ANALYSIS OF RAINFALL DISTRIBUTION IN THE AMAZON BASIN USING KRIGING, NONPARAMETRIC STATISTICS, AND GIS TECHNIQUES. I. SEASONAL OSCILLATIONS.

Elson D. Silva[1], Researcher Scientist, Ph. D.
Brazilian Enterprise for Agricultural Research, Satellite Monitoring Center (Embrapa-NMA)
Gary W. Petersen, Soil Scientist, Ph.D., Prof. of Soil and Land Resources
Agronomy Dept., The Pennsylvania State University.

The periods of increased and decreased rainfall within a yearly cycle are known as wet and dry seasons, and are important environmental phenomena in the tropics. The major climatic factors that influence plant phenological patterns are photoperiod, temperature, and precipitation. Temperature and photoperiod are important to temperate forests, but do not seem to affect tropical forests (Smith-Ramirez and Armesto, 1994). Rainfall patterns control also tree growth and regional extent of rainforests (Unwin and Kriedemann, 1990). The intensity of water stress experienced by trees during dry seasons has been shown to affect tree survival in temperate forests (Clinton et al., 1993).

Seasonality of rainfall directly affects evapotranspiration rates. During the wet seasons and at the beginning of the dry seasons, the rates of soil water depletion in both forest and clearings were up to 165 mm mo^{-1} in three different locations across the Amazon. Later in the dry seasons, when ET rates in the forest were sustained, however, pasture rates of ET fell to 45 mm mo^{-1} (Roberts and Cabral, 1993). Deep rooting in the tropical rainforest are related to water supply in the dry seasons, with up to 75% of soil water available to forests being supplied from two to eight m deep (Nepstad et al., 1994).

The maximum intensity of dry seasons that a dense forest withstands in the Amazon Basin is not well known. Some research has shown that evergreen forests endure only in places where monthly precipitation exceeds 100 mm in the dry seasons (Nobre et al., 1991). According to some model simulations, massive deforestation in the Amazon may cause the length of the dry seasons to increase (Eltahir and Bras, 1994).

Intensity and timing of dry and wet seasons throughout the Amazon Basin have not yet been precisely measured with a long term weather record using kriging, nonparametric statistics and GIS techniques. This research is proposed to better assess spatial natural oscillations of rainfall in the Amazon Basin that occur within a tropical year and have been called wet seasons for the maximum rainfall and dry seasons for the minimum rainfall.

The Amazon Basin is the greatest river system on earth, draining an estimated 6,860,350 km^2 of land. The Brazilian portion of the Amazon Basin occupies about 4,646,700 km^2, or 62% of the basin area. Rainfall data analyzed were collected from 533 weather stations (1925-1992). Historical rainfall data per weather station varies from 4 to 64 full years of collection (mean = 12.1 y station^{-1}).

The principal ecotypes of vegetation in the Brazilian Amazon were correlated with the dry quarters. According to the RADAM Project, the principal ecotypes in the Brazilian Amazon are the following: dense, closed-canopy evergreen forest (40.2%); dense, open-canopy evergreen forest (22.9%); deciduous and semi-deciduous forest (1.4%); capinarana (1.8%); and savanna (12.9%). The remaining (20.8%) is composed of a mixture of transitional vegetation from any of the above categories. Closed canopy forest is most abundant in the central portion of the basin along the equator. Open canopy forest is common south of this central core. Savanna intensifies in the southern portion of the basin (Projeto RADAMBRASIL, 1973-1984).

Projeto RADAMBRASIL (1973-1984) also has published the Brazilian Classification of Soils which is available in digital format. Understanding how rainfall patterns affect soil and vegetation distribution is an important factor concerning biodiversity of tropical regions.

The data analysis was divided into the following three major groups of variables for n weather stations: median of annual precipitation (mm year^{-1}), wet seasons (WS) defined as the rainiest quarters yearly, Timing of WS (central month), rainfall (%) in the WS, dry seasons (DS) characterized as the driest quarters yearly, Timing of the DS, rainfall (%) in the DS.

The Sign Test was performed using Minitab software at P-value of 0.05 to detect the existence of dry and wet seasons at each weather station (Minitab, 1994). Considering a 95% confidence interval for 533 sign tests analyzed, there is a possibility that 27 weather stations would report the dry or wet seasons when the phenomena do not exist (P>.05).

Vegetation and soil distributions within the Brazilian Amazon Basin are categorical data that were spatially assigned to 5 x 5 km cells according to a specific survey developed by Projeto RADAMBRASIL (1973-1984). To test if vegetation and soils are affected by seasonality of rainfall, a chi-square test for multicategorical data was applied (Steel and Torrie, 1980).

The assumption of normality is not particularly appropriate with most hydrologic variables. Rainfall distribution usually departs from normal distribution because the distributions of extremes are highly asymmetrical, usually being right skewed, and rainfall values are equal to or greater than zero (Matalas, 1991). Nonparametric methods are more practical than parametric statistics for these types of problems (Gibbons, 1985). Nonparametric statistics offers a more robust tool against anomalies caused by outliers, misrecording, or even missing data.

Geostatistics is concerned with the study of phenomena that change in space and/or time. This approach offers an assortment of deterministic and statistical tools aimed at understanding and modeling spatial variability. A technique called kriging, using moving averages to avoid systematic overestimation of reserves in the field of mining, was introduced by D. G. Krige (Matheron, 1965).

---

[1] Av. Dr. Júlio Soares de Arruda, 803, Parque São Quirino, 13088-300, Campinas, SP, email: **silva@nma.embrapa.br**.

Disclaim notice: The views expressed in this article are the author's and do not necessarily represent the official policy or interpretations of the Brazilian Enterprise for Agricultural Research (Embrapa).

Although kriging was originally developed for mining applications, it has been applied to analysis and mapping of precipitation fields (Delhomme, 1978). The goal was to describe variables that can be characterized by measurements that identify spatial structure. It treats properties as continuous, spatially-dependent, random variables. The optimal estimator (areal precipitation) is a linear, minimum variance, an unbiased estimator that requires knowledge of the semivariogram of the random variable as a function of space. It is based on the Intrinsic Hypothesis, theory that assumes a constant local mean and a stationary variance of the difference between places separated by a given distance and direction.

Before interpolation by kriging, a theoretical semivariogram model must be chosen and its parameters have to be estimated. This is part of structural analysis (Olea, 1991), involves estimation of other statistics and the semivariogram. The semivariogram contains useful information about the spatial variation of the property to be used within a limited neighborhood defined by the range. It is usually expressed as "½" or "semivariogram". The semivariogram (h) relates the differences or increments of the regionalized variable Z to the distance (lag) h between the data points.

Geostatistical analyses including exploratory analysis, variography, kriging interpolation, and cross-validation were carried out using GS^{+} - Geostatistics for the Environmental Sciences (Gamma Design Software, 1994).

By charting medians of monthly rainfall, major patterns of rainfall distribution can be observed throughout the Amazon Basin. Some major trends can be determined from the median charts. For example, near the mouth of the Amazon River, there is a very high wet season followed by a distinct dry season. Longer dry seasons can be noticed in the southeastern part of the basin where savanna vegetation predominates. Capinarana is a humid scrub forest that occurs in the central-northwest part of the basin, where rainfall is more evenly distributed annually showing less rainfall seasonality. Although there is still some seasonality, the orographic effect of the Andes apparently reduces the total amount of rainfall in the western part of the basin. Comparing the northern with the southern part of the basin, there is a six-month shift in the peak of the wet seasons caused by the movement of the Intertropical Convergence Zone (ITCZ) during the year. In the northern Amazon Basin, the wet season occurs mainly in June, while in the southern part it occurs in January.

Annual rainfall is an important variable describing high, low, and transitional periods of rainfall, as affected by geographical position and natural features. The Amazon Basin has two main areas of high rainfall rates. One is in the lowlands in the northwestern portion of the basin and the other is near the mouth of the Amazon river. Some researchers have reported three centers of abundant rainfall caused by the seasonal migration of low-pressure troughs over the Atlantic (Marengo, 1992). An abundant rainfall center over the central Amazon region around 5^{0} S reported in literature may only be an extension of the northwestern rainfall center that elongates southeastward as shown by a rasterized display. This difference is, perhaps, related to the errors imposed by contour lines and parametric statistics used in other studies.

The range of annual median rainfall estimated by kriging in the Amazon Basin is 557 to 3470 mm year^{-1}. Most of the Amazon Basin area (70%) receives precipitation between 1500 and 2500 mm year^{-1}. Precipitation below 1000 mm year^{-1} (5.3% of the area) occurs in the high elevations of the Andes Mountains. Low precipitation between 1000 and 1500 mm year^{-1} (8.2% of the area), occurs mainly in the high plateau of Guyana and the high plains of Central Brazil. A small portion of the basin (4.6%) is in the high convergence zone in the northwest and receives rainfall above 3000 mm year^{-1}.

All weather stations reporting more than six years of rainfall data have statistically significant wet seasons as confirmed by the Sign Test ($P<.05$). Rainfall in the wet season is almost evenly distributed across the basin. Rainfall in the wet seasons ranged from 311 to 1497 mm 3mo^{-1}. Low values occur in the Andes Mountains and high values occur near the mouth of the Amazon River. Wet seasons are an almost uniform variate with most of the basin receiving a uniformly distributed amount of rainfall. However, there are three regions of weakly standing water convergence centers, which agrees with data from other researchers (Marengo, 1992).

Wet seasons in the Amazon Basin generally occur from November to July, with rainfall concentrating in January (32% of the area), February (33%), and March (15%). This sequential pattern is associated with the sun`s path as it retreats northward and crosses over the Amazon Basin. The proportion of rainfall occurring in the wet seasons varies from 30 to 63% of the annual rainfall. Low rainfall proportion (30 to 40% of total rainfall) in the wet seasons occurs in 27% of the basin area, and is primarily in the northwest. This occurs because rainfall is more evenly distributed throughout the year. Moderate rainfall (40 to 50%) in the wet seasons occurs in 49.7% of the area, and is more centralized in the basin. High concentration of rain in the wet seasons (more than 50% of the total rainfall) occurs in 23% of the Amazon Basin area, and is mainly in the southeastern and central-northern part of the basin where savanna vegetation dominates the landscape. This high rainfall proportion in the wet seasons characterizes the landscape with high seasonal rainfall and the environment more appropriate to savanna.

The dry seasons are the driest quarters of the year ($P<.05$). This occurs even in the northwestern part of the Amazon Basin where rainfall is more regularly distributed during the year. Rainfall in the dry seasons varies from 0 to 655 mm 3mo^{-1}. Dry seasons are highly variable throughout the Amazon Basin. In the dry seasons, almost 7% of the basin area receives no rainfall for three continuous months. About 92% of the basin area receives rainfall less than the PET and 77% of the basin area receives rainfall less than half the PET (Thornthwaite, 1948). The driest part of the Amazon Basin is in the southern part in the highlands of Mato Grosso and in the southwestern part in the Andes.

The dry seasons generally occur from June to February. Sixty-one percent of the Amazon Basin area experiences the center of the dry season in July because during the northern summer the ITCZ shifts to the northern hemisphere. The pattern of timing of the dry seasons shows no relationship to the drainage and topography of the Amazon Basin — only to the sun's movement in the tropical cycle. The proportion of annual rain that falls in the dry seasons ranges from 0 to 20%. Overall, 43% of the Amazon Basin area receives rainfall less than 5% of its total in the dry seasons. Approximately 71% of the basin area receives rainfall less than 10% of its total in the dry seasons. Highly humid regions, where 15 to 20% of the annual rain falls in the dry seasons, occupy only 11% of the total basin area and are in the northwestern part of the basin.

This is an important spatial information regarding the amount, timing, and proportion of rainfall occurring in the dry season in the Amazon Basin. This represents an important information to be associated with the environmental features where water stress patterns' plays a major role.

The major groups of vegetation data were rasterized to allow correlation analysis with rainfall. The wet seasons are almost uniform throughout the basin and they were not correlated with vegetation distribution. On the other hand, a very high and well-described spatial correlation exists between rain in the dry seasons and major groups of vegetation. Vegetation types are significantly affected ($P<.05$) by the dry seasons according to the chi-square test. Dry season is a highly appropriate variable for describing potential water stress that vegetation has to endure during dry periods of the year. Dense forests occur where conditions are neither too dry nor too wet. In the driest environments, where the rainfall in the dry seasons is less than 75 mm $3mo^{-1}$, savanna and open forest dominates the landscape. On the other hand, when the dry seasons are very humid, capinarana is the primary vegetation. Intensities of water stress during dry seasons also affect tree survival in temperate forests (Clinton et al., 1993).

Assuming 423 mm $3mo^{-1}$ (4.7 mm $day.^{-1}$) as the maximum PET during the dry seasons (Thornthwaite, 1948), the dense forest would grow where rainfall is between 30% and 120% of the PET. At the highest water stress, where rainfall is less than 30% of PET, savanna and open forest dominate the landscape. As the water stress decreases (i.e., more rainfall in the dry seasons), the savanna decreases and open forests develop up to 75% of PET. ~~Where the~~ water stress is ~~practically nonexistent and~~ the rainfall in the dry seasons is almost the same as the PET, the open forest decreases and capinarana starts to increase. Where dry season rainfall is around 120% of the PET, capinarana dominates, which is the most appropriately adapted vegetation for excessively humid environment. Natural forests having distinctive growth and development cycles along a rainfall gradient have also been determined in Australia (Unwin and Kriedemann, 1990).

Rainfall seems to affect soil geneses more in the dry seasons than in the wet seasons because more rainfall variation occurs in the dry seasons. Soil type distribution in the Brazilian Amazon Basin is statistically related to the intensity of the dry seasons according to the chi-square test ($P<.05$). Podzol soils are the most significant soils correlated to dry seasons. This occurs because the primary characteristic of Podzols is the subsoil accumulation of humus and sesquioxides. According to the U.S. Soil Taxonomy, Podzols are mainly Spodosols (Soil Survey Staff, 1975), but Ultisols may occur as a Red-Yellow Podzolic, and Alfisols as a Eutrophic Red-Yellow Podzolic (Sanchez, 1976).

Water regimes in the soil profile is important to the genetic formation of Podzols. The proportion of Podzols in the Brazilian Amazon landscape increases as rainfall increases in the dry seasons. In drier environments Podzols represent only about 30% of the soils. As rainfall increases in the dry seasons, the proportion of Podzols increases. When the dry seasons supply water above the PET, Podzols are the main soils in the very humid environments. Moving across the Amazon landscape from the humid lowlands toward the drier highlands of the Mato Grosso shields, Podzols give way to Latosols as the intensity of the dry seasons increases.

Latosols are very well drained, and occur in higher proportions where more intense dry seasons exist also (Buol et al., 1989).

In conclusion, wet and dry seasons were determined to be part of an annual rainfall oscillatory phenomena that occur throughout the Amazon Basin with different intensities. The intensity of rainfall during the wet seasons is uniformly distributed over the basin. On the other hand, the intensity of the dry seasons is highly variable throughout the basin (0 to 1.5 times the PET). Dry seasons are therefore the more important climatic events influencing the kind of vegetation in the Amazonian landscape. Savanna vegetation appears to prevail where dry seasons have rainfall below 20% of the PET. Dense forest is the main vegetation in areas where rainfall in the dry seasons is between 30% and 120% of the PET. Capinarana is a humid scrub vegetation that proliferates where rainfall exceeds the PET in the dry seasons.

Latosols are well-drained soils that predominate where there are intense dry seasons. Latosols give way to Podzols in those areas with more humid dry seasons. This happens because Podzols is more dependent on water to translocate aluminum and/or iron and organic compounds essential to the formation of the spodic horizon.

REFERENCES

Buol, S. W., F. D. Hole and R. J. Mccracken. 1989: *Soil genesis and classification*. 3rd ed. Iowa State University Press. 446 pp.

Clinton, B. D., L. R. Boring, and W. T. Swank. 1993: Canopy characteristics and drought influences in oak forest in the Coweeta basin. *Ecology*, 74:1551-1558.

Delhomme, J. P. 1978: Kriging in the hydrosciences. *Adv. Water Resour.*, 5:251-266.

Eltahir, E. A. B. and R. L. Bras. 1994. Sensitivity of regional climate to deforestation in the Amazon Basin. *Adv. Water Res.*, 17:101-115.

Gamma Design Software. 1994. *Gs+: Geostatistics for the environmental science*. Gamma Design Software, 133 pp.

Gibbons, J. D. 1985: *Nonparametric Methods for Quantitative Analysis*. 2d ed. American Sciences Press, 481 pp.

Marengo, J. A. 1992: Interannual variability of surface climate in the Amazon basin. *Int. J. climatol.*, 2:853-863.

Matalas, N. C. 1991: Drought description. *Stoch. Hydrol. Hydraul.*, 5:255-260.

Matheron, G. 1965. *Les variables regionalisées et leur estimation, une aplication de la theorie des fonctions aleatoires aux sciences de la nature*. Masson, 306 pp.

Minitab. 1994: *Minitab User's Guide*, Minitab Inc.

Nepstad, D. C., C. R. Carvalho, E. A. Davidson, P. H. Jipp, P. A. Lefebvre, G. H. Negreiros, E. D. Silva, T. A. Stone, S. E. Trumbore, and S. Vieria. 1994: The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature*, 372:666-669.

Nobre, C. A., P. J. Sellers, and J. Shukla. 1991: Amazon Deforestation and Regional Climate. *J. Climatic Change* 4:957-988.

Olea, R. A. 1991. *Geostatistics glossary and multilingual dictionary*. Oxford University Press, 177 pp.

Projeto RADAMBRASIL. 1973-1983: *Levantamento de Recursos Naturais*. Vol. I-XXXI. Ministério das Minas e Energia.

Roberts, J. and O. M. R. Cabral. 1993: ABRACOS: a comparison of climate, soil moisture and physiological properties of forest and pastures in the Amazon Basin. *Commonw. For. Rev.*, 72:310-315.

Sanchez, P. A. 1976: *Properties and management of soils in the tropics*. Wiley and Sons, 618 pp.

Smith-Ramirez, C. and J. J. Armesto. 1994: Flowering and fruiting patterns in the temperate rainforest of Chiloé, Chile — ecologies and climatic constraints. *J. Ecol.*, 82:353-365.

Soil Survey Staff. 1975: *Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys*. Agric. Handb. No. 436. USDA. U. S. Government Printing Office.

Steel, R. G. D. and J. H. Torrie. 1980: *Principles and procedures of statistics: A biometrical approach*. 2d ed. McGraw-Hill, 633 pp.

Thornthwaite, C. W. 1948: An approach toward a rational classification of climate. *Geog. Rev.*, 38:55-94.

Unwin, G. I. and P. E. Kriedemann. 1990: Drought tolerance and rainforest tree growth on a North Queensland rainfall gradient. *For. Ecol. Manag.*, 30:113-123.

ANALYSIS OF RAINFALL DISTRIBUTION IN THE AMAZON BASIN USING KRIGING, NONPARAMETRIC STATISTICS, AND GIS TECHNIQUES. II. MONTHLY DEVIATIONS.

Elson D. Silva[1], Researcher Scientist, Ph. D.
Brazilian Enterprise for Agricultural Research, Satellite Monitoring Center (Embrapa-NMA)
Gary W. Petersen, Soil Scientist, Ph.D., Prof. of Soil and Land Resources
Agronomy Dept., The Pennsylvania State University.

The Amazon forest owes its existence, in part, to generous precipitation and, in turn, plays a pivotal role of its own in the functioning of the terrestrial-atmospheric hydrologic cycle. Assessing spatial and temporal variability of a water recharge by rainfall is important in hydrological studies of the Amazon Basin.

Rainfall characteristics can be assessed using nonparametric statistics. The median is the central tendency of nonparametrics and is protected from the displacing effects of outliers and skewness. Monthly rainfall is widely used as a partial measurement of a rainfall recharge during the tropical year. Usually it is important to know how much rainfall occurs during specific months, which is important in defining growing seasons, or determining water supply, and drought and flooding assessments. Measuring local rainfall departures from their medians and understanding their behavior can assess spatial rainfall variability and associate this pattern to climatic anomalies. This is a robust evaluation of rainfall variability and is vital when studying precipitation in the Amazon Basin.

Climate anomalies that affect the Amazon Basin are related to geographic position in the equatorial latitudes and to the orographic impact by the Andes Mountains. The Andes mountains extend through the entire South American continent along its western shore and serve as a barrier to the movement of moisture-bearing air masses (UNESCO, 1978). Equatorial sea surface temperature anomalies are believed to be related to changes in the tropical circulation systems (Rasmusson and Wallace, 1983). Anomalies have been linked to the occurrence of droughts and floods (Matalas, 1991). An improved understanding and ability to predict anomalies of rainfall are important for decision making.

Most meteorological studies designed to assess rainfall patterns try to rely on long-term rainfall data using normal distribution assumptions, and data transformations to correct skewness (Marengo and Hastenrath, 1993). However, a cube root employed to normalize the data in a study of seasonal variability of rainfall in the Pacific tropics was not successful. Weather stations reporting less than 16 years data or reporting erratic values were removed in a study by Hartmann and Gross (1988). Unfortunately, this procedure left large areas without estimated climatic references.

In the Amazon Basin, natural deviations in the hydrological cycle and the processes influencing those deviations must be determined before possible anthropogenic impacts can be assessed. For example, the El Niño-Southern Oscillation (ENSO) phenomenon in the tropical Pacific Ocean, has been linked to climate anomalies and

---

[1] Av. Dr. Júlio Soares de Arruda, 803, Parque São Quirino, 13088-300, Campinas, SP, email: **silva@nma.embrapa.br**.
Disclaim notice: The views expressed in this article are the author's and do not necessarily represent the official policy or interpretations of the Brazilian Enterprise for Agricultural Research (Embrapa).