Survey (USGS) in digital format in the form of the Digital Elevation Models (DEMs). The DEMs¹ were produced at the 1:24,000 map scale and cover the same area as the 7.5-minute by 7.5-minute quadrangle. They are projected in the Universal Transverse Mercator (UTM) coordinate projection; the elevations are in meters and are sampled at a 30-meter by 30-meter spacing.

The USGS uses four processes to collect the digital elevation data for production of the 7.5-minute DEMs. They are: (1) the Gestalt Photo Mapper II (GPM2), (2) manual profiling from photogrammetric stereomodels, (3) stereomodel digitizing of contours, and (4) derivation from Digital Line Graphs (DLGs) hypsography and hydrography categories or pseudo-DLGs (tagged vector contours) (USGS, 1993). The 7.5-minute DEMs are classified at accuracy level-1 -the lowest class, according to USGS standards (USGS, 1993). Crawford (1990) states that level-1 DEMs are considered to be elevation datasets in a standard format where only gross blunders have been removed. There are 27, 1:24,000 scale DEMs that cover the study area. Their quad names and general attributes are listed in table 2.

A USGS 1:24,000 DEM has the following characteristics:

¹ 1. A topographic surface arranged in a data file as a set of regularly-spaced x,y,z locations where z represents elevation. 2. An elevation database for elevation data by map sheet from the National Mapping Division of the USGS. 3. The format of the USGS digital elevation data sets (ESRI, 1992).

Table 2. USGS quadrangles and their characteristics.

Quad name	Scale	State	UTM Zone	Min Elev. (m)	Max Elev. (m)	Xmin (utm)	Ymin (utm)	Xmax (utm)	Ymax (utm)	Datum	Spheroid
Blockhouse	1:24,000	TN	17	262	812	228285	3945975	240015	3960165	NAD27	Clarke1866
Bryson City	1:24,000	NC	17	521	1427	272895	3917025	284565	3931155	NAD27	Clarke1866
Bunches Bald	1:24,000	NC	17	719	1817	295905	3930375	307545	3944475	NAD27	Clarke1866
Cades Cove	1:24,000	TN,NC	17	463	1506	239205	3931785	250935	3945975	NAD27	Clarke1866
Calderwood	1:24,000	NC,TN	17	266	1443	227865	3932085	239625	3946305	NAD27	Clarke1866
Clingmans Dome	1:24,000	NC,TN	17	653	2027	273225	3930885	284925	3945045	NAD27	Clarke1866
Cove Creek Gap	1:24,000	NC	17	475	1781	307545	3943995	319155	3958095	NAD27	Clarke1866
Dellwood	1:24,000	NC	17	728	1723	307245	3930135	318885	3944235	NAD27	Clarke1866
Fontana Dam	1:24,000	NC	17	389	1333	238815	3917895	250545	3932085	NAD27	Clarke1866
Gatlinburg	1:24,000	TN	17	336	1468	262275	3945045	273945	3959205	NAD27	Clarke1866
Hartford	1:24,000	NC, TN	17	239	1539	296565	3958095	308145	3972225	NAD27	Clarke1866
Jones Cove	1:24,000	TN	17	318	896	285255	3958365	296865	3972495	NAD27	Clarke1866
Kinzel Spring	1:24,000	TN	17	270	1141	239625	3945645	251325	3959835	NAD27	Clarke1866
Luftee Knob	1:24,000	NC, TN	17	613	1928	296235	3944235	307845	3958365	NAD27	Clarke1866
Mount Guyot	1:24,000	TN, NC	17	419	2018	284925	3944475	296565	3958635	NAD27	Clarke1866
Mount Le Conte	1:24,000	NC,TN	17	396	2003	273585	3944745	285255	3958905	NAD27	Clarke1866
Noland Creek	1:24,000	NC	17	521	1578	261525	3917295	273225	3931455	NAD27	Clarke1866
Richardson Cove	1:24,000	TN	17	274	786	273945	3958635	285585	3972765	NAD27	Clarke1866
Silers Bald	1:24,000	TN,NC	17	668	2008	261885	3931155	273585	3945345	NAD27	Clarke1866
Smokemont	1:24,000	NC	17	596	1637	284565	3930615	296235	3944745	NAD27	Clarke1866
Tallassee	1:24,000	TN	16	248	847	760365	3932085	772125	3946305	NAD27	Clarke1866
Tapoco	1:24,000	NC,TN	17	266	1621	227445	3918225	239205	3932445	NAD27	Clarke1866
Thunderhead Mtn.	1:24,000	TN,NC	17	481	1685	250545	3931455	262275	3945645	NAD27	Clarke1866
Tuskegee	1:24,000	NC	17	521	1479	250185	3917595	261885	3931785	NAD27	Clarke1866
Waterville	1:24,000	NC, TN	17	390	1298	307845	3957855	319455	3971955	NAD27	Clarke1866
Wear Cove	1:24,000	TN	17	308	1213	250935	3945345	262635	3959505	NAD27	Clarke1866
Whittier	1:24,000	NC	17	536	1314	284235	3916755	295905	3930885	NAD27	Clarke1866
Chattanooga	1:250,000			158	1651	43501	229578	3876902	3995410	NAS_C	Clarke1866
Corbin	1:250,000			132	1067	49143	233104	3987857	4106418	NAS_C	Clarke1866
Johnson City	1:250,000			244	1896	229538	411067	3984157	4098941	NAS_C	Clarke1866
Knoxville	1:250,000			226	2011	226161	409885	3873247	3987992	NAS_C	Clarke1866

- 1)The data consist of a regular array of elevations referenced horizontally in the UTM coordinate system.
- 2)The unit of coverage is the 7.5-minute quadrangle: no overedge coverage is provided.
- 3)The data are ordered from south to north in profiles that are ordered from east to west.
- 4)The data are stored as profiles in which the spacing of the elevations along and between each profile is 30 meters, and the profiles do not always have the same number of elevations (USGS, 1993).

The structure of a 7.5-minute DEM is shown in figure 4.

Additional terrain data models needed for the study were in the form of the 1:250,000 DEMs. These DEMs are distributed by the USGS, produced by the Defense Mapping Agency (DMA) and are also available in digital format. The 1:250,000 DEMs have the following characteristics²:

- 1) The product consists of a regular array of elevations referenced horizontally on the geographic (latitude/longitude) coordinate system of the World Geodetic System 1972 Datum.
- 2) The spacing of the elevations along and between each profile is three arc-seconds. Therefore, the actual spacing between profiles varies with latitude.
- 3) The unit of coverage is a one degree by one degree block with data ordered from south to north in profiles ordered from west to east. The first and last data points are at the integer degrees of latitude. Two models are needed to cover the area of a standard DMA 1:250,000 scale topographic map.
- 4) Each model, south of fifty degrees north latitude, has 1,201 profiles containing 1,201 elevations.

² Reproduced from Crawford, 1990.

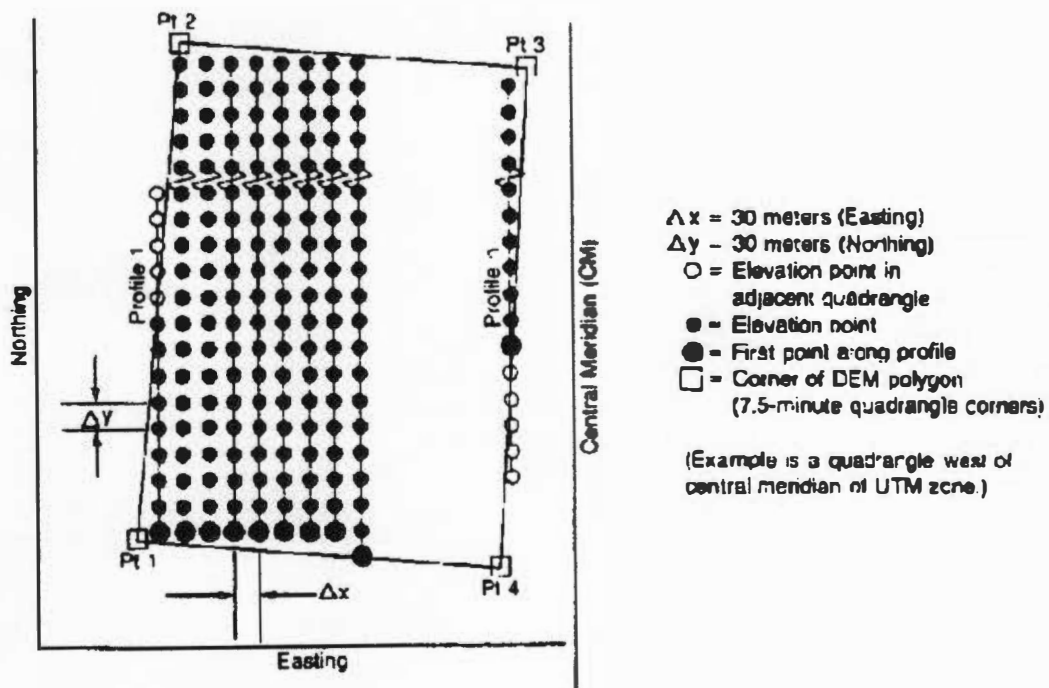


Figure 4. Structure of a 7.5 minute DEM.

All 1:250,000 scale DEMs are classified as level-3 (Crawford, 1990). Crawford (1990) gives a description of how the 1:250,000 DEMs are produced. Four 1:250,000 DEMs were needed for this study. The structure of a 1-degree (1:250,000 scale), USGS DEM can be found in figure 5. Their quad names and general attributes are also listed in table 2.

According to Liu (1988), the accuracy of a DEM depends upon three factors. These factors are the sampling density, the measuring error introduced by sampling a continuous quantity and converting it into digital form, and the interpolation method employed for generating a continuous surface from discrete data. The horizontal accuracy of DEM data depends on the horizontal spacing of the elevation matrix, whereas the vertical accuracy of DEM data depends on the spatial resolution (horizontal grid spacing), quality of the source data, collection and processing procedures, and digitizing systems (USGS, 1993). Therefore, the accuracy of data derived from a DEM, such as aspect and slope, is dependent upon the accuracy of the DEM itself. Carter (1987) concluded that the 1:250,000 DEM database was an accurate representation of the topographically diverse area of the GSMNP.

Precipitation Data

A dense network of weather stations and long-term records of meteorological observations are necessary to give an accurate account of the climate in an area. Ideally, an established network of stations would be monitoring the meteorological conditions in an area and would continue to monitor them into the future. Unfortunately, this is not always the case. Some stations are no longer in operation and records are no longer kept for various reasons, including lack of interest and/or lack of funding. Therefore,

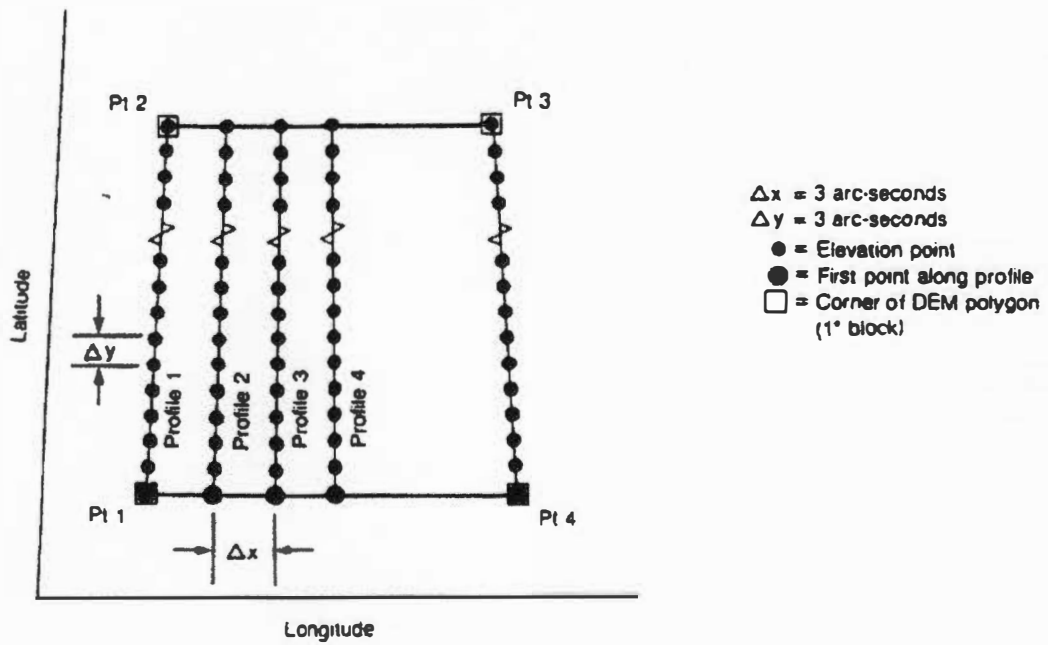


Figure 5. Structure of a 1-degree DEM.

researchers often use historical meteorological records for their analysis.

The Tennessee Valley Authority (TVA) has kept precipitation records within the Tennessee River Basin, of which the Great Smoky Mountains National Park is a part, for over 50 years. Together with other organizations such as the U. S. Weather Bureau (USWB), the U. S. Department of the Interior (USDI), the U. S. Department of Agriculture (USDA), the Aluminum Company of America (ALCOA), Nantahala Power Company (NPCO), Champion Paper & Fiber (CP&F) and the Hiwassee Land Company (HLCO), TVA was once able to maintain a dense network of precipitation stations within the vicinity of the GSMNP. This is not the case today. Many of these stations are no longer in operation and the need to look at past precipitation records became apparent to the success of this study.

Examination of the annual precipitation records published by TVA indicate that the greatest density of precipitation stations and the greatest accumulated length of precipitation records, within the vicinity of the GSMNP, may have occurred by the year 1969. The 1969 annual publication³ lists 26 precipitation stations that had precipitation records for 30 years or more and a total of 31 stations that had records for 20 years or more. Many of these stations were in operation 10 years later and the 1979 annual publication⁴ updates the number of stations that have records for 30 years or more to a total of 34 stations. The 1979 publication also updates the number of stations having precipitation records for 20 years or more to a total of 40. Nine stations had records for

³ T.V.A. Div. of Water Control Planning, Hydraulic Data Branch, Precipitation in Tennessee River Basin, 1969. Report No. 0-243.

⁴ T.V.A. Div. of Water Control Planning, Hydraulic Data Branch, Precipitation in Tennessee River Basin, 1979. Report No. 0-243-A79.

less than 20 years. Data for two stations involved in this study were taken from the 1966 and 1974 annual publications. Thus, data from a total of 51 precipitation stations have been obtained for use in this study. The geographic coordinates (latitude and longitude) of each station were obtained through TVA personnel (table 3).

Lutgens and Tarbuck (1992) define a "normal" as simply an average of a climatic element over a 30-year period. They state that a "normal" is a standard that is used to make a comparison. The data used in this study were the "normals" taken from the TVA publications.

The 1969 "normals" were determined by the following procedure:

"Figures in the "mean or normal" column in the following tabulation are determined as follows: For the U. S. Weather Bureau stations, the figures are normals based on the 30-year period 1931-1960, computed by the Weather Bureau. For TVA and other agency stations with 21 or more years of record through 1969, the figures are long-term means adjusted to the 35-year period 1935-1969. For stations with 5 to 20 years of record in 1969, the figures are running averages for the period of record. No means are listed for the records of less than 5 complete years." (TVA, 1969).

The 1979 "normals" were determined by this procedure:

"Figures in the "mean or normal" column in the following tables are determined as follows: For the National Weather Service stations, the figures are normals based on the 30-year period 1941-1970, computed by the National Weather Service. For TVA and other agency stations with 30 or more years of record through 1970, the figures are means based on the 30-year period 1941-1970. For stations with less than 30 continuous years of record in 1970, the figures are running averages for the period of record. No means are listed for stations with records of less than 5 complete years." (TVA, 1979).

The other "normals" used in this study were determined in similar fashion, but calculated for their respective time periods.

Table 3. The precipitation stations and their geographic coordinates.

TVA-ID	Station name	Recording Agency	Latitude Degrees	Minutes	Seconds	Longitude Degrees	Minutes	Seconds
171	MCGHEE ES	TVA	35	36	39	84	12	34
173	KITTIE ES	TVA	35	27	10	84	9	48
174	TELLICO PLAINS ES	TVA	35	21	45	84	17	40
176	CALDERWOOD POWERHOUSE	ALCOA	35	29	41	83	59	18
178	CHEOAH DAM	ALCOA	35	26	52	83	56	23
180	SANTEETLAH DAM	ALCOA	35	22	35	83	52	25
182	STECOAH ES	TVA	35	22	10	83	41	48
183	NOLAND CREEK ES	TVA	35	29	4	83	30	31
185	BRYSON CITY R ES	TVA	35	25	12	83	26	52
186	OCONALUFTEE ES	USDI	35	30	46	83	18	20
194	NEEDMORE ES	TVA	35	19	35	83	31	22
196	FRANKLIN POWERHOUSE	NPCO	35	13	10	83	22	13
197	WAYAH BALD R ES	TVA	35	10	50	83	33	39
198	FRANKLIN ES	NPCO	35	10	45	83	23	37
209	GATLINBURG NEAR ES	USWB	35	42	50	83	32	14
210	MT LECONTE ES	TVA	35	39	11	83	26	30
241	NEWPORT ES	USWB	35	58	51	83	9	42
243	HARTFORD ES	TVA	35	48	57	83	8	40
245	MT STERLING ES	TVA	35	43	29	83	5	22
248	EAGLENEST MTN. ES	TVA	35	27	30	83	0	0
249	BALSAM ES	TVA	35	25	54	83	4	54
362	TEYAHALLEE BALD R ES	TVA	35	15	28	83	47	44
394	PROVIDENCE ES	TVA	35	50	57	83	47	8
407	CATALOOCHEE RANCH Z ES	TVA	35	32	30	83	5	0
409	KNOXVILLE ARPT R XX ES	USWB	35	47	30	83	57	30
496	PIGEON FORGE ES	TVA	35	47	13	83	33	14
525	ELA NEAR	NPCO	35	26	35	83	19	53

Table 3. The precipitation stations and their geographic coordinates. (cont.)

TVA-ID	Station name	Recording Agency	Latitude Degrees	Minutes	Seconds	Longitude Degrees	Minutes	Seconds
538	COSBY NO.4 ES	USDI	35	45	10	83	12	24
542	CHEROKEE ES	USDI	35	28	42	83	19	26
564	THORPE DAM	NPCO	35	11	45	83	9	8
586	CARTOOGECHAYE CREEK ES	TVA	35	9	22	83	27	47
592	FONTANA DAM	TVA	35	27	2	83	48	20
593	DOUGLAS DAM	TVA	35	57	43	83	32	26
599	BIG COVE RADIO ES	TVA	35	34	52	83	15	54
637	US COTTON FIELD STA ES	USDA	35	52	41	83	55	38
642	SEVERIVILLE ES	TVA	35	54	17	83	34	47
660	TWENTYMILE ES	USDI	35	28	1	35	52	40
668	ABRAMS CREEK ES	USDI	35	33	29	84	0	38
716	WILDWOOD ES	TVA	35	47	10	83	53	5
742	SUNBURST RADIO ES	CP&F	35	22	23	82	56	20
754	JONES COVE ES	TVA	35	49	40	83	19	39
767	NORTH CITICO CREEK NO.1 R ES	TVA	35	22	44	84	2	11
783	VONORENEAR Z ES	HLCO	35	36	53	84	14	2
177A	CADES COVE ES	USDI	35	36	8	83	46	38
184A	CLINGMANS DOME RADIO ES	TVA	35	33	32	83	29	42
209A	GATLINBURG R ES	TVA	35	42	30	83	30	34
399A	PITTMAN CENTER R ES	TVA	35	45	33	83	23	44
564A	THORPE POWERHOUSE	NPCO	35	14	0	83	7	34
642A	SEVIERVILLE XX ES	TVA	35	52	33	83	34	36
715A	TOWNSEND R ES	TVA	35	40	44	83	45	5
767C	NORTH CITICO CREEK NO.4A DP ES	TVA	35	23	50	84	0	56

Instruments

The precipitation data obtained by TVA and the other associated agencies were collected by three types of rain gauges. These types include the nonrecording rain gauge, the recording rain gauge and the radio rain gauge. The nonrecording rain gauge consists of two types; the eight-inch nonrecording gauge and the four-inch nonrecording gauge. The eight-inch nonrecording gauge consists of a large diameter (eight inches) outer can and a smaller diameter measuring tube which is inside the can. These two pieces are connected by a funnel. The measuring tube is 20 inches tall and holds exactly two inches of rainfall⁵. Measurements are made with the measuring stick and observations can be measured to the nearest hundredth of an inch. The four-inch nonrecording gauge consists of a four-inch outer can and an inner measuring tube that holds one-inch of precipitation. The two pieces are connected by a four-inch funnel. The measuring tube is graduated to hundredths of an inch. Both the four-inch and the eight-inch gauges have overflow catches in case precipitation exceeds their respective measuring tube limits. The nonrecording rain gauges are read manually on a daily basis (NWS, 1989). Data from 38 nonrecording rain gauges were obtained from the TVA publications.

The Belfort (Fischer & Porter) gauge and the Universal gauge are two types of recording (weighing type) rain gauges. The weighing-type of recording gauges are designed to record the rate⁶ and amount⁷ of precipitation. These gauges consist of a receiver with an inside diameter of exactly eight inches that funnels precipitation into a

⁵ Each rain gauge is equipped with an overflow tube to catch precipitation in excess of two inches.

⁶ The rate is measured in hundredths or tenths of an inch per unit time (NWS, 1989).

⁷ The amount is measured in hundredths or tenths of an inch (NWS, 1989).

collector mounted on weighing mechanism. In the Universal gauge, the weight of the precipitation in the collector compresses a spring, which is connected to a pen (ink) arm. The pen leaves a trace on a paper chart (graduated to .05 inch) which is wrapped on a clock-driven cylinder. The cylinder makes a revolution once every 24 hours. The paper charts record precipitation for the past week and are changed weekly. The Belfort recording rain gauge works in the same manner as the Universal gauge. As precipitation is collected in the collector, a machine punches holes in a paper tape on a moving scroll based on the weight of the precipitation. Holes are punched every 15 minutes (NWS, 1989). Ten of the 51 precipitation stations used in this study are of the recording type of precipitation gauge.

Precipitation data for three of the stations used in this study were collected by radio rain gauges. These rain gauges were simply Belfort weighing bucket rain gauges equipped with radio transmitters/receivers. The agency observing precipitation at that location would “dial-up” the precipitation station every two hours and retrieve the precipitation data. These two hour observations were summarized into daily and monthly totals (Goodman, 1994). Table 4 shows the precipitation stations used in the study, the type of collection method and the precipitation normals for the respective stations.

Site Factors and Measurement Errors

Any method of measuring precipitation should aim to obtain a sample representative of the true amount falling over the area which the measurement is intended to represent (WMO, 1983). Therefore, when establishing an area as a site to acquire

Table 4. Annual precipitation normals and corresponding station information.

TVA-ID	Station	Recording Agency	Number of Years	Normal Precipitation (mm)	Gauge Type	Publication Year
171	MCGHEE ES	TVA	65	1291.8	NR	1969
173	KITTIE ES	TVA	35	1304.0	NR	1969
174	TELLICO PLAINS ES	TVA	56	1345.2	NR	1969
176	CALDERWOOD POWERHOUSE	ALCOA	39	1373.6	NR	1969
178	CHEOAH DAM	ALCOA	40	1474.7	NR	1969
180	SANTEETLAH DAM	ALCOA	39	1417.3	NR	1969
182	STEOAH ES	TVA	35	1490.7	NR	1969
183	NOLAND CREEK ES	TVA	30	1470.7	REC	1969
185	BRYSON CITY R ES	TVA	82	1262.9	REC	1969
186	OCONALUFTEE ES	USDI	37	1446.0	NR	1969
194	NEEDMORE ES	TVA	35	1336.8	NR	1969
196	FRANKLIN POWERHOUSE	NPCO	36	1298.4	NR	1969
197	WAYAH BALD R ES	TVA	35	1751.1	REC	1969
198	FRANKLIN ES	NPCO	36	1298.4	NR	1969
209	GATLINBURG,NEAR ES	USWB	44	1401.8	NR	1969
210	MT LECONTE ES	TVA	0	1954.3	NR	1966
241	NEWPORT ES	USWB	79	1137.2	NR	1969
243	HARTFORD ES	TVA	35	1221.2	NR	1969
245	MT STERLING ES	TVA	35	1355.1	NR	1969
248	EAGLENEST MTN. ES	TVA	35	1405.1	NR	1969
249	BALSAM ES	TVA	38	1518.9	NR	1979
362	TEYAHALLEE BALD R ES	TVA	32	1725.7	REC	1969
394	PROVIDENCE ES	TVA	31	1196.6	NR	1969
407	CATALOOCHEE RANCH Z ES	TVA	31	1590.0	NR	1969
409	KNOXVILLE ARPT R XX ES	USWB	31	1164.6	REC	1969
496	PIGEON FORGE ES	TVA	29	1175.3	NR	1969
525	ELA, NEAR	NPCO	38	1436.9	NR	1979

Table 4. Annual precipitation normals and corresponding station information (cont.).

TVA-ID	Station	Recording Agency	Number of Years	Normal Precipitation (mm)	Gauge Type	Publication Year
538	COSBY NO.4 ES	USDI	39	1416.1	NR	1979
542	CHEROKEE ES	USDI	28	1308.4	NR	1969
564	THORPE DAM	NPCO	39	1637.5	NR	1969
586	CARTOOGECHAYE CREEK ES	TVA	28	1470.4	NR	1969
592	FONTANA DAM	TVA	28	1413.0	NR	1969
593	DOUGLAS DAM	TVA	38	1130.8	NR	1979
599	BIG COVE, RADIO ES	TVA	38	1520.7	RAD	1979
637	US COTTON FIELD STA ES	USDA	35	1239.0	NR	1969
642	SEVERVILLE ES	TVA	51	1216.4	NR	1969
660	TWENTYMILE ES	USDI	34	1525.3	NR	1979
668	ABRAMS CREEK ES	USDI	34	1472.2	NR	1979
716	WILDWOOD ES	TVA	29	1299.7	NR	1979
742	SUNBURST, RADIO ES	CP&F	24	1454.7	RAD	1979
754	JONES COVE ES	TVA	13	1247.6	NR	1969
767	NORTH CITICO CREEK NO.1 R ES	TVA	10	1562.4	REC	1969
783	VONORE, NEAR Z ES	HLCO	8	1306.8	NR	1969
177A	CADES COVE ES	USDI	15	1423.9	NR	1969
184A	CLINGMANS DOME, RADIO ES	TVA	30	2105.9	RAD	1969
209A	GATLINBURG R ES	TVA	8	1413.0	REC	1974
399A	PITTMAN CENTER R ES	TVA	17	1194.8	REC	1969
564A	THORPE POWERHOUSE	NPCO	38	1401.6	NR	1979
642A	SEVIERVILLE XX ES	TVA	14	1133.9	NR	1969
715A	TOWNSEND R ES	TVA	29	1293.4	REC	1979
767C	NORTH CITICO CREEK NO.4A DP ES	TVA	8	1756.4	REC	1969
	REC - recording					
	RAD - radio rain gauge					
	NR - non-recording					

precipitation measurements, many factors need to be considered in order to obtain an accurate account of the sampled data. These factors include site location, gauge height, large- and small-scale turbulence in the air flow, splash-in and evaporation (Barry and Chorley, 1982). Additional factors include wetting of the internal walls of the gauge, the collector and the container and blowing of snow from or into the gauge (WMO, 1983). Any of these factors could alter the true catch of precipitation, thus resulting in precipitation records as only being *estimates* (Barry and Chorley, 1982). The best location for a precipitation gauge would be in a large opening in a grove of trees (NWS, 1989). This will allow for protection of the gauge from most or all of these factors.

An examination of the precipitation "normals" used in the study was needed to determine if they would be representative of the amounts of precipitation that occur in the GSMNP. Thirty-year moving averages were calculated using long-term data for two additional weather stations that were located near the park- Knoxville, TN⁸ and Waynesville, NC⁹.

The Geographic Information System

ARC/INFO¹⁰ was the Geographic Information System (GIS) used in this study. This GIS was developed by the Environmental Systems Research Institute (ESRI), Inc. of Redlands, CA. The geographic analysis work was done with the release version of 6.1.1 and the current pre-release version of 7.0.1. It was used on a VAX computing system with a Tektronics graphics emulator and on a UNIX operation system using a SUN

⁸ National Oceanic and Atmospheric Administration. Climatological Data: Tennessee, 1910-90. US Dept. of Commerce, Asheville, NC.

⁹ National Oceanic and Atmospheric Administration. Climatological Data: North Carolina, 1931-90. US Dept. of Commerce, Asheville, NC.

¹⁰ ARC/INFO is a registered trademark of the Environmental Systems Research Institute, Inc. Redlands, CA.

SPARCstation 10. ARC/INFO was chosen as the Geographic Information System to use due to the researcher's familiarity with this GIS to perform the selected operations.

ESRI (1989) provides this definition of their GIS software:

"ARC/INFO provides users with friendly, yet sophisticated capabilities to perform analytic, tabular, and graphic functions through the use of an easy to learn command language. Within ARC/INFO are a whole series of commands which perform a number of GIS functions. ARC/INFO is a cartographic system built around a hybrid data model. It organizes geographic data using a relational and topological model. This facilitates efficient handling of the two generic classes of spatial data: locational data describing the location and topography of a point, line and area features; and attribute data describing the characteristics of these features."

ESRI has placed the functionality of ARC/INFO into four broad categories. These categories include input, analysis, data management and data display and conversion. Below is a brief description of each of these categories.

1)***Input***¹¹ - includes such functions as digitizing, editing and reformatting data. The purpose of the input operation is to take data, whether electronic or visual, and convert it into a form usable by ARC/INFO.

2)***Analysis*** - examines the data with the intent to extract or create new data that fulfills some required condition or conditions.

3)***Data Management*** - is the handling of large sets of digital geographic or cartographic data. Management operations oversee the storage and retrieval of this data in a consistent and convenient form.

4)***Display and conversion*** - includes all operations that produce graphic output and reports.

ARC/INFO is designed so that logical groups of functions or routines are organized within individual modules (ESRI, 1989). Each of the different functions described above takes place in one of the many modules of ARC/INFO.

¹¹ One of the major advantages of ARC/INFO is its ability to integrate data from many different sources including the USGS 7.5 minute DEMs.

Features on the earth's surface are mapped onto flat, two-dimensional maps as points, lines and areas. An {x,y} or Cartesian coordinate system is used to reference map locations to ground locations (ESRI, 1989). ARC/INFO stores individual geographic features as a set or series of sets of {x,y} coordinates with unique user-ids¹² to distinguish the different geographic features. The coordinates are usually stored in a real world coordinate system such as Universal Transverse Mercator (UTM) with the units being meters. Figure 6 shows the structure of geographic information referenced in a Cartesian coordinate system. The spatial relationship established between the geographic features is called topology¹³. Similar thematic map features are stored in ARC/INFO as a single coverage¹⁴.

ARC/INFO contains a Database Management System (DBMS) that is capable of creating and managing georeferenced tables of statistical and thematic data which are associated to the geographic features. This relational DBMS model contained in ARC/INFO allows the user to easily associate and interrelate information from several files by matching selected codes which are common to each file (ESRI, 1989). These data base files, or feature attribute tables¹⁵, contain descriptive information or attributes¹⁶ about the geographic features and are associated to them by the feature's unique "User-id" number.

¹² A user-assigned identifier (ID) for a feature in a coverage. Feature attribute tables store the User-IDs along with the locational data for a feature class in a coverage (ESRI, 1992).

¹³ Topology is a mathematical procedure for explicitly defining the spatial relationships. It is used to store three spatial relationships for map features: area definition, connectivity and contiguity (ESRI, 1989).

¹⁴ A set of thematically associated data considered as a unit. A coverage usually represents a single theme or layer, such as soils, streams, roads or land use (ESRI, 1992).

¹⁵ A table used to store attribute information for a specific coverage feature class; a point attribute table (.PAT), an arc attribute table (.AAT), and a polygon attribute table (.PAT) (ESRI, 1992).

¹⁶ A characteristic of a geographic feature described by numbers or characters, typically stored in a tabular format, and linked to the feature by a user-assigned identifier (ESRI, 1992).

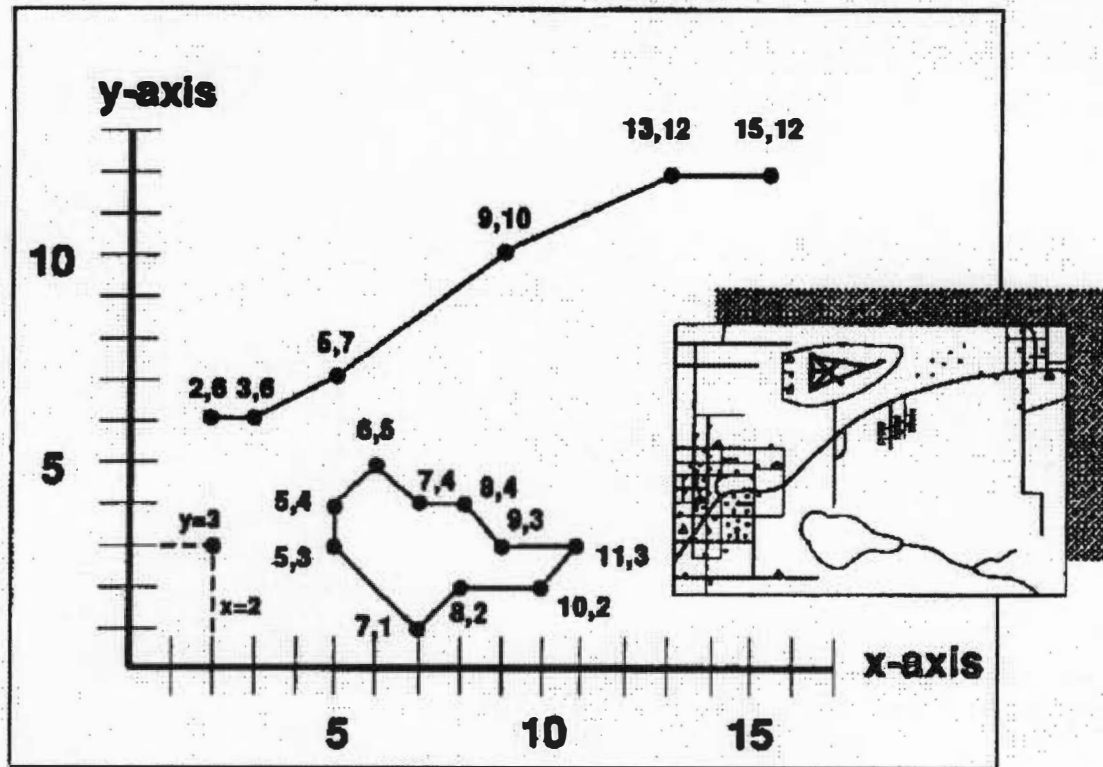


Figure 6. Geographic Information referenced in a Cartesian Coordinate System.

Creating ARC/INFO Coverages

For this study, three primary types of coverages were needed. These include a point coverage representing the geographical location of the precipitation stations, a polygon coverage representing the boundary of the GSMNP and the area encompassed within, and a lattice coverage representing the elevations of the study area. The point and polygon coverages are considered vector¹⁷ types of coverages. The lattice coverage is a surface representation that uses a rectangular array of points spaced as a constant sampling interval in the *x* and *y* directions relative to a common origin (ESRI, 1992). From the lattice type of coverage, various other coverages can be derived. ARC/INFO is capable of reading the American Standard Code for Information Interchange (ASCII) files. Each of these coverages were created from this type of file.

The Point Coverage

The latitudes and longitudes of each of the precipitation stations involved in this study were obtained in degrees, minutes and seconds from TVA personnel. These coordinates were converted into decimal degrees¹⁸ by the equation:

$$\text{decimal degrees} = \text{degrees} + \text{minutes}/60 + \text{seconds}/3600$$

The longitude values were multiplied by a factor of -1 to place the coordinates in the correct quadrant¹⁹ of the globe. Each station was assigned a "user-id" value and formatted into an ASCII text file. An example of one line in the text file would be:

¹⁷ A coordinate-based data structure commonly used to represent linear map features. Each linear feature is represented as a list of ordered {*x*,*y*} coordinates. Attributes are associated with the feature (ESRI, 1992).

¹⁸ ARC/INFO is not capable of reading three separate pieces of information such as degrees, minute and seconds in its GENERATE routine. Converting to decimal degrees allows for the input of a single value representing these three values.

where the first value represents the station-id value and the next two values represent the x-coordinate and y-coordinate, respectively. The “id” value will be used to join the geographic point locations with their respective attributes using the relational DBMS.

This ASCII text file was placed in ARC/INFO's GENERATE routine. The GENERATE routine will INPUT the text file and create POINTS by reading in the “id” value and then the x-coordinate and y-coordinate and placing the information into a Cartesian coordinate plane. Topology of the coverage is created after running the BUILD routine with the POINT option. The BUILD routine also creates the subsequent attribute tables such as the .PAT, .BND²⁰ and the .TIC²¹.

The polygon coverage and the lattice coverages are in the UTM coordinate system with the units being meters. The need to place the point coverage into this coordinate system is necessary so coverage overlay can take place. ARC/INFO has two routines that will perform this operation. The PROJECT routine takes the tics²² of the input coverage and projects these coordinates into a new set of tics for the output coverage based on user defined input and desired output projections. In this case, the coordinates needed to be projected from *geographic* coordinates with the units being *decimal degrees* to *utm* coordinates with the units being *meters* in UTM zone 17. The second part of this operation requires the use of the ARC/INFO's TRANSFORM routine. This routine takes

¹⁹ The globe is divided into four quadrants with 0° longitude and 0° latitude representing a {0,0} x,y origin. The study area is in the northwest quadrant of the globe giving negative longitude and positive latitude values for the study area.

²⁰ Coverage boundary file (ESRI, 1991).

²¹ File containing tic coordinates and id's for a coverage (ESRI, 1991).

²² Registration or geographic control points from a coverage representing known locations on the earth's surface. They allow all coverage features to be recorded in a common coordinate system (ESRI, 1992).

the newly calculated tics determined from the PROJECT routine and changes the coverage coordinates of the geographic data into the new coordinate system based on the control points (tics) (ESRI, 1989). These two steps in manipulating the data will place the point coverage into the UTM coordinate system and allow coverage overlay to take place.

The DBMS was used to create INFO files that contained the desired attributes for each precipitation station in the point coverage. ASCII files were set up and this information was placed into the GIS as an INFO data file. An example of one line of the attribute text file includes:

24,210,'Mt Leconte',TVA,0,1954.3,NR,1966

where the first text field is the assigned station-id, the second text field is the TVA id, the third field is the station name, the fourth field is the agency that records the precipitation data, the fifth field is the number of years of precipitation records, the sixth field is the yearly normal precipitation calculated for that station, the seventh field is the type of precipitation gauge and the eighth field is the year of the publication from which the data was retrieved. The fields of the INFO data file were defined and the attributes were added to the file. Using the user-id of the point coverage and the defined user-id of the INFO data file, these two files were joined together using the JOINITEM routine. This routine joins two data files based on a common field in each; for example, the user-ids

The Polygon Coverage

A text file containing the outline (boundary) of the GSMNP was obtained from the National Park Service (NPS) personnel. The original coverage was digitized by the park personnel from the 1:125,000 scale map that covers the Great Smoky Mountains National

Park for use in their GIS. The {x,y} coordinates of the coverage in the text file were already in the UTM coordinate system. Thus, no coordinate transformation was needed. The primary purposes of this coverage are to provide an account of the area of the GSMNP and to cut away or CLIP any information outside of the park.

The text file was INPUT into ARC/INFO's GENERATE routine and the LINE option was given. This option will read in the "id" value and then the corresponding {x,y} coordinates (vertices) for each instance the arcs change direction. The routine will continue to read in the lines of the coverage until the file is completely read. Topology of the polygon coverage was created by using the BUILD routine with the POLYGON option. As with the point coverage, this routine creates a .TIC, .BND and the .PAT²³ file for the polygon coverage. The default attributes for the polygon coverage are the AREA and PERIMETER of the polygon or park boundary. No other attributes associated with the park boundary coverage were needed for this study.

Creating the LATTICES

The ARC/INFO data input routine DEMLATTICE can take a standard USGS 7.5-minute or 1-degree DEM file and read it into a coverage (lattice). This routine begins by reading the header information contained in the DEM file and setting up the lattice environment. The header contains information containing the extent²⁴ of the DEM, the surface range²⁵ of the DEM, the number of rows and columns contained in the DEM and

²³ In this case, the POLYGON ATTRIBUTE TABLE.

²⁴ The lower left-hand {x,y} coordinates and the upper right-hand {x,y} coordinates in UTM.

²⁵ The minimum and maximum elevation values in meters.

the sample distance (cell size)²⁶ in {x,y} values. This information is necessary in setting up the output lattice.

After the routine has read in the header information, it starts loading the DEM data into the lattice, by beginning at the lower left corner of the lattice and reading the first data value from the file into the first cell. The routine moves horizontally across the first row reading each value from the DEM file, into each of the cells. When the end of the first row is reached, the routine moves up to the next row in the lattice and begins loading data from left to right again. This process continues until the routine reaches the upper right corner of the lattice and in which the routine then begins to write out the lattice. This routine was issued for the twenty-seven 1:24,000 scale DEMs which were used for the terrain data and the four 1:250,000 scale DEMs used for the surrounding areas. An example of a lattice structure is shown in figure 7.

After each of the DEM files were run through the DEMLATTICE routine, each of the lattice's projection files were examined to ensure that each of the lattices contained the same projection parameters. Having the same projection parameters would guarantee that the lattices would be successfully joined together. Each of the four 1:250,000 lattices had the same projection file and required no additional steps before joining them together. Twenty-six of the 1:24,000 lattices contained the same projection file including falling into the UTM zone 17 coordinate system. The 27th lattice fell into the UTM zone 16 coordinate system. This lattice (Tallassee) had to be projected into the UTM zone 17 coordinate system. This step required placing the lattice in the PROJECT routine within

²⁶ 30m x 30m meter for the 1:24,000 DEMs. 90m x 90m for the 1:250,000 DEMs.

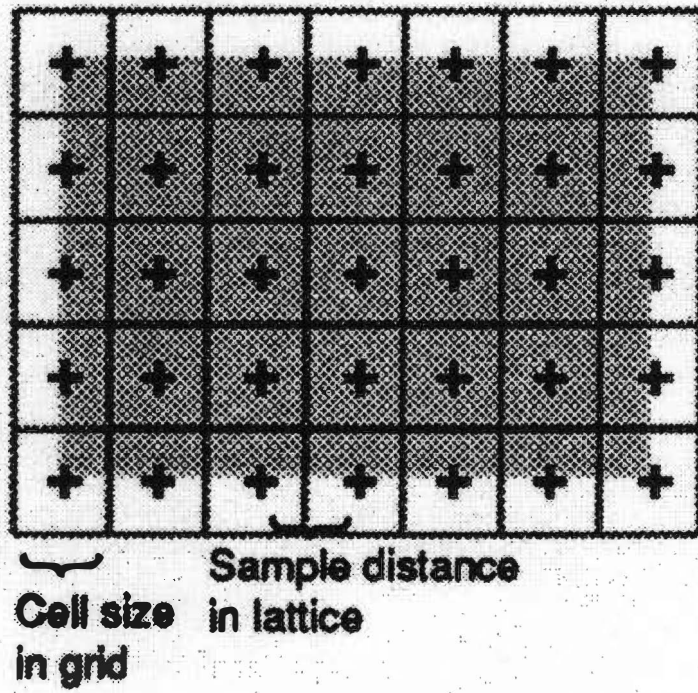


Figure 7. Structure of a Lattice.

the GRID module of ARC/INFO. This routine works in the same fashion as the ARC module PROJECT routine. The lattice was placed in the routine and given the parameter of UTM zone 17 as the output coordinate system.

The next step involved joining the lattices together using the LATTICEMERGE routine. This routine is used to join adjacent lattices created from USGS DEMs (ESRI, 1994). The routine takes each lattice input by the user and writes then out to a single lattice covering the larger area. The LATTICEMERGE routine was used to create a single lattice representing the elevation for the 1:250,000 data and a single lattice representing the elevation for the 1:24,000 data.

The 1:250,000 lattice required the additional steps of PROJECTing the coverage into a coordinate system that would allow proper coverage overlay. This lattice was originally in a *geographic* projection with the units being *decimal seconds*. It contained a datum²⁷ of *wgs72*. The lattice was projected with the GRID routine PROJECT, giving the output parameters as being a *utm* projection, with the units as *meters*, and the datum of *nad27*. As with the other coverages, performing this step would allow for proper coverage overlay.

The 1:24,000 and 1:250,000 surfaces were needed in various capacities. The 1:24,000 LATTICE served as the surface of the terrain data for the park and was used as the base for implementing the statistical model. It also served as the source to estimate some of the terrain data for the precipitation stations. Many of the precipitation stations fell outside of the area covered by the boundary of the 1:24,000 LATTICE. The sole

²⁷ A set of parameters and control points used to accurately define the three-dimensional shape of the Earth (e.g., as a spheroid). The corresponding datum is the basis for a planar coordinate system (ESRI, 1992).

purpose of the 1:250,000 LATTICE was to estimate the terrain data (elevation, slope and aspect) for these stations.

Creating the Precipitation Coverages for the “Normals”

After the precipitation data and the terrain data were collected and the ARC/INFO coverages were constructed, a methodology to determine how to best represent precipitation over a large area of rugged terrain needed to be found. There are three methodologies presented here. Two of these methods include only using ARC/INFO routines. A third method requires the use of the ARC/INFO routines and statistical analysis of the data outside of the GIS.

The Thiessen Method

A. H. Thiessen (1911), a climatologist, devised a method that would allow representation of precipitation data collected from precipitation stations that are not evenly distributed. His method defined regions based on a set of data points such that regions be enclosed by a line midway between the station under consideration and the nearest surrounding stations (Thiessen and Alter, 1911). ESRI has developed a routine that works in a fashion similar to Thiessen's method.

ARC/INFO's THIESSEN routine takes a point coverage and converts it to a coverage of Thiessen or proximal polygons. The THIESSEN routine starts by triangulating the points from the point coverage into a TIN (Triangulated Irregular Network) that meets the Delaunay²⁸ criterion. Then the perpendicular bisectors for each triangle's edge are generated, forming the edges of the Thiessen polygons. The locations

²⁸ A Delaunay triangle forms a circumscribing circle which includes no other points in the data distribution (Crawford, 1990).

at which the bisectors intersect determine the locations of the Thiessen polygon vertices. Finally, the Thiessen polygons are built to generate polygon topology (ESRI, 1994). The points from the original coverage are used as the label points of the Thiessen polygons and all attributes that were assigned to the points are carried over. Figure 8 shows the steps taken in constructing a Thiessen polygon coverage. The THIESSEN routine was issued on the point coverage that represents that precipitation stations in and around the GSMNP.

After the THIESSEN routine was performed, the Thiessen polygon coverage was then converted to a raster coverage with the POLYGRID command. The POLYGRID routine will take a polygon coverage and convert it into a grid or lattice with a specified attribute. In the case of the Thiessen polygons, the yearly normal value was used and the cellsize of each raster was given as 30m x 30m. The rasterized coverage will aide in the analysis of the precipitation data over such a large area.

Using TINs

Another method examined for characterizing the precipitation regime of the GSMNP is through the direct use of the Triangulated Irregular Network (TIN) in ARC/INFO. The concept is to let ARC/INFO fix the geographic locations of the precipitation stations with the {x,y} coordinates and use the yearly normal precipitation values as the z values for the TIN. This will produce a three-dimensional surface of the normal yearly precipitation for the GSMNP. Then, isolines of equal precipitation values can be drawn to represent the precipitation differences for the park.

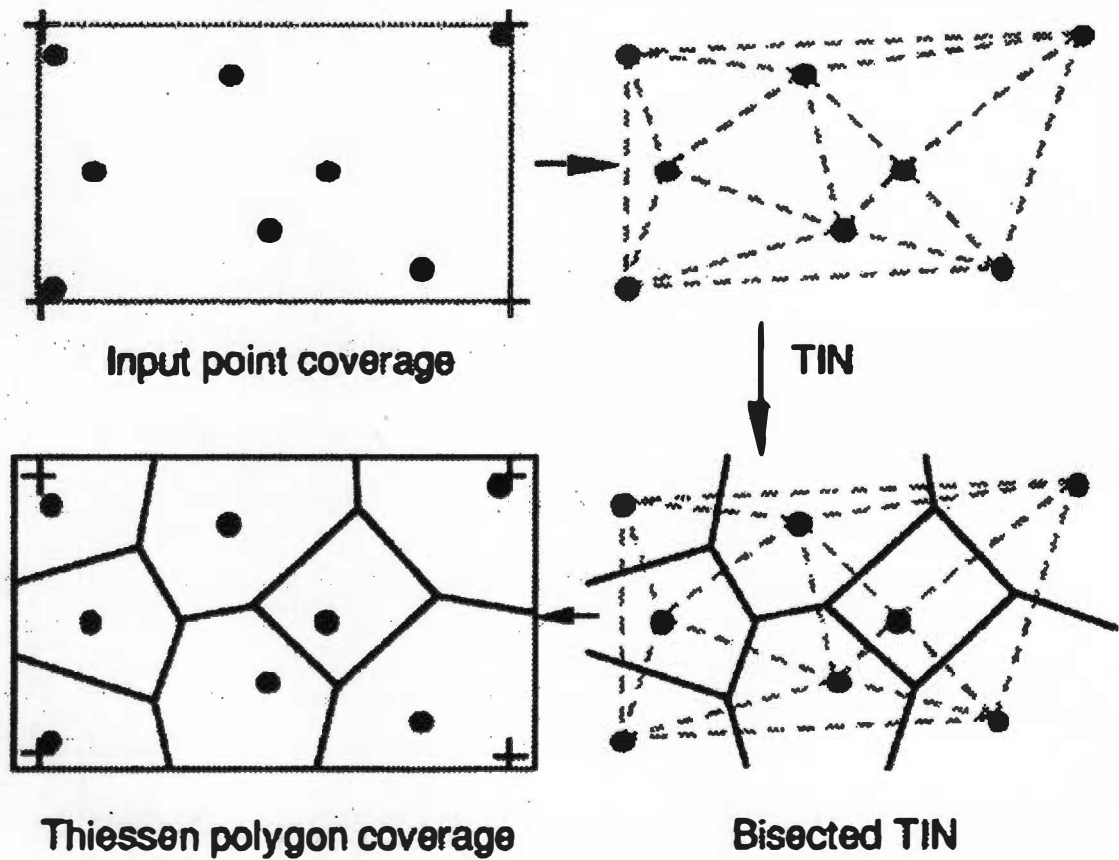


Figure 8. Steps involved in the THIESSEN routine.

The CREATETIN routine was used to construct a TIN to represent the precipitation surface of the GSMNP. This routine uses the Delaunay method of triangulation and creates a TIN from multiple input sources (ESRI, 1994). The POINT coverage for the CREATETIN routine. The normal yearly precipitation values were established as the z values by specifying them as the SPOT_ITEM²⁹. The CREATETIN routine used the {x,y} coordinates to geographically locate the spot for the placement of the z value. The yearly precipitation values were then read in as the z values for that location. This created a three-dimensional surface representing precipitation differences. The newly created TIN contained the same projection parameters as the input coverage.

The next step involved creating isohyets³⁰ with the TINCONTOUR routine. This routine converts a TIN to a line coverage containing contours (ESRI, 1994) at a specified interval. The precipitation TIN was placed in the TINCONTOUR routine, given an out-cover name and specified an interval of 1.27 mm of precipitation. This step created the isolines of precipitation from the TIN. The CLIP routine was used with the park boundary coverage to remove all isolines outside of the GSMNP.

The isoline coverage was converted to a lattice coverage with the LINEGRID routine. This routine converts a coverage containing line features into a lattice (grid) at a specified cellsize. In this case 30m x 30m. This step will again aide in the analysis of the precipitation data over the large area.

²⁹ The source of z values for input coverage features (ESRI, 1994) from the coverage attribute table.

³⁰ A line of connecting places having equal rainfall (Lutgens and Tarbuck, 1992).

The Statistical Method

The statistical method used to relate precipitation over the terrain of the GSMNP is similar to that of Spreen's (1947) in which he related precipitation to elevation, slope, exposure and orientation in western Colorado. The objective is to relate annual precipitation totals to the site factors of elevation, slope and aspect³¹.

The first step in this method involved the creation of two additional lattices from each elevation lattice at the different map scales. These include two lattice coverages containing aspect and slope values as the cell values. Within the GRID module of ARC/INFO there are two functions that can convert an elevational lattice to an aspect lattice and a slope lattice. These functions are called simply SLOPE and ASPECT. Each function takes the elevation lattice and determines the slope and/or aspect values for the corresponding cells of the new lattice. The function then writes out a new lattice containing the newly determined slope and/or aspect values. The SLOPE and ASPECT functions were performed on both the 1:24,000 and 1:250,000 lattices to create the respective lattices. The projection parameters and cell sizes for the new lattices were carried over from the elevation lattices.

Once the slope and aspect lattices were created, site factors for each of the precipitation stations had to be determined. ARC/INFO contains a routine that will compute surface values for each point in a point coverage by interpolating from a lattice (ESRI, 1994). This routine is called LATTICESPOT. Figure 9 shows how the LATTICESPOT routine is performed.

³¹ Aspect identifies the down slope direction of the maximum rate of change in value from each cell to its neighbors. It is the direction that the slope is facing (ESRI, 1993).

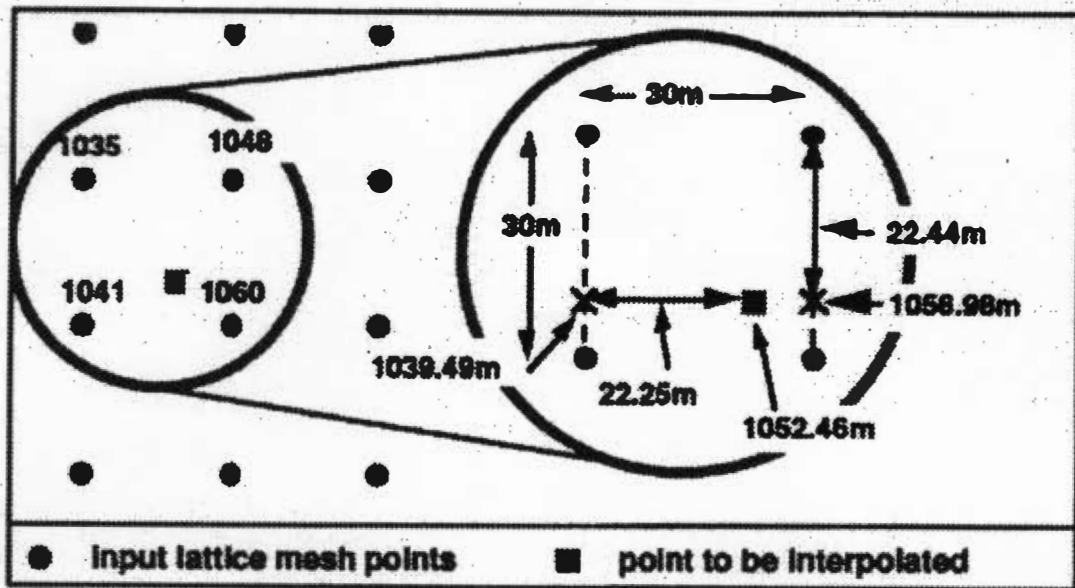


Figure 9. The LATTICESPOT routine.

The LATTICESPOT routine was issued for each of the three lattices at the 1:24,000 scale and each of the three lattices at the 1:250,000 scale. It interpolated an elevation value, an aspect value and a slope value for each of the precipitation stations involved in this study and added these values to the precipitation stations point attribute table. The DBMS of ARC/INFO was used to UNLOAD the needed values that were necessary for the statistical analysis. These values include the yearly normal precipitation values and the interpolated elevation, slope and aspect values from each of the lattices. These are the values that were used to develop the multiple linear regression model.

The LATTICESPOT routine determined an elevation, slope and aspect value for each of the 51 precipitation stations. Twenty-four of the precipitation stations fell within the boundaries of the twenty-seven 1:24,000 DEMs. Thus, their interpolated elevation, slope and aspect values came from these DEMs. The terrain data for the remaining 27 stations were interpolated from the four 1:250,000 DEMs.

The data were downloaded to a microcomputer system and placed in an EXCEL spreadsheet. Columns were arranged according to the appropriateness of the data. The aspect values determined from ARC/INFO were in degrees of aspect. To keep all values of aspect in equal perspectives, the degree values needed to be converted to radians and the cosine of that value needed to be taken. This would make aspect values of 0° and 360° (north-facing) equal to 1 and aspect values of 180° (south-facing) equal to -1. All subsequent values would be between -1 and 1 based on their orientation.

Once the appropriate columns were established in the EXCEL spreadsheet, the EXCEL function "regression" was performed on the data. This required specifying

columns to represent the dependent and independent variables for development of the model. In the case of this study, the multiple linear regression model was created by holding the yearly precipitation values as the dependent variable with the elevation, slope and aspect values as the independent variables. The product of this equation would be a predicted value of precipitation for each 30m x 30m cell, based on the input of slope, elevation and aspect, plus the determined constant.

The next step involved implementing this equation with the map algebra functions of the GRID module in ARC/INFO. But before this could be done, the lattice containing the aspect values (in degrees) needed to be converted to cosine values. The GRID function COS was issued on the aspect lattice, thus converting all degree values to cosine values. The COS function assumes that all aspect values in the lattice are radians before it the conversion is made. The values of other lattices did not need to be converted.

Once ARC/INFO was used to create the necessary coverages, coverage overlay and analysis can take place. Area and precipitation values were obtained from the relational database within ARC/INFO. Subsequent maps and figures were also created with the GIS.

The resulting vegetation coverage from MacKenzie's (1993) study was obtained and converted to an ARC/INFO lattice (grid). This lattice was then converted into a point coverage using the GRIDPOINT routine of ARC/INFO and the resulting point contained a vegetation code within the .PAT file. The LATTICESPOT routine was performed using the vegetation point coverage and the precipitation coverage that is the best representation for the GSMNP. This resulted in a precipitation value associated with a vegetation type at

a particular location. Average precipitation values were determined for each vegetation type.

Results and Discussion

The Precipitation Data

Examination of the “Normals”

Figures 10 and 11 show the moving averages of precipitation for Knoxville and Waynesville, respectively. Data from the Knoxville station ranged from the year 1910 to 1990. The moving averages for the thirty year periods were first calculated in 1939 and continued through the year 1990. The long-term average for the Knoxville station was 1185.2 mm of annual precipitation. The 52 moving averages for the Knoxville station deviated from this number by -26.2 to +31.5 mm of annual precipitation. The moving average calculated from these data for the 30 year period ending in 1969 was 1160.8 mm. This number deviated from the long-term average by a factor of -24.4 mm of annual precipitation.

Data from the Waynesville station ranged from the year 1931 to 1990. The first moving average for this station was calculated in 1960. The long-term annual average for Waynesville was 1186.2 mm. The 31 moving averages deviated from this number by -24 to +19 mm of annual precipitation. For the 30 year period ending 1969 the moving average was 1175.8 mm of annual precipitation. This number deviated from the long-term average by a factor of -10.4 mm. The deviations of the long-term averages for each station were small. Therefore, the 1969 “normals” used in this study were representative of the precipitation that could occur in the GSMNP.

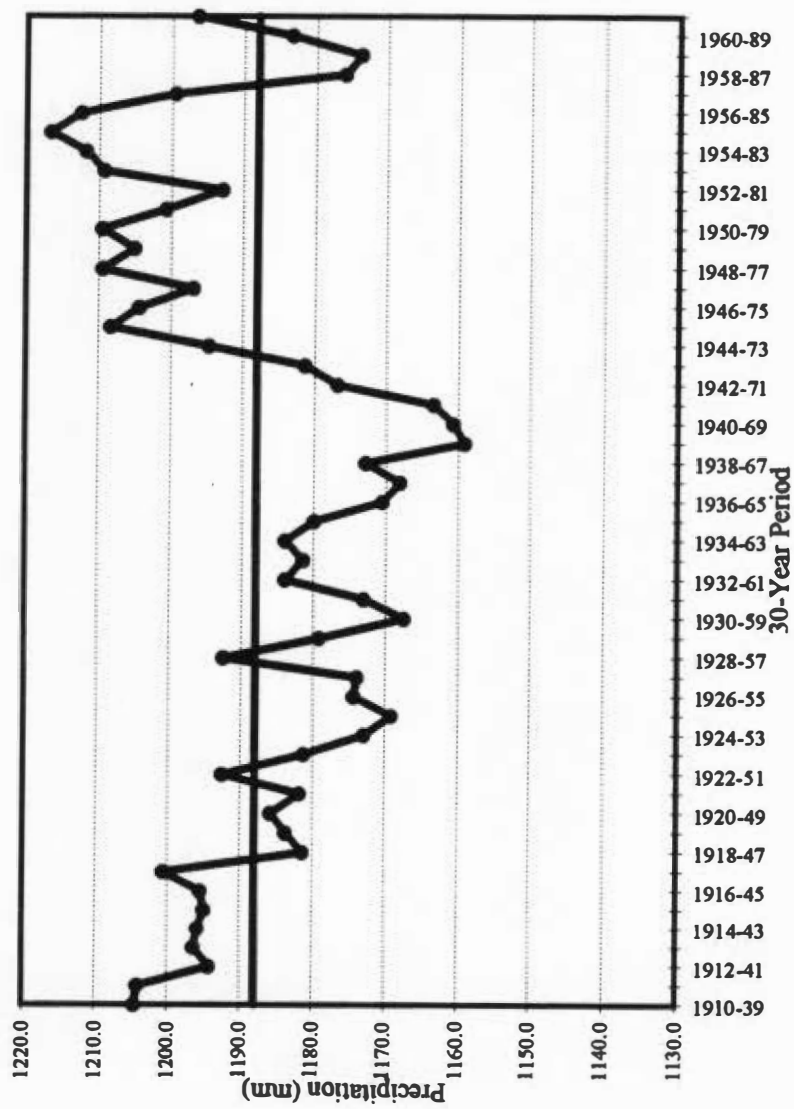


Figure 10. Thirty-year moving averages of precipitation for Knoxville, TN.

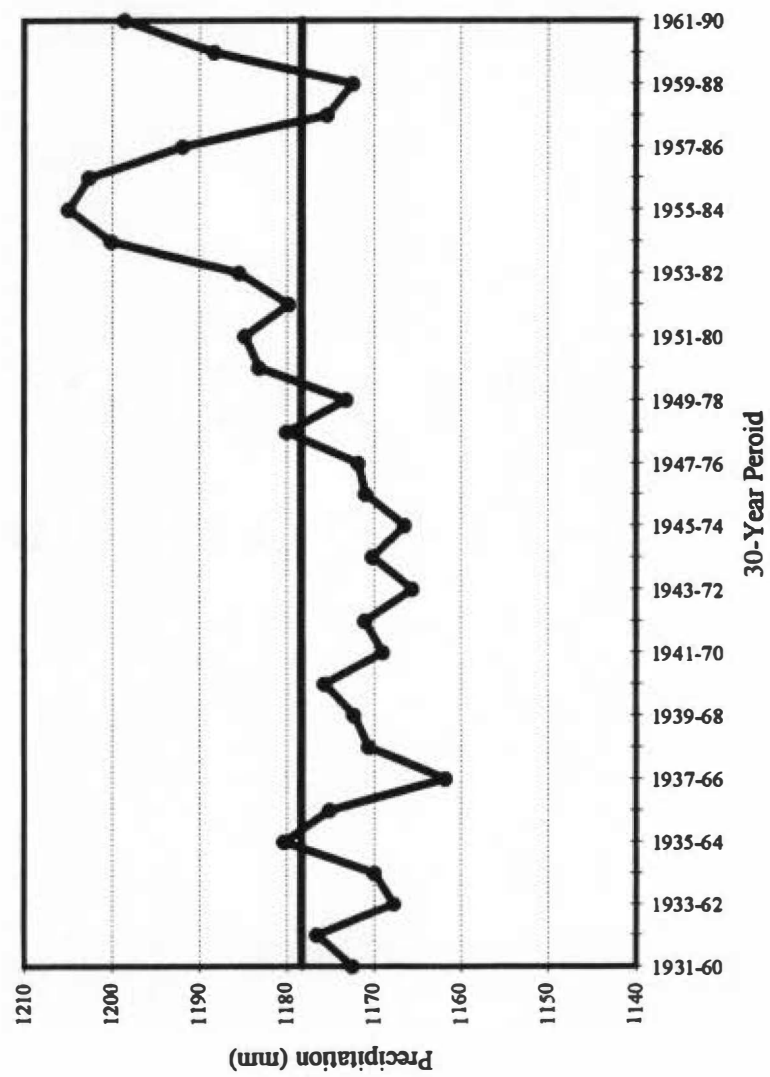


Figure 11. Thirty-year moving averages of precipitation for Waynesville, NC.

The Normals

The TVA rain gauge located at Douglas Dam had the lowest (1130.8 mm) average annual precipitation used in the study. The TVA radio rain gauge located at Clingman's Dome had the highest (2105.9 mm) average annual precipitation. The two extremes gave a range of precipitation for the 51 stations as 975.1 mm. The average precipitation for the 51 stations was 1407.7 mm.

Implementing the GIS

Precipitation Stations/Park Boundary

The total area of the park determined from the GIS is 2063.1 square kilometers. Nine of the 51 precipitation stations used in this study fell within the park boundary. These stations were: Cosby No.4 ES, Mt. Sterling ES, Mt. LeConte ES, Cades Cove ES, Clingman's Dome Radio ES, Oconaluftee ES, Noland Creek ES, Twentymile ES and Fontana Dam. The remaining 42 precipitation stations fell outside of the park but were within a 39 kilometer buffer of the GSMNP. Thorpe Dam was the farthest away from the park at 38.1 kilometers. Figure 12 shows the overlay of the precipitation stations and the park boundary coverages.

The Thiessen Method

The THIESSEN routine constructed 51 Thiessen polygons from the 51 precipitation stations used in this study. Of these 51 Thiessen polygons, only 23 of them overlapped with the boundary of the park. The remaining 28 thiessen polygons did not cross the park boundary. Therefore, their associated precipitation values did not influence

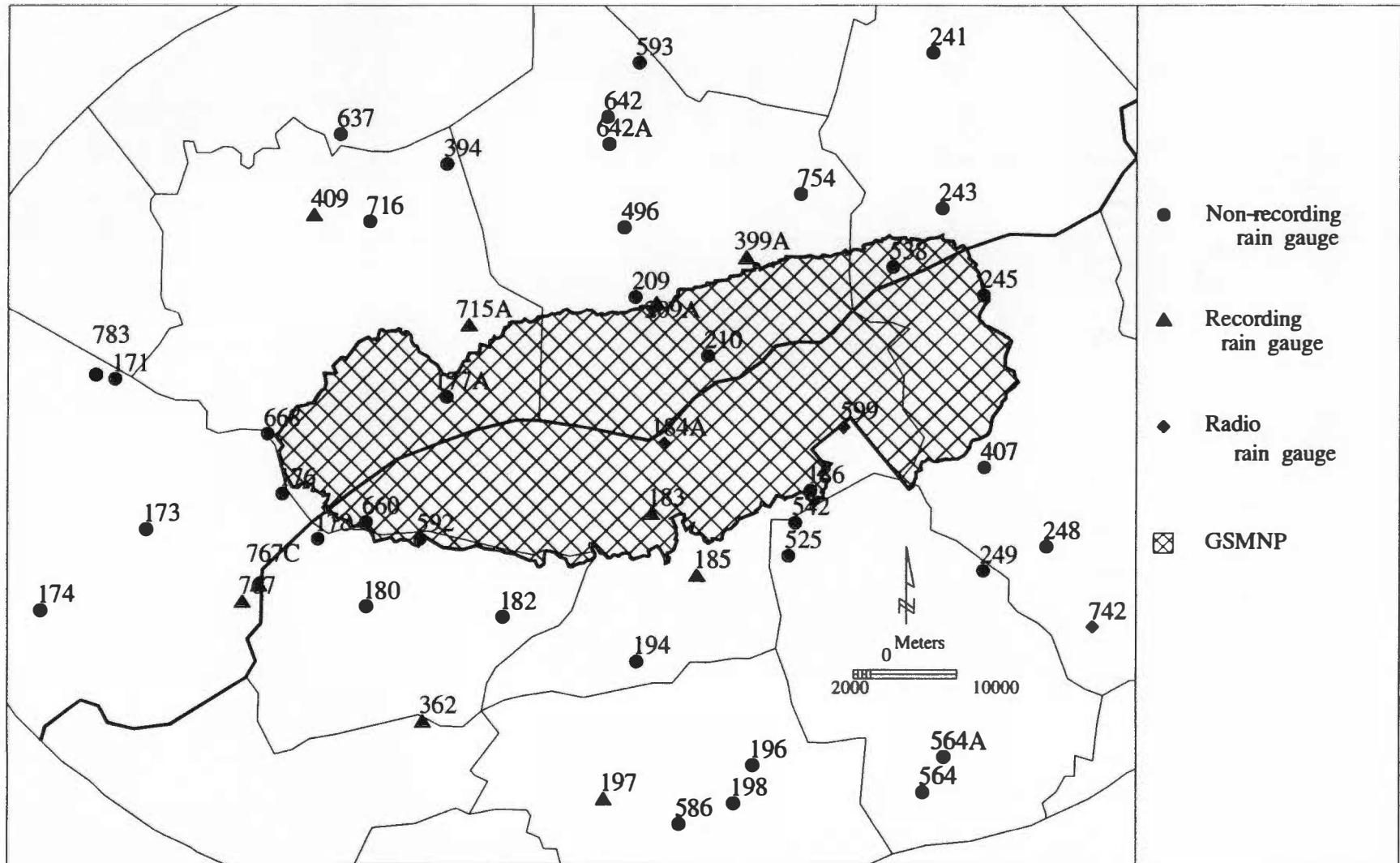


Figure 12. Location of the precipitation stations in and around the GSMNP.

the values for the park. Figure 13 shows the results of the THIESSEN routine. Figure 14 shows only the Thiessen polygons that overlapped with the boundary of the park.

The THIESSEN polygon method gave an annual mean precipitation value for the GSMNP as 1542.5 mm. This value was determined by averaging the precipitation values from each of the 2,292,296 30m x 30m cells from the rasterized thiessen polygon coverage. The minimum precipitation value determined here was 1194.8 mm. This was the normal value associated with the station at Pittman Center. The area represented by this minimum value was 78.3 square kilometers or 3.79% of the park. The maximum value for the park was 2105.9 mm. This was the normal value for the Clingmans Dome station. This value represented 215.01 square kilometers or 10.42 % of the park area. The precipitation data for the park had a standard deviation of 251.0 mm and a range of 911.1 mm.

The precipitation normal from the Cades Cove station represented the largest area of the park. The value of 1423.9 mm of precipitation covered 285.5 square kilometers (13.84%). The Jones Cove station represented the smallest Thiessen polygon area with a normal of 1247.6 mm covering an area of .75 square kilometers (0.04%). Table 5 lists of the Thiessen polygon areas of the GSMNP and the precipitation stations with the station normals that represent them. Figure 15 shows the distribution of precipitation within the GSMNP using the THIESSEN method.

The THIESSEN routine resulted in the construction of 23 Thiessen polygons that covered the GSMNP. The precipitation data from each of the stations within their respective Thiessen polygons, represented large Thiessen areas of the park. For example,

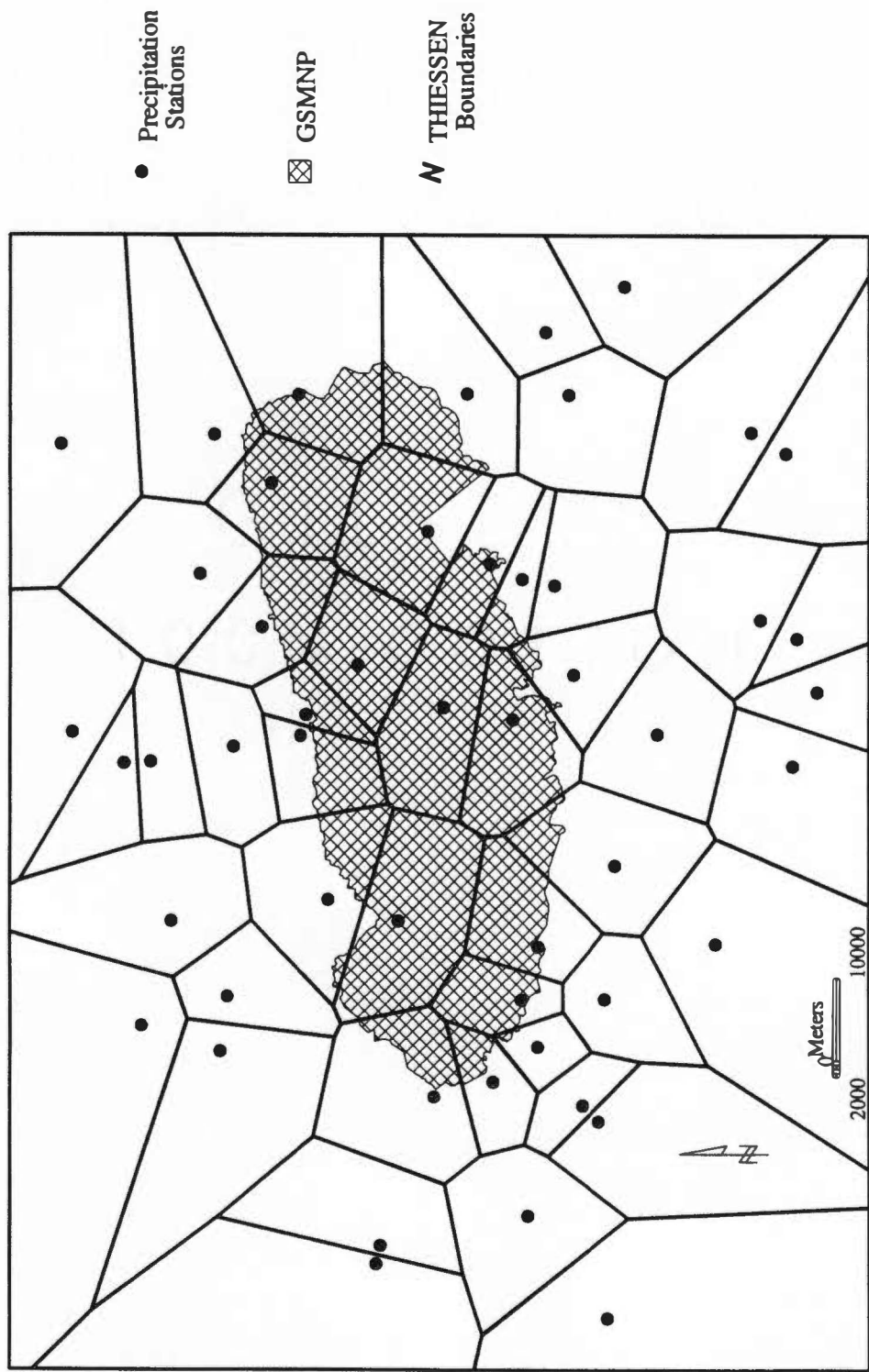


Figure 13. Results from using the THIESSEN Routine.

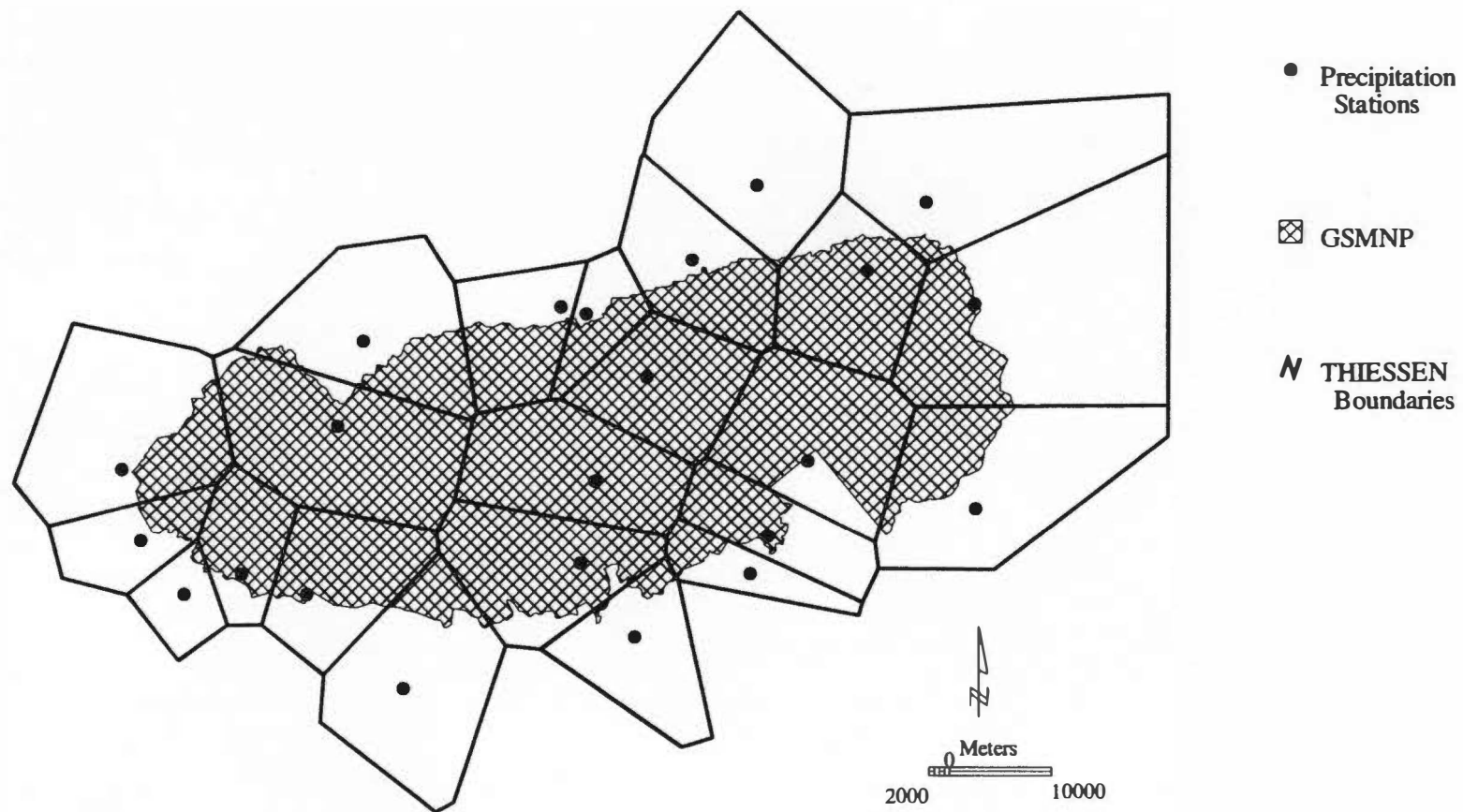


Figure 14. THIESSEN polygons that overlapped with the GSMNP boundary.

Table 5. The precipitation stations with their respective THIESSEN polygon areas.

Station	TVA-ID	Recording Agency	Normal Precipitation (mm)	Area Square km
ABRAMS CREEK ES	668	USDI	1472.2	63.3
BIG COVE, RADIO ES	599	TVA	1520.7	197.7
BRYSON CITY R ES	185	TVA	1262.9	10.6
CADES COVE ES	177A	USDI	1423.9	285.5
CALDERWOOD POWERHOUSE	176	ALCOA	1373.6	25.3
CATALOOCHEE RANCH Z ES	407	TVA	1590.0	78.0
CHEOAH DAM	178	ALCOA	1474.7	2.0
CHEROKEE ES	542	USDI	1308.4	19.8
CLINGMANS DOME,RADIO ES	184A	TVA	2105.9	215.0
COSBY NO.4 ES	538	USDI	1416.1	157.3
FONTANA DAM	592	TVA	1413.0	118.0
GATLINBURG R ES	209A	TVA	1413.0	41.2
GATLINBURG,NEAR ES	209	USWB	1401.8	70.9
HARTFORD ES	243	TVA	1221.2	6.7
JONES COVE ES	754	TVA	1247.6	0.8
MT LECONTE ES	210	TVA	1954.3	165.5
MT STERLING ES	245	TVA	1355.1	109.1
NOLAND CREEK ES	183	TVA	1470.7	176.0
OCONALUFTEE ES	186	USDI	1446.0	61.4
PITTMAN CENTER R ES	399A	TVA	1194.8	78.3
STECOAH ES	182	TVA	1490.7	31.7
TOWNSEND R ES	715A	TVA	1293.4	65.5
TWENTYMILE ES	660	USDI	1525.3	83.3

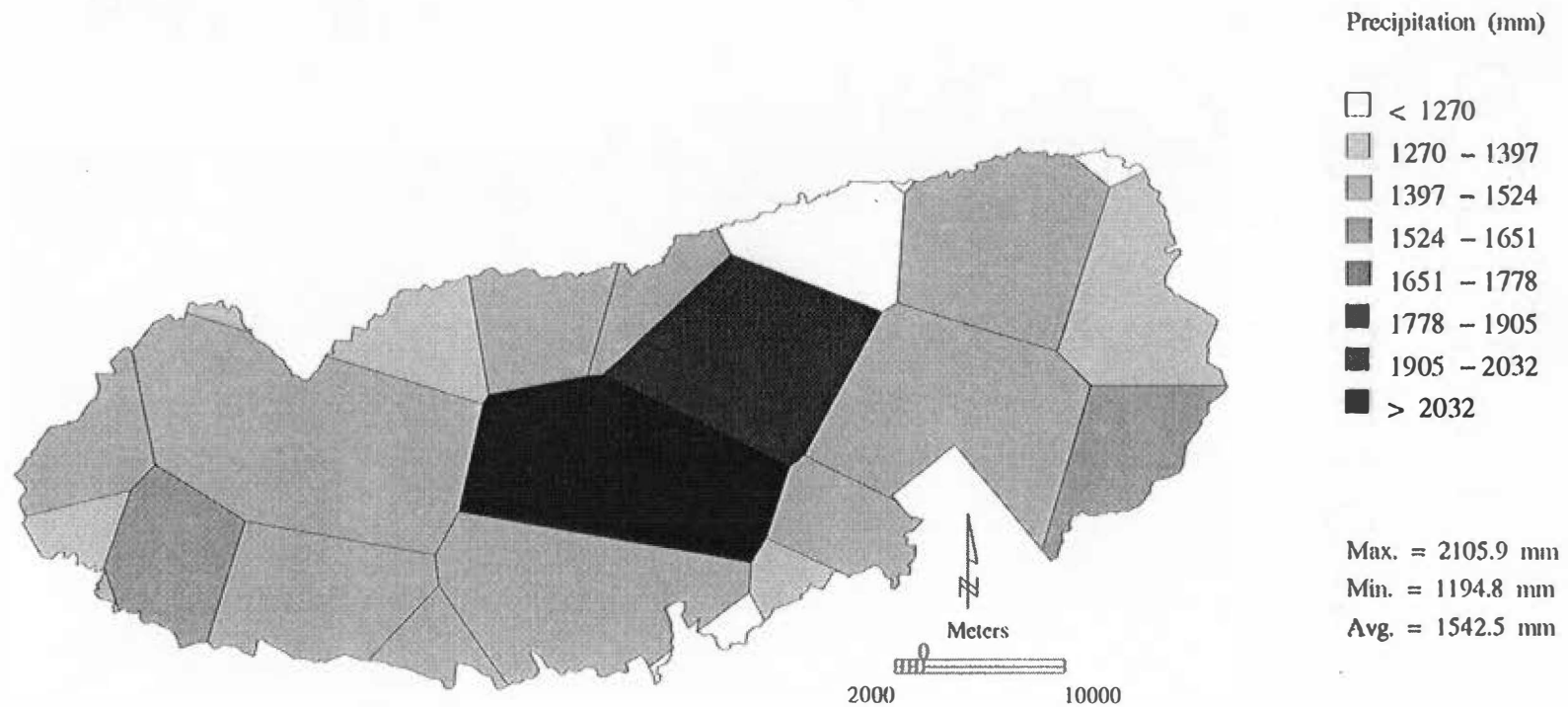


Figure 15. Precipitation of the GSMNP using THIESSEN polygons.

Abrams Creek had an annual precipitation normal of 1472.2 mm. That value represented 63.3 square kilometers of the park. The 1472.2 mm represented the precipitation that occurred at 35° 33' 29" latitude and 84° 00' 38" longitude, not the precipitation that could have occurred over the entire area of that polygon. The THIESSEN method constructs a polygon in which the point value, in this case the precipitation data, is supposed to represent the entire area of that Thiessen polygon. This, however, is a misrepresentation, as precipitation has the tendency to change spatially.

It has been determined that precipitation amounts increase with an increase in elevation. However, elevational characteristics were not taken into account by using the Thiessen polygons. For example, the polygon which the Cades Cove precipitation normal (1423.9 mm) represented contained vast differences in elevation (300 m to 2000 m).

Aspect and slope factors were also not accounted for in the determination of precipitation values by the Thiessen method. Aspect and slope changes were evident within the terrain of the GSMNP and are responsible in altering precipitation amounts across large areas. It was determined that the northeasterly facing slopes and slopes that had ranged between 20-30° of inclination were wetter than their counterparts.

Precipitation changes between polygons were very abrupt by using the Thiessen method. There were no gradual increases or decreases of precipitation. For example, the precipitation value for the Thiessen polygon represented by the Noland Creek precipitation station was 1470.7 mm. An adjacent Thiessen polygon to the Noland Creek polygon is the Clingmans Dome polygon. This polygon was represented by a precipitation value of 2105.9 mm. These polygons share a common border, but the precipitation

difference across this common border was 635.3 mm. This was a sharp contrast in precipitation differences. Other sharp contrasts like this one were evident among the Thiessen polygons (figure 16).

A horizontal transect was drawn across the rasterized Thiessen polygon coverage that represents the precipitation of the GSMNP (figure 17). Using the LATTICESPOT routine, a precipitation value was interpolated at every 1 kilometer from this precipitation coverage. The interpolated precipitation values were plotted against their corresponding UTM x-coordinate (figure 16). The figure shows the very abrupt changes followed by a series of similar values associated with using the THIESSEN method to represent the precipitation.

Using TINs

The TIN routine (CREATETIN) constructed 91 triangles from the 51 precipitation stations. The maximum Z value from the TIN was 2105.9 mm from the station at Clingmans Dome. The TIN had a minimum Z value of 1130.8 mm from the station at Douglas Dam. The TINCONTOUR routine created 1601 isolines at an interval of 1.27 mm. The highest and lowest isolines created were 2105.7 mm and 1130.3 mm of precipitation, respectively, giving a range of precipitation as 975.4 mm. Figure 18 shows the TIN structure created by ARC/INFO.

The rasterized coverage of the isolines contained 2,292,296 30m x 30m cells. The mean value from these cells was 1532.1 mm of precipitation. The coverage had a maximum cell value of 2099.3 mm and a minimum cell value of 1217.9 mm. The data from the cells had a standard deviation of 164.7 mm. Cell values between the range of

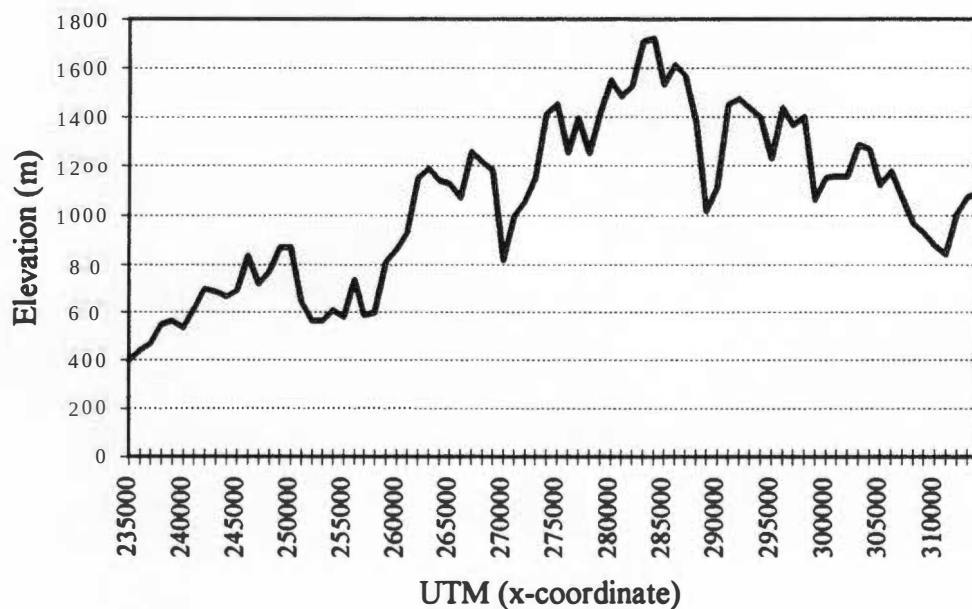
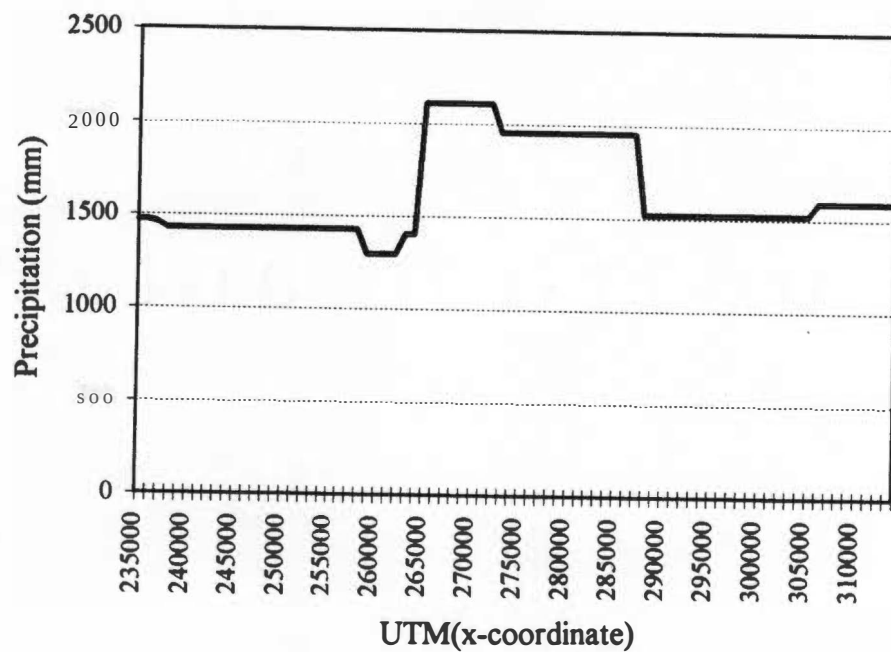


Figure 16. Top - UTM (x-coordinate) vs. THIENSEN precipitation value. Bottom - UTM (x-coordinate) vs. elevation from the 1:24,000 scale lattice.

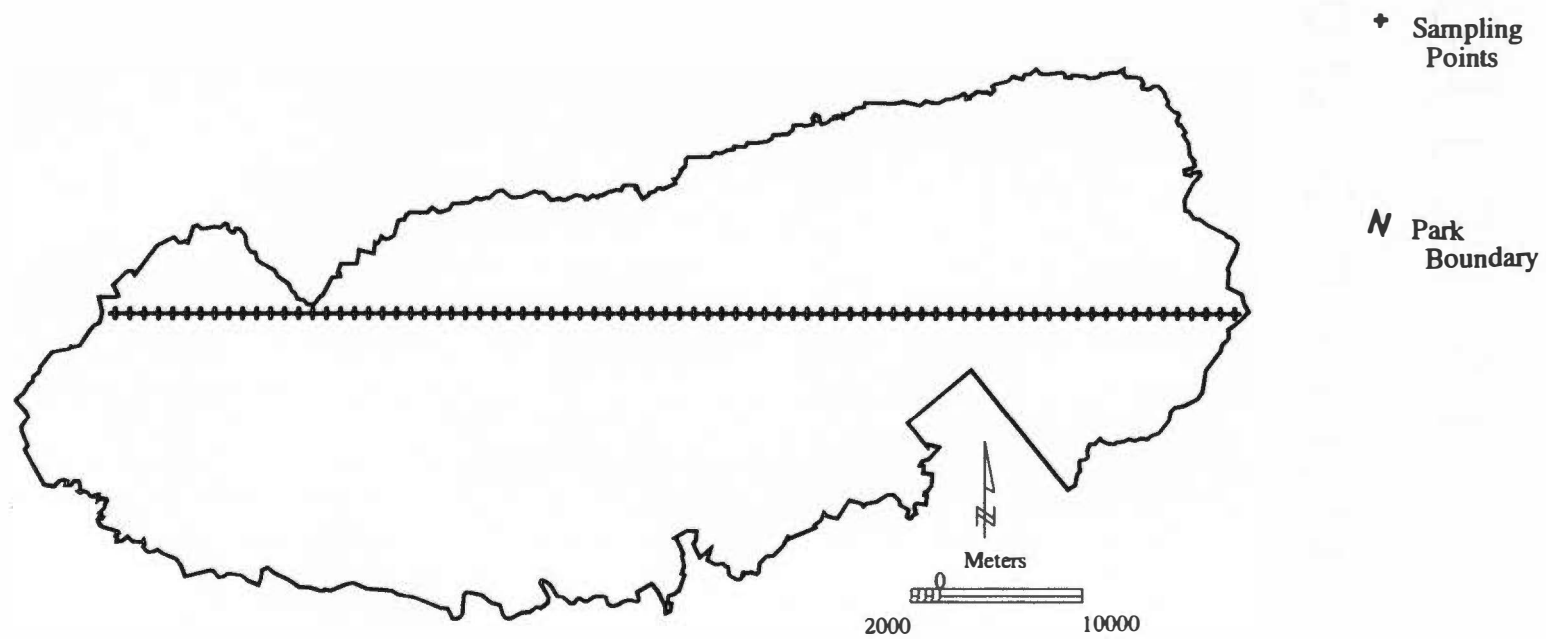


Figure 17. Transect sampling points for the precipitation coverages.

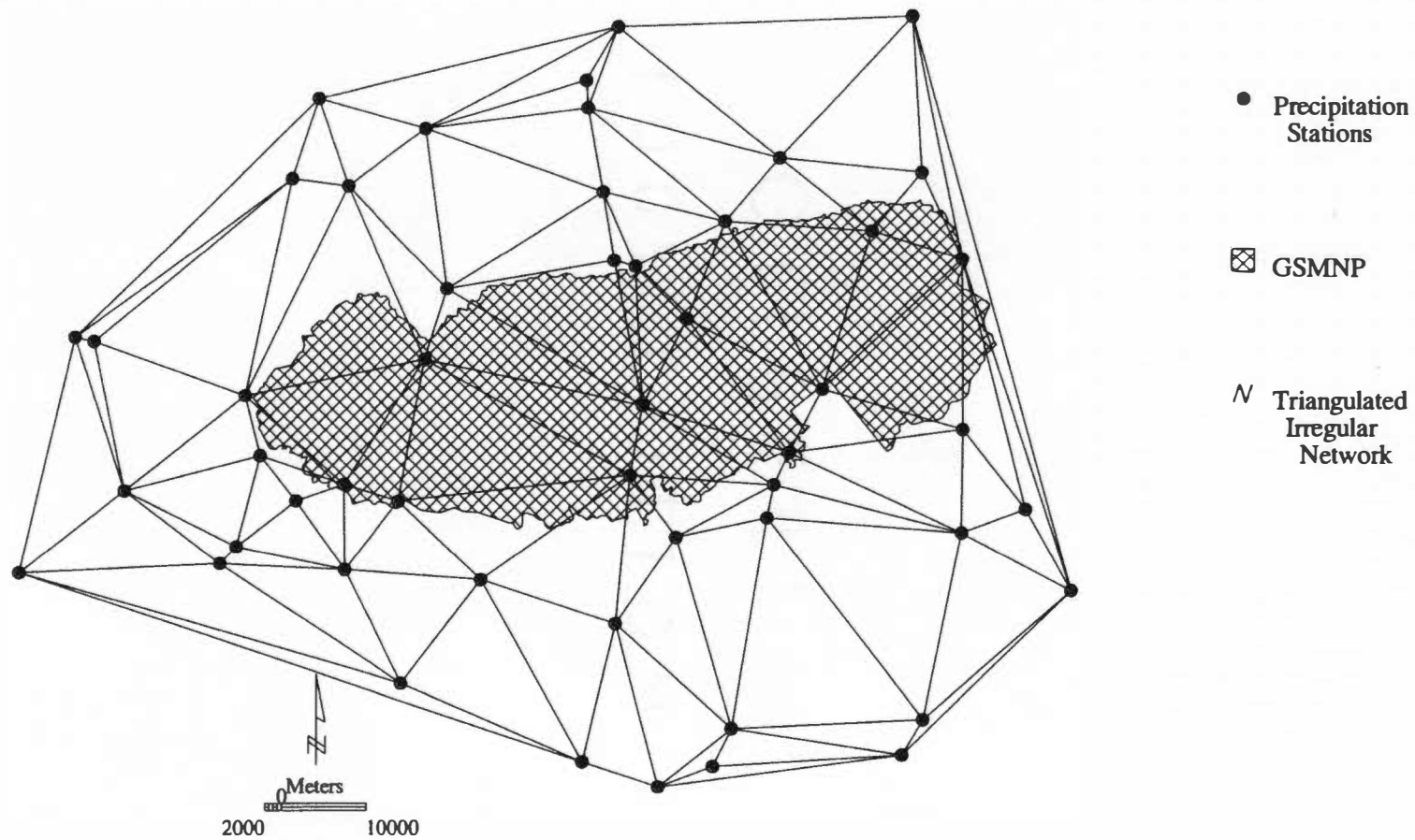


Figure 18. TIN of the precipitation stations.

1397-1524 mm occupied the largest area of the park. The values covered 1108.9 square kilometers or 53.8% of the entire park. The cell whose values were less than 1270 mm of precipitation covered 0.49% (10.1 square kilometers) of the park. Figure 19 shows 127 mm increments of precipitation that cover the GSMNP based on the TIN method.

The lack of precipitation stations in remote areas of the park seem to shift the TIN structure toward the center of the park. The station located at Clingmans Dome had a annual normal precipitation value of 2105.9 mm. This resulted in a TIN structure that had a peak value at this point. When subsequent isolines were drawn, they were forced to descend from here. This resulted in other high-elevation areas of the park to be not well represented by the lower than expected precipitation that resulted. As previously discussed, precipitation has a tendency to increase with increasing elevation. However, with the TIN method, this was not evident in the park as a whole. The results of the TIN method are similar to those of McMaster and Hubbard (1970) shown in figure 2.

The area represented by the precipitation values in the 1397-1524 mm range covered a wide range of elevations (300 m to 2000 m), slopes and aspect values. As with the Thiessen method, the TIN method indicated that 1397-1524 mm of precipitation represented the varied topography of this area.

Like the precipitation coverage derived from the THIESSEN method, a horizontal transect line was drawn across the precipitation coverage which was derived from the TIN (figure 17). The precipitation values were interpolated at the same 1 kilometer locations. Figure 20 shows the plot of the TIN precipitation values and the corresponding UTM x-coordinate. This figure shows a smoother transition of precipitation across the park with a

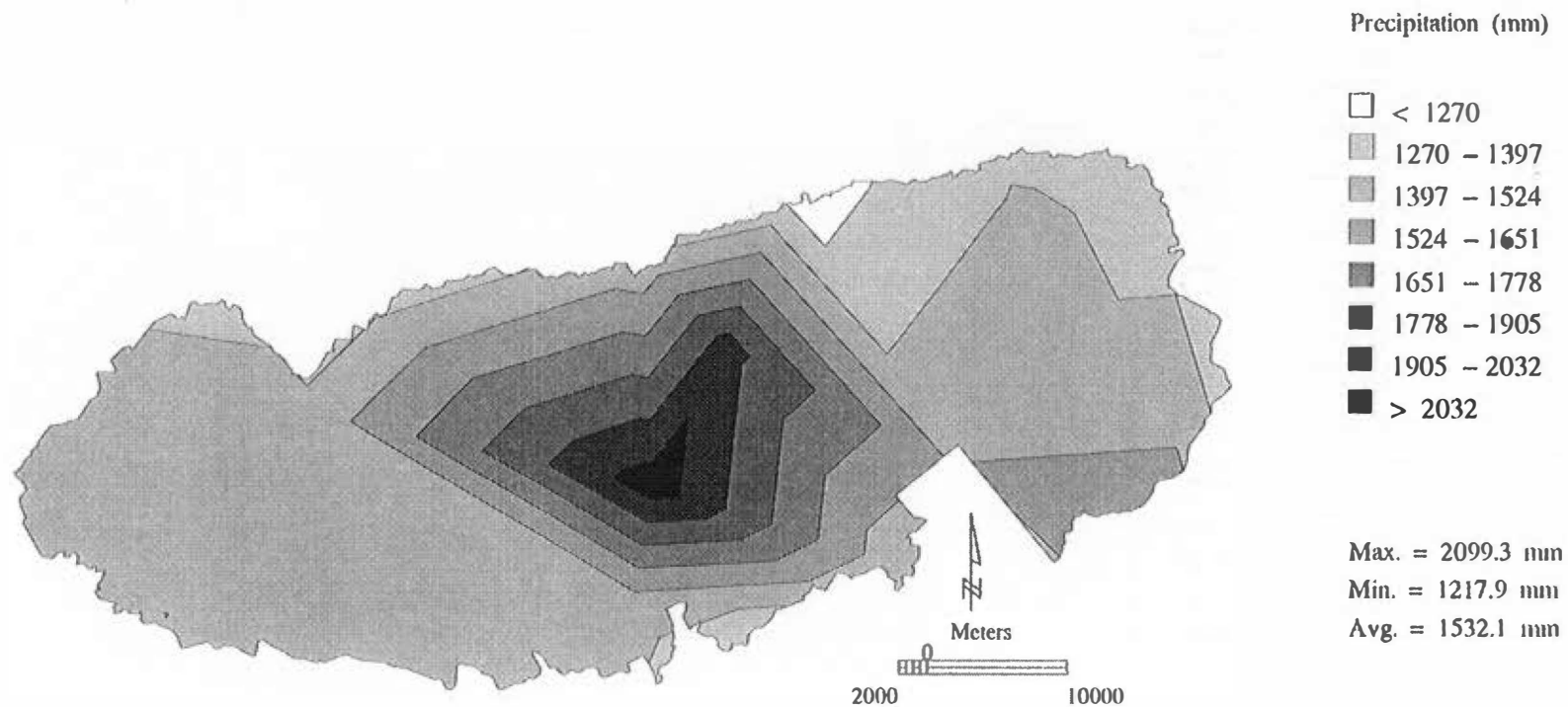


Figure 19. Precipitation of the GSMNP using TINs.

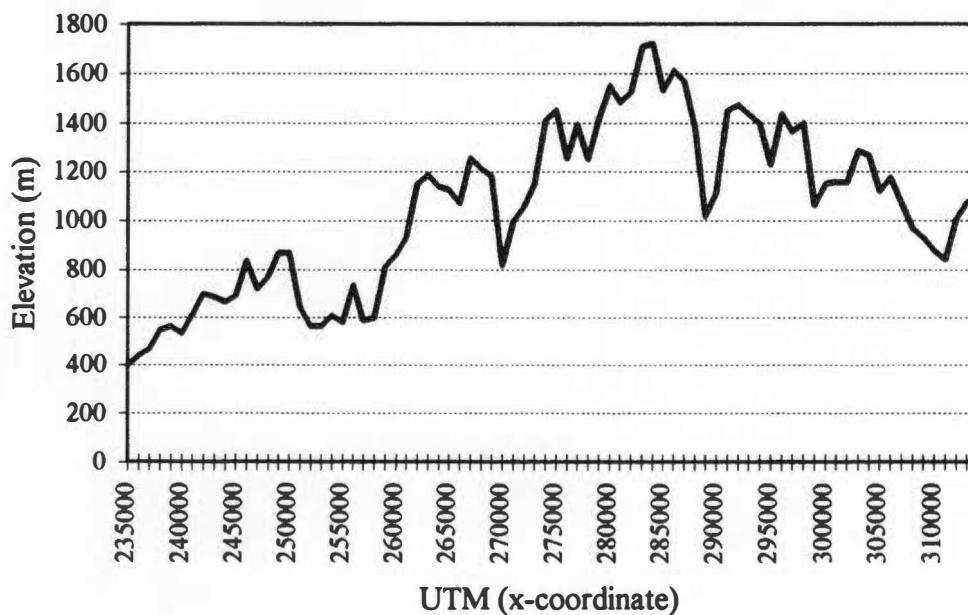
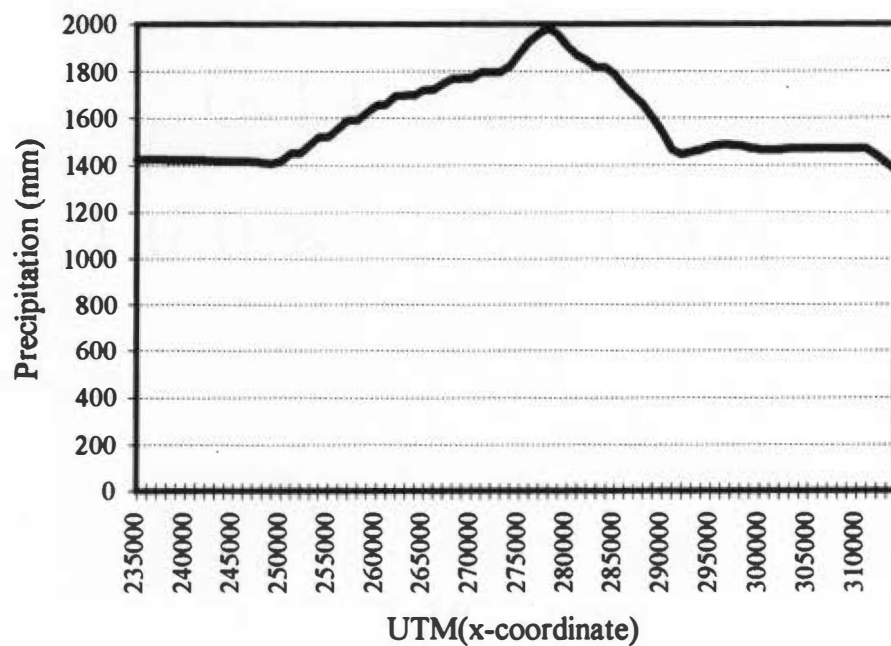


**Figure 20. Top - UTM(x-coordinate) vs. TIN precipitation value.
Bottom - UTM (x-coordinate) vs. elevation from the 1:24,000 scale lattice.**

peak near the center. This peak is caused by the highest precipitation value associated with the TIN structure: the station at Clingmans Dome. Values near the east and west ends of the park are relatively the same due to the lack of precipitation data collected in these areas. The values for these areas influenced by the precipitation data from stations of lower elevations located outside the park.

The Statistical Method

Terrain Data

The 1:24,000 elevation lattice covering the GSMNP contained 2,292,296 30m x 30m cells. This coverage had a maximum elevation of 2027 meters and a minimum elevation of 266 meters. The mean elevation of the GSMNP, as determined by these methods, was 1015 meters. The elevation data for this coverage had a standard deviation of 345 meters. Figure 21 shows the elevations of the GSMNP.

The aspect and slope lattices were determined from the 1:24,000 elevation lattice. Thus, these two lattices had the same number of 30m x 30m cells: 2,292,296. The aspect lattice values (degrees) ranged from minus one¹ to 360. The mean aspect value determined for the GSMNP was 183°. This value indicates that the slopes of the mountains have a tendency to face a southerly direction. The aspect values had a standard deviation of 104°. The slopes of the GSMNP ranged from 0.00° (flat) to 64°. The average slope in the mountains was 23°. The standard deviation for this data was 8.7°. Figures 22 and 23 show the aspect and the slope characteristics of the GSMNP.

¹ Cells in the input grid of zero slope (flat) are assigned an aspect of -1 (ESRI, 1991).

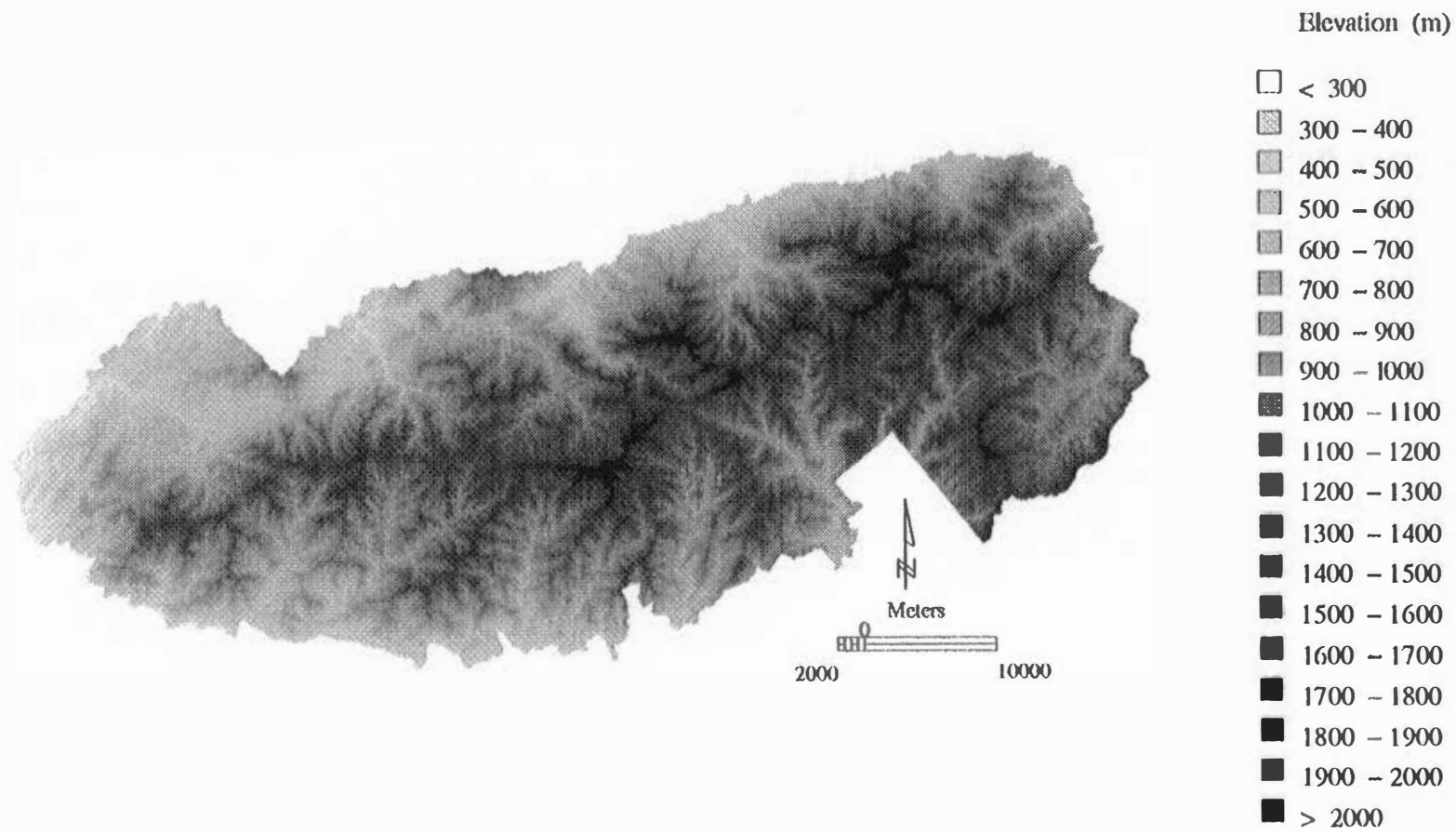


Figure 21. The elevations of the GSMNP.

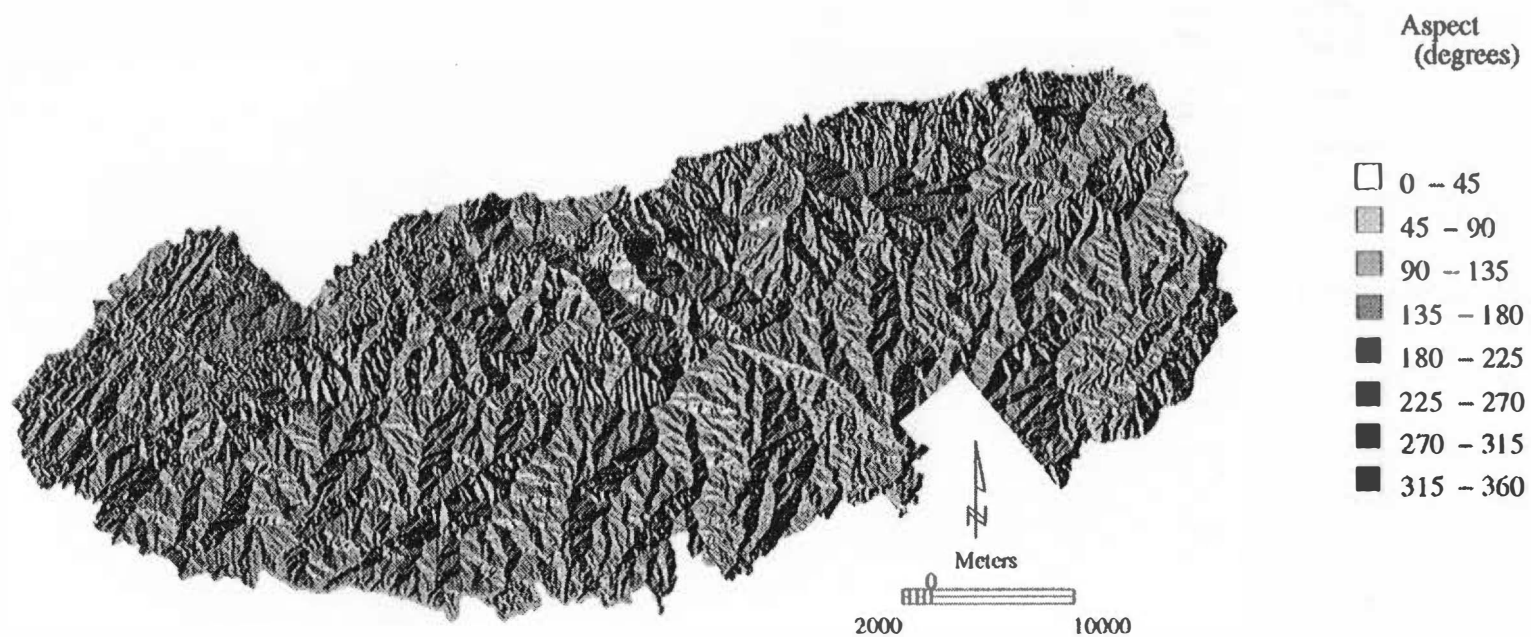


Figure 22. The aspects of the GSMNP.

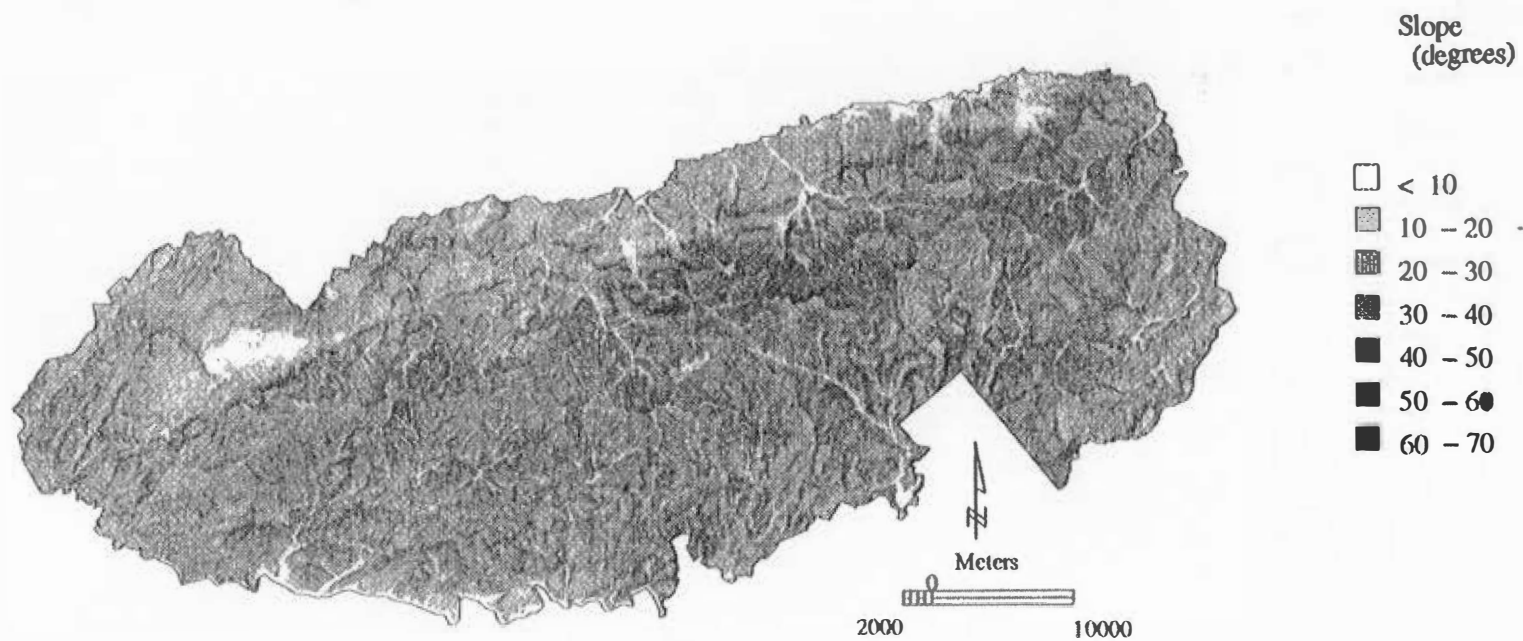


Figure 23. The slopes of the GSMNP.

Station Site Factors

Elevation

The interpolated elevation data for the 51 precipitation stations had a range of 1679 meters. The station with the lowest elevation was located at Vonore^a, with an interpolated value of 241 meters. The Clingmans Dome^b station had the highest interpolated elevation value at 1920 meters. Nine of the 51 stations were situated above 1000 meters and 20 stations were below 500 meters in elevation. The average elevation for the 51 precipitation stations was determined to be 658 meters.

Aspect

The interpolated values for aspect covered nearly the entire face of a compass, ranging from 4.2° to 355.9°. A total of 17 stations faced a northerly direction (9 stations facing NE, 8 stations facing NW) and 31 stations faced a southerly direction (15 stations facing SE, 16 stations facing SW). Three of the 51 stations were located in flat areas as their interpolated aspect value was determined to be -1: : Sevierville, Fontana Dam and Sunburst.

Slope

The average slope for the precipitation stations was determined to be 11.2°. Thirty-one stations had a slope value of less than 10° and 8 stations had slope values greater than 20°. The precipitation station located on the steepest surface was located at Calderwood Powerhouse with a slope value of 40°. Again, three of the 51 stations were located in flat areas as their interpolated slope value was determined to be 0.00° of slope.

^a Interpolated from the 1:250,000 DEM.

^b Interpolated from the 1:24,000 DEM.

These were the same three stations that had an aspect value of -1: Sevierville, Fontana Dam and Sunburst. Table 6 lists the interpolated elevation, slope and aspect values.

Examining the Precipitation Data and the Terrain Data

Precipitation verses Elevation

Precipitation amounts in and around the GSMNP tend to increase with an increase in elevation. This is evident in the station data used here. The average for the stations below 500 meters was 1271.8 mm. The average for the stations between 500 and 1000 meters increased to 1397.8 mm. For stations between 1000 and 1500 the average moved up to 1649.0 mm. Stations greater than 1500 meters had an average annual precipitation amount of 2030.2 mm. These figures reflected an increase in precipitation amounts with an increase in elevation.

Precipitation verses Aspect

Precipitation averages were calculated for all stations facing in the same range of aspect. These ranges included 0-90°, 90-180°, 180-270° and 270-360°. The average amounts of precipitation for these four ranges were 1594.9, 1385.6, 1344.4, and 1392.4 mm, respectively. The slopes facing a northeasterly (0-90°) direction were the wettest as they had the highest annual average precipitation (1594.9 mm). Slopes facing a southwesterly (180-270°) direction tend to be the driest as the average for this direction was only 1344.4 mm.

Precipitation verses Slope

The average amounts of precipitation were calculated for slopes ranging between 0-10°, 10-20°, 20-30° and greater than 30°. The lowest average was 1347.7 mm which

Table 6. The interpolated terrain values for the precipitation stations.

Station	TVA-ID	Normal	From the 1:250,000 Lattices		From the 1:24,000 Lattices			
		Precip. (mm)	Elevation (m)	Slope (°)	Aspect (°)	Elevation (m)	Slope (°)	Aspect (°)
ABRAMS CREEK ES	668	1472.2	284.6	149.1	12.0	334.4	71.6	11.0
BALSAM ES	249	1518.9	1008.2	243.7	4.0	*	*	*
BIG COVE, RADIO ES	599	1520.7	853.9	152.4	1.5	811.2	169.9	8.5
BRYSON CITY R ES	185	1262.9	546.1	244.9	3.9	545.4	62.4	14.1
CADES COVE ES	177A	1423.9	583.0	279.5	3.4	588.2	205.7	8.2
CALDERWOOD POWERHOUSE	176	1373.6	489.2	242.7	16.0	407.8	260.6	40.0
CARTOOGECHAYE CREEK ES	586	1470.4	698.5	49.6	6.8	*	*	*
CATALOOCHEE RANCH Z ES	407	1590.0	1432.1	168.9	11.9	1478.3	101.6	26.6
CHEOAH DAM	178	1474.7	371.7	196.3	4.6	466.9	187.8	12.7
CHEROKEE ES	542	1308.4	617.0	119.6	9.9	650.1	197.7	15.6
CLINGMANS DOME,RADIO ES	184A	2105.9	1930.8	89.4	19.0	1920.8	75.0	28.9
COSBY NO.4 ES	538	1416.1	687.3	327.4	4.9	670.5	312.1	5.6
DOUGLAS DAM	593	1130.8	312.3	178.0	14.0	*	*	*
EAGLENEST MTN. ES	248	1405.1	877.5	317.7	3.4	*	*	*
ELA, NEAR	525	1436.9	606.4	212.0	1.1	608.0	106.7	9.4
FONTANA DAM	592	1413.0	520.3	170.6	0.8	521.0	-1.0	0.0
FRANKLIN ES	198	1298.4	648.9	154.9	3.1	*	*	*
FRANKLIN POWERHOUSE	196	1298.4	605.4	199.4	2.4	*	*	*
GATLINBURG R ES	209A	1413.0	460.9	297.2	11.0	405.2	307.3	8.9
GATLINBURG,NEAR ES	209	1401.8	585.1	127.5	9.8	625.6	145.5	18.6
HARTFORD ES	243	1221.2	394.0	210.5	0.7	418.0	249.0	9.1
JONES COVE ES	754	1247.6	365.0	141.3	0.7	367.2	226.3	12.9
KITTIE ES	173	1304.0	305.3	33.7	3.3	*	*	*
KNOXVILLE ARPT R XX ES	409	1164.6	266.9	328.8	0.6	*	*	*
MCGHEE ES	171	1291.8	245.3	269.2	1.0	*	*	*
MT LECONTE ES	210	1954.3	1848.8	3.6	25.6	1813.2	61.7	36.2

Table 6. The interpolated terrain values for the precipitation stations (cont.).

Station	TVA-ID	Normal	From the 1:250,000 Lattices			From the 1:24,000 Lattices		
		Precip. (mm)	Elevation (m)	Slope (°)	Aspect (°)	Elevation (m)	Slope (°)	Aspect (°)
MT STERLING ES	245	1355.1	878.2	78.3	12.3	874.6	98.7	26.7
NEEDMORE ES	194	1336.8	56.6	186.4	9.0	*	*	*
N W P RT ES	241	1137.2	324.1	234.9	3.4	*	*	*
NOLAND CREEK ES	183	1470.7	780.1	131.7	30.6	847.8	177.1	33.2
NORTI CITICO CREEK N0.1 RES	767	1562.4	1017.5	338.5	15.9	*	*	*
NOR TIC f CO CREEK N0.4A DP ES	767C	1756.4	1293.7	269.2	13.5	*	*	*
O ON A U FEE ES	186	1446.0	622.6	108.2	2.2	613.5	105.4	6.7
PIGEON FORGE ES	496	1175.3	312.0	255.0	1.3	*	*	*
P T I C E N E R R E S	399A	1194.8	396.6	231.4	4.9	508.4	322.1	16.9
PROV IENCE ES	394	1196.6	334.2	168.1	0.6	*	*	*
SA N EETI. A DAM	180	1417.3	67.7	207.5	1.6	624.9	141.4	7.5
SEVERI V EES	642	1216.4	274.9	219.7	1.4	*	*	*
SEV I R V E XX ES	642A	1133.9	273.0	-1.0	0.0	*	*	*
STECOAH ES	182	149.7	655.4	196.3	8.7	*	*	*
SUNBURST, R IO ES	742	1454.7	945.0	-1.0	0.0	*	*	*
TELLICO PLANS ES	174	1345.2	274.0	322.5	0.2	*	*	*
TEYAHALEE BALD RES	362	1725.7	1292.1	65.3	22.8	*	*	*
T DRPE DAM	564	1637.5	1046.4	355.9	5.8	*	*	*
T DRPE P WERHOUSE	564A	1401.6	715.5	109.3	6.8	*	*	*
TOWNSE N RES	715A	1293.4	322.7	163.9	4.2	36.0	97.8	7.3
TWENTYMILE ES	660	1525.3	422.7	219.6	3.4	562.9	140.2	27.0
US CO T ON FILD STA ES	637	1239.0	268.7	207.3	1.3	*	*	*
VO N RE, NEAR Z ES	783	130.8	241.4	14.4	0.8	*	*	*
WAYAH BALD RES	197	1751.1	1485.3	4.2	17.1	*	*	*
WIDW O DES	716	1299.7	26.7	113.5	1.2	*	*	*

represented the 0-10° range. These were the more gradual slopes. The highest average was 1660.4 mm which represented the 20-30° range. Slopes steeper than 30° had a lower average (1599.5 mm) than the 20-30° range. This indicated that a precipitation maximum could occur on slopes between 20-30°.

The Linear Model

A multiple linear regression model was developed using the precipitation data and the interpolated terrain data. The elevation, aspect and slope values of the mountains were the independent variables, while the precipitation data from the 51 stations were the dependent variable. The result was the multiple linear regression equation of:

$$y = 1130.2 + 0.4241 * A + -0.0738 * B + 1.0059 * C$$

was developed from this application. Where, 'A' is the elevation value, 'B' is the aspect value, 'C' is the slope value, 1130.2 is the intercept and 'y' is the estimated precipitation value. The R-square value from this relationship was 0.80 at the 95% confidence interval, indicating a high level of significance. Summary output from the statistical analysis can be found in table 7. This equation was used to estimate a new precipitation value for each of the 2,292,296 30m x 30m cells.

Applying the Linear Model

Using the map algebra functions within the GRID module of ARC/INFO, the linear regression equation was applied to calculate a new lattice of precipitation values. The maximum precipitation value from this calculation was 2013.5 mm. This value occurred in a raster cell that was approximately .9 kilometers west of the station located at

Table 7. Summary output from the statistical analysis.

<i>Regression Statistics</i>	
Multiple R	0.896855111
R Square	0.80434909
Adjusted R Square	0.791860734
Standard Error	90.88564048
Observations	51

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	3	1596066.947	532022.3155	64.40792455	1.12075E-16
Residual	47	388229.3834	8260.199646		
Total	50	1984296.33			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
Intercept	1130.236599	35.77790282	31.59035355	2.62246E-33	1058.260811	1202.212388
Elevation	0.424146355	0.038921679	10.897432	1.85969E-14	0.345846109	0.5024466
Aspect	-0.073830732	0.128959807	-0.572509629	0.569705459	-0.333264156	0.185602693
Slope	1.005854049	1.523399878	0.660269219	0.512304189	-2.058828314	4.070536411

Clingmans Dome. The minimum value was 1217.7 mm which occurred approximately 2 kilometers west of the Abrams Creek station. This gave a range of the data as 807.7 mm of precipitation. The lattice had a mean precipitation value of 1575.1 mm with a standard deviation of 148.6 mm of precipitation. Figure 24 shows the precipitation regime of the GSMNP by applying the statistical model.

A horizontal transect was cut across the precipitation coverage that was generated through the use of the statistical model and the precipitation values were sampled at every one kilometer in a similar fashion as the previous two coverages. The plot of the statistically generated precipitation data verses the UTM x-coordinate can be found in figure 25. This figure shows the more random pattern of precipitation associated with the random patterns of terrain in the GSMNP. The statistical method resulted in precipitation values which reflected the rugged terrain of the GSMNP.

Hydrology of the Park

McMaster and Hubbard (1970) estimated the annual precipitation of the park as a whole to be 1625.6 mm. Their methods also estimated the annual influx of water to be 3.36 billion cubic meters via precipitation. Of this 3.36 billion cubic meters of water, 1.89 billion cubic meters (56.2%) are discharged through the streams and rivers. The remaining 43.8% of this annual influx is lost through either evaporation, transpiration or filtered into the ground (McMaster and Hubbard, 1970). The numbers computed from the three methods examined here are not far from these marks.

The THIESSEN method gave an annual precipitation value of 1542.5 mm. This value converts to 3.17 billion cubic meters of water. This would give 1.78 billion cubic

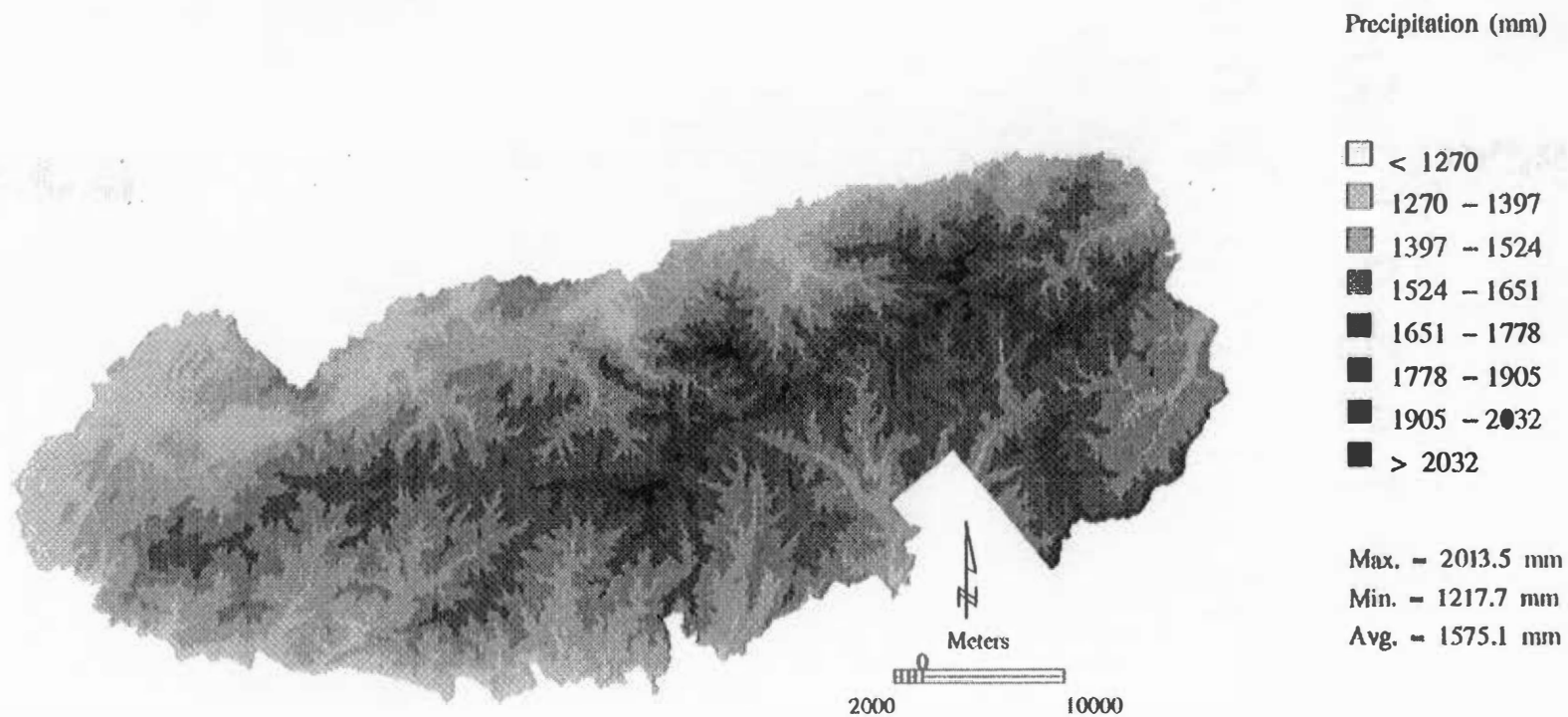


Figure 24. Precipitation of the GSMNP using statistical analysis.

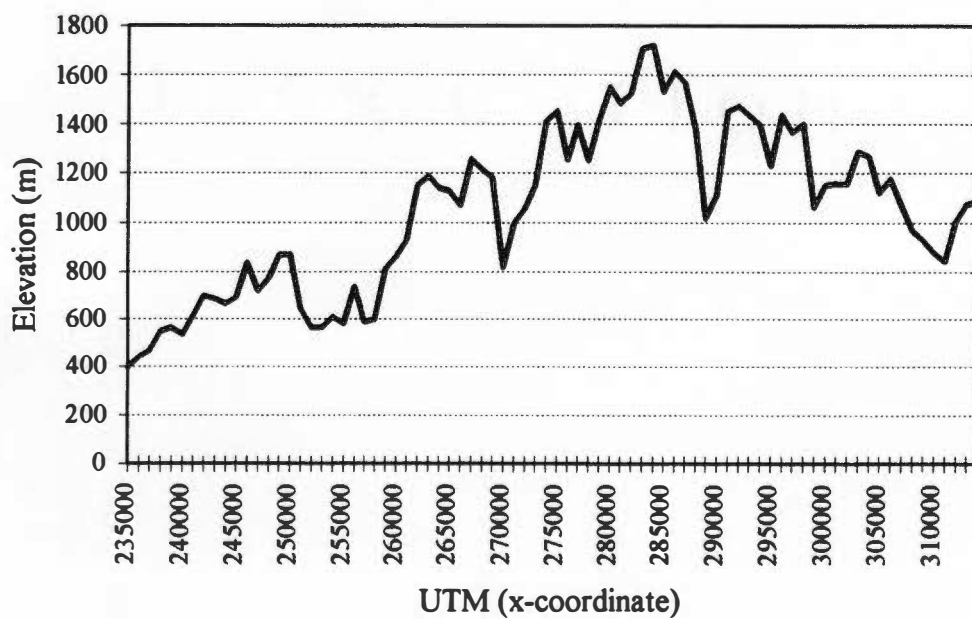
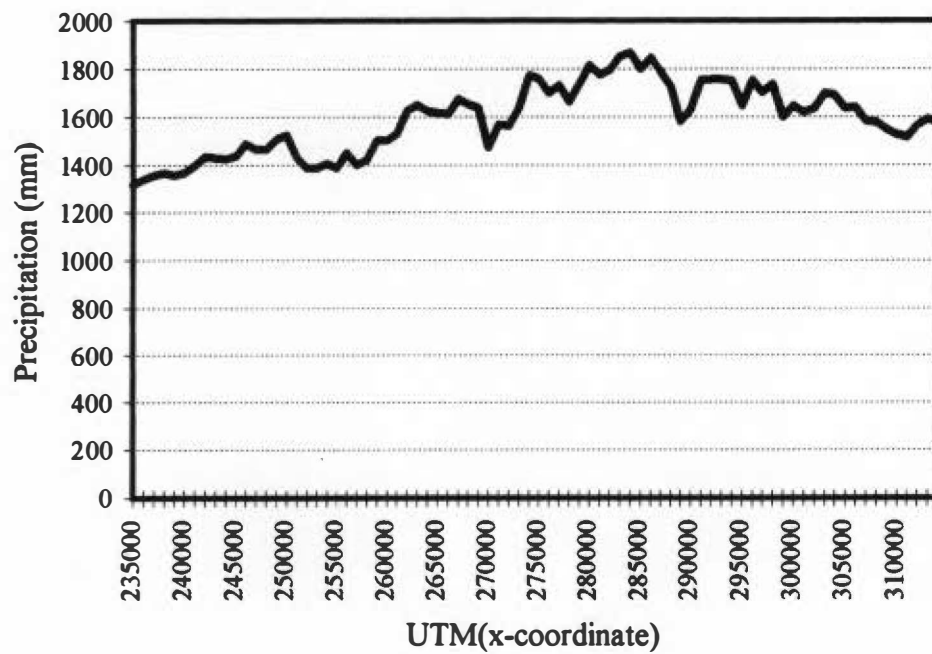


Figure 25. Top - UTM (x-coordinate) vs. the statistical precipitation value. Bottom - UTM (x-coordinate) vs. elevation from the 1:24,000 scale lattice.

meters of water exiting the park via streams and rivers. The remaining 1.39 billion cubic meters would be lost via evaporation, transpiration and/or seepage. An annual precipitation value of 1532.1 mm was obtained from using TINs. This method gave 3.15 billion cubic meters of water entering the park through the precipitation processes. The amount of water discharged by streams and rivers would be 1.77 billion cubic meters with 1.38 billion cubic meters being lost through the natural processes. The statistical method gave the highest annual precipitation estimate of 1575.1 mm. Therefore, this method will give the highest estimate of water influx of 3.24 billion cubic meters, with 1.82 billion cubic meters lost through stream discharge and 1.42 billion cubic meters lost through evaporation, transpiration and/or infiltration.

Overlaying the Vegetation with the Precipitation

The precipitation coverage determined by the statistical method represents the precipitation regime of the GSMNP best as concluded by reasons that are discussed later. This coverage was overlain with the MacKenzie's (1993) vegetation coverage to determine average precipitation values for each vegetation type. The spruce/fir forest classification had the highest average annual precipitation value which was 1860 mm. This should be true as the spruce/fir forest occurs at the highest elevations in the park. The lowest average annual precipitation value occurred in the treeless vegetation classification² (1387 mm). This vegetation classification occurred mainly in Cades Cove. The treeless surface area of Cades Cove is protected by mountain walls and is not exposed to the larger amounts of precipitation that occurred in the study area. Thus, this

² Excluding the water classification.

vegetation classification should have one of lower average annual precipitation values.

The remaining vegetation classifications and their determined annual precipitation values can be found in appendix A-6.

Conclusions

The three methods used to examine the precipitation characteristics of the GSMNP resulted in three similar annual precipitation averages. These values were also close to the estimated average precipitation (1626 mm) derived by McMaster and Hubbard in 1970. But of the three precipitation averages determined in this study, the value (1575.1 mm) obtained by the statistical approach represented the precipitation of the park most effectively by taking into account the relationship between the precipitation data and the topographic features. Like Spreen's study in 1947, the statistical approach used the terrain (elevation, slope and aspect) factors, which greatly influence precipitation amounts, to estimate the precipitation data over the study area and accounted for a significant amount of the variability in the precipitation data ($R\text{-square} = 0.80$, $p = 0.05$). As a result, the statistical method was more realistic in determining an average precipitation value for the park, as it estimated a larger variety (2,292,296 values each covering 900 square meters) of precipitation values which are more closely associated with the varied terrain of the GSMNP. Thus, the statistical method was the most successful of the three methods in estimating the precipitation data, both in accuracy and on a small spatial scale.

The precipitation data obtained from this study could aid researchers and other interested personnel in their studies of the GSMNP. As individuals establish study sites in remote areas of the park, the precipitation database could be accessed to determine the precipitation characteristics for their specified study areas. Hydrologists, ecologists or soil scientists could use the data from this study to model stream discharge, nutrient transport or soil erosion potential.

Limitations

The results from the statistical method appear to be the best representation of the average annual precipitation for the GSMNP. However, this method is not without limitations in its representation. Stephens (1969) discussed the possibilities of the precipitation within the GSMNP as being greater through the “gaps” in the mountains than on the adjacent peaks. Stephens (1969) attributed these precipitation maximums through the “gaps” as a funneling effect on the clouds. The funneling was caused by the ascent of the surrounding mountain slopes. The statistical method has no way of determining these potential precipitation maximums through the mountain “gaps”.

Precipitation maximums through the “gaps” were evident in the data used in this study. A precipitation station located at Newfound Gap TN/NC (elevation 1524 meters) had a normal precipitation values of 2297 mm. Stations located at Clingmans Dome (elevation 1905 meters) and Mt. LeConte (elevation 1935 meters), the nearest peaks with collection devices, had normal precipitation values of 2106 mm and 1954 mm, respectively. Thus, the Newfound Gap station was determined to be an outlier and was not used in developing the statistical model of relating precipitation amounts to the changes in the elevations, aspects and slopes of the GSMNP.

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Appendix

Table A-1. Geographic information obtained from the BDMS of ARC/INFO for the polygon coverage derived from the TIN method.

Number of Polygons	Precipitation Range From (mm)	To (mm)	Area Square meters
1	less than	1270	12002605
10	1270	1397	236651262
2	1397	1524	1120943586
3	1524	1651	281545475
1	1651	1778	179525488
1	1778	1905	135005856
1	1905	2032	83849984
1	2032	greater than	13542235

Precipitation Data

Maximum value	2099.3 mm
Minimum value	1217.9 mm
Average value	1532.1 mm

Table A-2. Geographic information obtained from the BDMS of ARC/INFO for the polygon coverage representing the elevation of the GSMNP.

Number of Polygons	Elevation range From (m)	To (m)	Area Square meters
17	less than	300	1567800
55	300	400	22653000
175	400	500	61384500
221	500	600	206418626
313	600	700	192043836
158	700	800	164255444
161	800	900	174948338
187	900	1000	184267841
120	1000	1100	196298176
119	1100	1200	194394680
102	1200	1300	183792640
113	1300	1400	164946644
92	1400	1500	133887615
99	1500	1600	88578006
42	1600	1700	53768700
35	1700	1800	27742500
27	1800	1900	9548100
10	1900	2000	2466000
4	2000	greater than	104400

Table A-3. Geographic information obtained from the BDMS of ARC/INFO for the lattice coverage representing the aspect of the GSMNP.

Number of 30m x 30m Cells	Aspect range From (°)	To (°)	Area Square meters
18445	flat	-	16600500
270798	0	45	243718200
260089	45	90	234080100
273207	90	135	245886300
291990	135	180	262791000
283875	180	225	255487500
291605	225	270	262444500
316681	270	315	285012900
285606	315	360	257045400

Table A-4. Geographic information obtained from the BDMS of ARC/INFO for the lattice coverage representing the slopes of the GSMNP.

Number of 30m x 30m Cells	Slope range From (°)	To (°)	Area Square meters
205999	less than	10	185399100
597659	10	20	537893100
1021742	20	30	919567800
437232	30	40	393508800
29218	40	50	26296200
438	50	60	394200
8	60	70	7200

Table A-5. Geographic information obtained from the BDMS of ARC/INFO for the lattice coverage representing the precipitation of the GSMNP from the statistical analysis.

Number of 30m x 30m Cells	Precipitation range From (mm)	To (mm)	Area Square meters
2973	less than	1270	2675700
331693	1270	1397	298523700
566164	1397	1524	509547600
625088	1524	1651	562579200
550132	1651	1778	495118800
201828	1778	1905	181645200
14418	1905	2032	12976200

Precipitation Data

Maximum value	2013.5 mm
Minimum value	1217.7 mm
Average value	1575.1 mm

Table A-6. Annual precipitation values for each vegetation classification of the GSMNP.

Vegetation Classification	Minimum Precipitation (mm)	Minimum Precipitation (mm)	Average Annual Precipitation (mm)	One Standard Deviation
Spruce fir	2011	1565	1860	51
Northern Hardwood	1987	1523	1762	69
Cove Hardwood	1997	1243	1648	94
Mesic Oak	1927	1380	1632	78
Mixed Mesic Hardwood	1812	1252	1501	76
Tulip Poplar	1903	1322	1482	103
Xeric Oak	1832	1230	1427	82
Pine Oak	1816	1251	1414	54
Pine	1834	1232	1401	60
Heath Bald	1895	1533	1726	60
Grassy Bald	1975	1678	1812	88
Grass Thicket	1765	1238	1462	86
Treeless	1952	1243	1387	115
Water	1382	1229	1345	8

VITA

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