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HIERARCHICAL ANALYSIS OF RELIEF FEATURES IN A SMALL WATERSHED IN A TROPICAL DECIDUOUS FOREST ECOSYSTEM IN MEXICO

ABSTRACT: LÓPEZ-BLANCO J., GALICIA L. & GARCÍA-OLIVA F., *Hierarchical analysis of relief features in a small watershed in a tropical deciduous forest ecosystem in Mexico.* (IT ISSN 0391-9838, 1999).

A hierarchical analysis of relief features in a small watershed (Watershed No.1, extent area of 16 ha) was analyzed based on frequencies of slope-angle and slope-morphology parameters in different functional scales (spatial or thematic units), using a geographic information system (GIS) as an essential analyzing information tool. The hierarchical arrangement of watershed's relief is strongly influenced by geologic structure. The following four scale non-nested hierarchical levels were analyzed: 1. The total experimental watershed (shaped by its hydrologic division), 2. Two generalized orientation facing slopes (North and South, formed by hydrologic division and generalized aspect), 3. Three altitudinal segments (Bottom, Middle and Top, caused by geologic structure and altitudinal division) and 4. Hillslope units (sub-hydrologic division and geometric form). Fourteen hillslope units were delineated, which were grouped in four types according to their configuration (straight or curved along both length and width). Two main fractures divide the watershed into three altitudinal sectors. The top sector has flat homogeneous hillslope units, the middle sector has steeper convex hililslope units and the bottom sector has steeper convex and steeper homogeneous hillslope units. South-facing slope have a longer length slope than northfacing slopes. Longer slopes have greater numbers of changes in the degree of inclination and, as a result, south-facing hillslope units are heterogeneous. Stream-channel network arrangement are not explained at the watershed level and, slope grade have not correlation with the first-order subcatchments area. However, the fluvial network is strongly influenced by the hillslope-unit morphology. Finally, the results suggest that exist three different environments where their both, processes of channel initiation and water movement are different.

KEY WORDS: Hierarchical analysis, Hillslope unit, Small experimental watershed, Tropical deciduous forest, Chamela, Mexico.

INTRODUCTION

During the last decade, the importance of complex terrain configuration in the study of water, soil and biota dynamics has been observed (O'Loughlin, 1990; Turner, 1989; Forman & Godron, 1986; Swanson & *alii*, 1988). Furthemmore, the incorporation of topography in simulation models had been possible with the development of geographic information systems (GIS, Band, 1989). GIS technology have led to obtain favorable results as much in theoretical as applied studies (Moore & *alii*, 1988; Willgoose & *alii*, 1992). However, the effect of spatial scale in geomorphology processes has received considerably less attention (De Boer, 1992). Furthermore, it is clear that a geomorphic system must be viewed in its complex and hierarchical context (Beven, 1990; De Boer, 1992).

The geomorphological system is a result of interaction of processes acting at different time and spatial scales. The characteristics of topographic surfaces (i.e. angle and forms of slope) often it is necessary to be known over a spectrum of scales for water and soil studies. These studies range from an individual hillslope to a tributary channels network and contributing areas for run-off, sediments and nutrients (Band, 1989). For this reason, it is important to know at which scale different hydrological processes dominate. For example, runoff is a consequence of the integration of various variables/processes present within a watershed, but

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working at different time and spatial scales (soil humidity, infiltration, throughflow, etc., De Boer, 1992).

The aim of the present study is related to the hierarchical analysis of relief features of a small watershed in a tropical deciduous forest ecosystem, Western Coast of Mexico, based on frequencies of slope-angle and slope-morphology parameters in different functional scales, using a geographic information system (GIS). This research forms part of a long-term ecosystem evaluation project that we are performing in five small experimental watersheds (lesser than 20 ha each).

STUDY SITE

Chamela is located on the Pacific Coast of Mexico, in the State of Jalisco (19°29' N and 105°01' W) (fig. 1). This area corresponds to the physiographic province of the Sierra Madre del Sur (SMS). The SMS mountains were formed during the late-Tertiary and the early-Quaternary periods in association with subduction of both the North American and the Cocos plates (Lugo, 1990). The dominant relief of the Chamela area consists of low and steep hills under Cretaceous granite and granodiorite rocks (Cordova, 1988). Soils are shallow sandy-loams with poor structure (Inceptisol and Entisol; Solis, 1993). They have an organic matter content of less than 5% and pH values between 6 to 7 (García-Oliva, 1992).

The mean annual precipitation is 748 mm, concentrated during the summer months (July to October; Bullock, 1986). The rainfall pattern is random with considerable yearly variation as a result of the tropical cyclone influence (García-Oliva & *alii*, 1991). Four to six storms typically account for 50% of the total annual precipitation; with high rainfall intensity associated with such events, the average annual erosivity is 6525.2 MJ mm ha^{-1} yr^{-1} (García-Oliva & *alii*, 1995b). The mean annual temperature is 24.9°C (Bullock, 1986). The mean annual runoff is 30.3 mm (±40.4), which represents only 4% of the total annual rainfall (López-Guerrero, 1992).

The dominant vegetation type is the tropical deciduous forest (Rzedowsky, 1983). This is a dense forest with a well-developed understorey of shrubs (Lott & *alii*, 1987). The floristic diversity is high: Lott (1985) has reported 758 species of herbaceous and arboreal species in 1,600 ha. Forest phenology is strongly seasonal (Bullock & Solís-Magallanes, 1990; Martínez-Yrízar & Sarukhán, 1990).

METHODS

The present study was undertaken in one (WS-1) of the five watersheds of the long-term ecosystem project mentioned. The main spatial database used was a digitized topographic map (at 1:2,000 scale) with a 2 m contour interval (SEDUE, non dated). The topographic and watershed information (water divides of first-order subcatchments, hydrological network, etc.) was obtained from that basic map

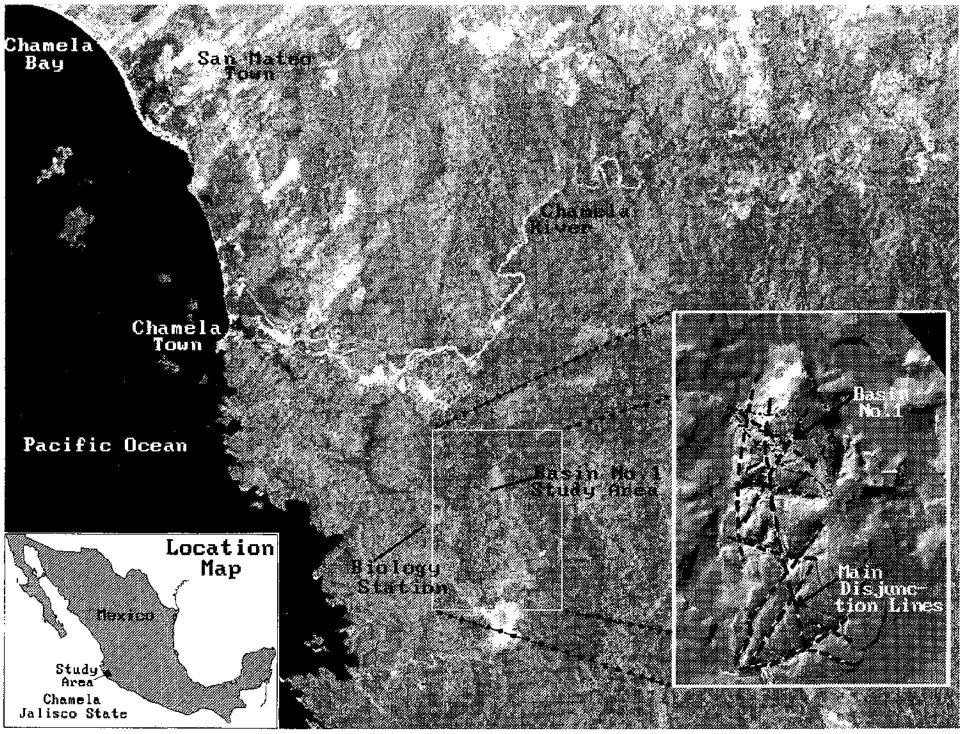

FIG. 1 - Location of the study area, State of Jalisco, Western Coast of Mexico. Notice in the hillshading map (vectangle) the main disjunction lines in the minor tectonic block where the five small watershedsare located.

and the result was a set of raster maps of geomorphic features using a 1.5 m pixel size (Pixel area = 2.25 m^2). The geographic information system (GIS) used was ILWIS (Integrated Land and Water-Management Information System; ITC, 1992) installed on a personal computer.

From the topographic map, every 2 m contour line were digitized. The contour-segment file (vector format) was rasterized and then interpolated to generate a digital terrain model (DTM; Gorte & Koolhoven, 1990; Waibel & Heller, 1991, p. 269-297; ITC, 1992). From the DTM a hill shading map (Pelton, 1987; Romo, 1989; Ware, 1989; Savazzi, 1990, Palacio-Prieto & *alii*, 1991), slope aspect, slope and drainage pattern maps were obtained (ITC, 1992). DTM is the most applicable database to model the relief characteristics. In a GIS, DTMs provide an opportunity to model, analyze, and display phenomena related to geomorphology (Dikau, 1989, 1993). The hierarchical organization of drainage network was made following to Strahler (1964).

The data obtained from the GIS were analyzed based on frequencies of slope-angle and slope-morphology parameters in different functional spatial scales (thematic units) following the next four non-nested hierarchical levels: 1. The total experimental watershed (shaped by its hydrologic division), 2. Two generalized orientation facing slopes (north and south, formed by hydrologic division and generalized aspect), 3. Three altitudinal ranks (bottom, middle and top, segmented by geologic structure and altitudinal division) and 4. Hillslope units (HU) (subhydrologic division and geometric form).

The analysis at the total watershed level was performed using the total number of pixels (from the raster map) that correspond to the total area of the WS-1 without be grouped (70,576 altitudinal values from the DTM). Considering that the main channel has a SE-NW orientation, the watershed was separated into two aspects according to a broad or dominant exposure (north and south). This generalized orientation facing slopes were delineated by means of continuing the line that define the main-stream direction (channel) until upper watershed (where the water divide cutting at two general slopes). The watershed contains two main fractures perpendicular to the main channel; for this reason, the watershed was separated into three altitudinal ranges: bottom, middle and top.

The use of GIS for collecting, storing and processing the spatial database was useful to interpret and determine the relief features and delineate the hillslopes boundaries, particularly in the interactive user-GIS process of on-screen digitizing. This process was a main step in the methodology to delineate the hillslopes-units boundaries (López-Blanco & Villers-Ruiz, 1995; López-Blanco & *alii*, 1996). This GIS capability allows one to «draw» segments with the digitizer's cursor on a raster image backdrop (an image that is displayed on the graphics screen). In this process, different thematic information layers (slope-, altitude-, aspect-classes, profiles, etc.) were selected and overlaid (single, alternately or inset) on the hillshading map generated from the digital terrain model. Those thematic information led us to have more certitude in delineating such kind of geomorphologic units.

Considering the procedure explained before, hillslope units were delineated using field data, slope profiles and the DTM. The specific processes were as follows: First, seven longitudinal and cross slope-profiles (transects) were selected within the watershed using a morphological configuration basing on fieldwork observations. Each profile was divided into sectors according to slope-gradient changes. In each sector, slope length and angles were measured. Secondly, those fieldwork data was converted to a horizontal projection (plane) and the cross slope profiles were considered from the topographic map. Thirdly, hillslope boundaries and their corresponding areas were obtained using hill-shading maps, produced by applying different lighting-source directions.

Afterwards, fourteen hillslope units (HU) were obtained, they were used in our study as the main and more detailed mapping-unit, related to the hierarchical-levels of functional spatial scales mentioned. Finally, the hillslope units were divided into crest (summit), backslope and footslope sections following to England & Holtan (1969). Head slopes were considered as Ruhe explained in 1975 (p. 101).

To test the independence of the distribution of pixel frequency in slope-angle classes among groups in different hierarchical levels, contingency tables analysis were used (Everitt, 1986). The null hypothesis was that the pixel frequency distribution was independent among groups tested; this means if we can not reject the null hypothesis, the frequency distributions are random. We analyzed three contingency tables: i) slope-aspect level (south and north-aspect slopes), ii) multidimensional contingency table with aspect and altitudinal ranges (bottom, middle and top portions) and iii) hillslope units (HU). To identify the categories responsible for a significant chi-square value, adjusted residuals analysis was performed (Everitt, 1986).

RESULTS: HIERARCHICAL LEVELS ANALYSIS

Total watershed Level

The watershed has a surface area of 158,795 m^2 and a perimeter of 2,094 m. The relative relief is 140 m. The dominant slopes are steep, 70% of the area had slopes inclinations higher than 16° (fig. 2 and tab. 1). The main parent material is granite and granodiorite, which are highly fractured. The main channel is on a clearly visible fracture (inverse fault (?)). Five fractures were delineated nearly perpendicular to the main trajectory of stream mentioned. This suggests that both drainage patterns and slope arrangement are affected by their structural geologic characteristics (See hillshading map in fig. 1).

The main channel at the watershed mouth is a Strahler's third-order-stream. The total area was occupied by 19% of first-order, 46% of second-order and 33% of

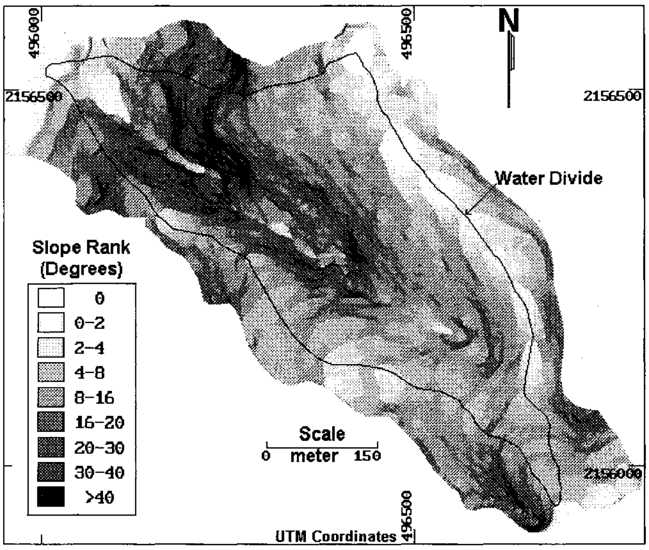

FIG. 2 - Slope gradient map of the WS-1, Biology Station in Chamela, Mexico.

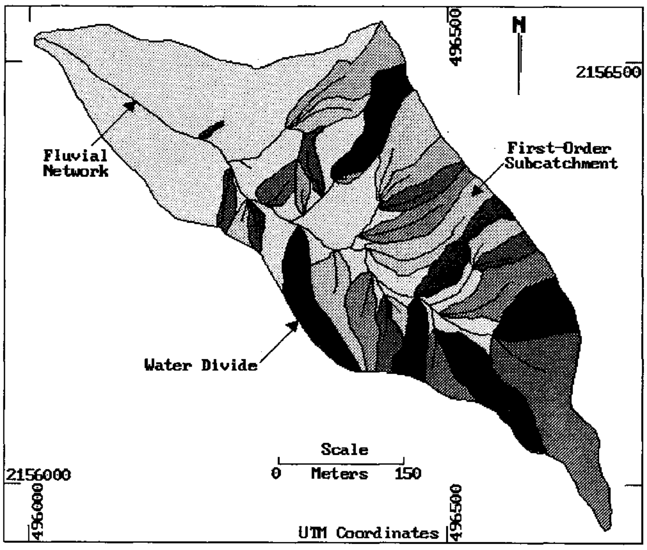

FIG. 3 - First-Order subcatchment map and fluvial network of the WS-1. Gray-scale (tones) is used only for proposes of highlight the different and adjacent first-order subcatchments.

TABLE 1 - Area distribution among slope ranks considering both north – and south – facing slopes

Slope	South m^2	North m^2
0°	616.5 (0.6%)	31.5 (0.1%)
2°	7,364.3 (7.5%)	949.5 (1.6%)
4°	7,616.3 (7.7%)	3,091.5 (5.1%)
8°	12,573.0 (12.8%)	15,846.8 (26.2%)
16°	34,112.3 (34.6%)	18,972.0 (31.4%)
20°	11,346.8 (11.5%)	5,357.0 (8 7%)
30°	13,844.3 (14.1%)	9,488.3 (15.7%)
40°	5,539.5 (5.6%)	4,797.0 (7.9%)
50°	3,638.0 (3.7%)	1,689.8 (2.8%)
>60°	1,838.0 (1.7%)	324.0 (0.4%)
Total	98,489.4 (100%)	60,457.5 (100%)

third-order inter-rill flows (tab. 2). Figure 3 shows the distribution of the first-order subcatchment within the watershed. Both channel length and area were greater in the south-facing slope than in the north-facing slope. In the same way, the south-facing slope had more second-order streams than the north-facing slope. These results suggest, considering a more detailed study, that the south-facing slope could have a higher hydrological network hierarchy than the north-facing slope.

TABLE 2 - Means and (standard error) of area, channel length and drainage density of different Strahler order-area subcatchment in Chamela, Mexico

Strahler-order subcatchment	Area (m^2)	Channel length (m)	Drainage density ($m\ m^{-2}$)
First-order			
North (N=5)	3,144.5 (1,546)	66.3 (15.9)	0.028 (0.021)
South (N=4)	3,959.2 (1,405)	86.3 (30.2)	0.022 (0.006)
Second-order			
North (N=3)	4,448.5 (3,827)	93.0 (35.3)	0.026 (0.010)
South (N=5)	12,161.4 (5,321)	202.5 (52.5)	0.023 (0.011)
Third-order	53,094.8	595.5	0.011

Generalized orientation facing slopes level

The main channel divided the watershed into two slopes in a north-south orientation. The south-facing and the north-facing slopes cover 62% and 38% of the total area, respectively. The major axes of the hillslopes were perpendicular to the main channel.

Table 1 shows the area of slope in each slope class. The greatest difference of relative area of slope between the north and the south facing slopes are in the flat areas. South-facing slopes have more extensive flat areas than the north-facing ones; 16% of the south-facing slope area has slopes lower than 4°, while in the north-facing slope, this area only represents 6.7%. However, in slope classes higher than 16°, both slopes show similar pattems (tab. 1).

The chi-square analysis of frequencies of adjusted residuals for each slope rank, considering both the north- and the south-facing slopes, resulted with statistic significance ($p<0.005$); for this reason, the hypothesis of no difference was rejected. Figure 4 shows the adjusted residuals of the slope-class frequencies. Comparing these absolute values with the 5% standard normal deviate (1.96), many of the adjusted residuals are highly significant. Considerable differences are observed in slope classes lower than 8° (fig. 4). The south-facing slope have more extensive flat areas than randomly expected, while the north-facing slopes have a general deficit in these classes. However, the pattern of adjusted residuals is unclear in slope classes higher

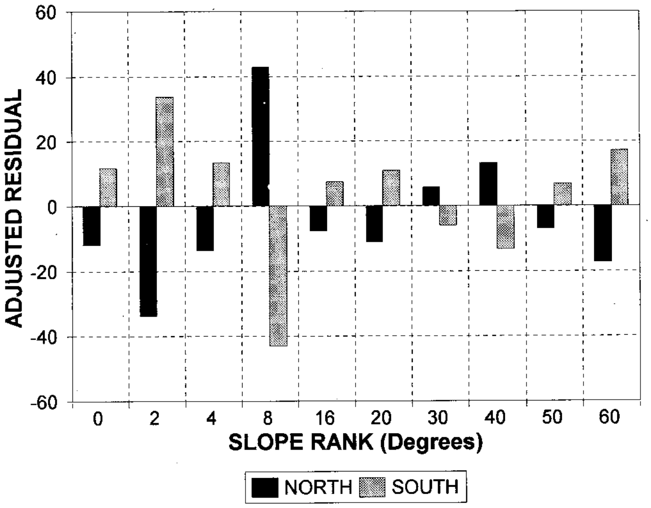

FIG. 4 - Adjusted residuals of slope gradient rank, from the contingency tables analysis, considering north and south-facing slope.

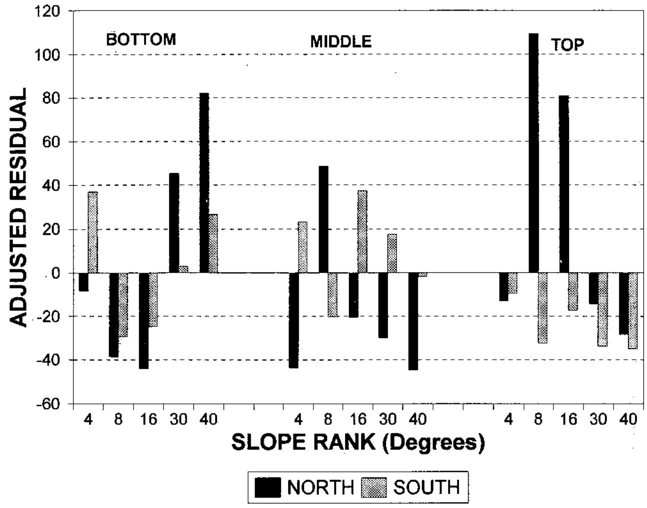

FIG. 5 - Adjusted residuals of slope gradient class from multidimensional contingency tables analysis and considering the altitudinal divisions.

than 8°. This pattern is more apparent in analysis at a lower scale.

Altitudinal ranks level: Segmented by geologic structure

The watershed was divided into three altitudinal sectors. From the total area, 28%, 59% and 13% corresponded to bottom, middle and top altitudinal sectors, respectively. The flat areas were dominant in the top sector, while the bottom one has strongly inclined slopes (tab. 3).

This pattern is clearest when each sector is analyzed by aspect; the multidimensional contingency table is significant ($p<0.005$). The north-facing slopes in the bottom sector have the steepest slope classes. In contrast, the north-facing slopes in the top sector have the flattest slope classes (fig. 5).

TABLE 3 - Percentage of area distribution in the WS-1 regarding to slope ranges and considering three altitudinal divisions

Slope	Bottom	Middle	Top
4°	14.9	11.4	7.8
8°	9.4	19.6	37.0
16°	22.2	36.1	42.3
30°	31.9	24.6	12.0
>40°	21.5	8.3	0.9

Hillslope units

Fourteen HU were delineated in the watershed (fig. 6). On the basis of hillslope curvature, slope gradient, hillslope length and number of slope-gradient-changes, we can classify hillslope units in four groups (tab. 4):

A. Steep convex hillslopes (1, 2, 3 and 4). This group have numerous slope gradient changes (x=6), and the longest length slopes (x=118 m; SD=34.5). The strongly inclined slopes (steepest) (57° to 77°) in the watershed are in this group (considering the maximum slope pixel value in the raster map, per its corresponding hillslope).

TABLE 4 - Characteristics of the fourteen hillslope units delineated by means of interpreting the relief features using the hillshading map. Column G correspond to the set of hillslope units classified by morphologic features, #CS: numbers of slope changes in each hillslope units, L: lineal, Cx: convex and Cv: concave

HU (ID)	Length m	Area %	G	#CS	Crest (Summit)	Backslope	Footslope
1	164	17	A	7	L (4°)	Cx (30°)	Cv (2°)
2	124	16	A	8	L-Cx (4°)	Cx-L (30°)	—
3	94	5	A	5	L (2°)	Cx (16°)	—
4	89	11	A	4	L (4)	Cx (16°)	—
5	68	9	C	5	L (4°)	L (8°)	Cv (8)
6	41	4	C	2	L-Cx (4°)	L (2°)	—
7	60	8	C	3	Cx (4°)	L (16°)	
8	57	2	C	2	Cx (4°)	L-Cx (8°)	
9	62	6	B	4	Cx (4°)	Cx (16°)	
10	76	5	B	4	Cx (4°)	Cx (20°)	—
11	100	6	B	4	Cx (8)	Cx (16°)	—
12	43	5	D	5	L (8°)	L-Cx (40°)	—
13	52	3	D	3	L (8°)	L-Cx (40°)	—
14	26	3	D	3	Cx (8)	L-Cx (30°)	Cv (8°)

B. Convex hillslopes (9, 10 and 11). This group has a middle-length slope (x=77 m; SD=19.2), slope gradients between 16° and 20°, and few slope gradient changes (x=4).

C. Flat linear hillslopes (5, 6, 7 and 8). This group has short length slopes (x=57 m; SD=11.3) with the lowest

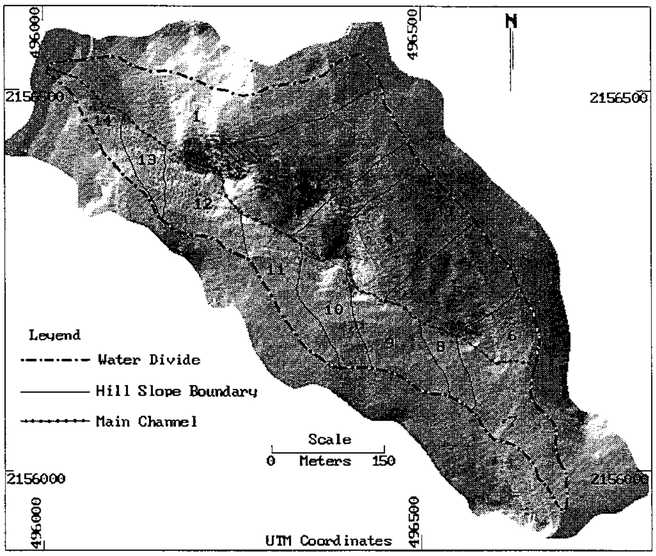

FIG. 6 - Hillslope Units (HU) overlaid on the WS-1 hillshading map (obtained from the DTM). Numbers identify each hillslope.

slope gradient (between 2° and 16°) and few slope gradient changes (x=4).

D. Steep linear-convex hillslopes (12, 13 and 14). This group has short length slopes (x=40 m; SD= 13.2), few slope gradient changes (x=3.6) and high slope gradients (30° to 40°).

The effect of HU in the distribution of slope-gradient classes is significant (p=0.005). In group C, 80% of the area has slopes of less than 16°. In contrast, 60% of the group D area has slopes higher than 30° (fig. 7). Because in both groups few slope gradient classes dominate, they are considered homogeneous. On the other hand, A and B groups have longer length slopes than the C and D groups. Slope length has a significant correlation ($p = 0.001$, $R^2 = 0.60$) with the number of slope gradient changes. Longer slopes show a greater number of slope gradient changes, and thus both the A and B groups have a complex hillslope morphology.

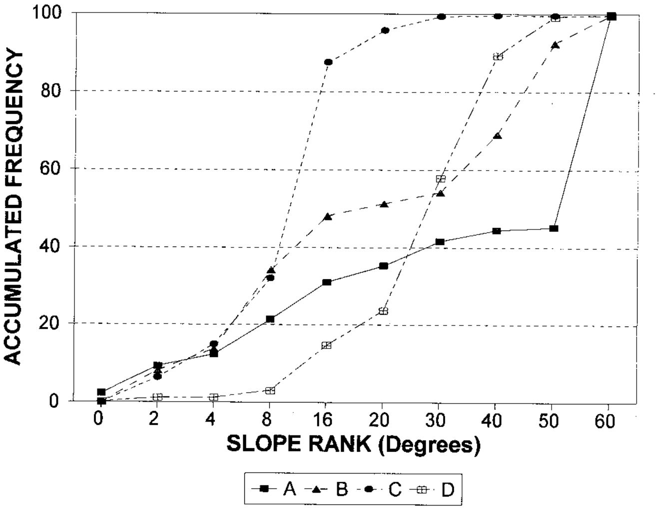

FIG. 7 - Accumulated frequency of slope gradient rank for each HU group.

Two fractures play an important role in the configuration of slope morphology. The southfacing HUs have a greater length slope (x=97 m) than the north facing one (x=68 m). The main channel has two main slope changes caused by fractures. For this reason, the altitudinal gradient of HUs in each segment is different. The HU of the bottom segment is higher than that of the top segment.

The distribution of the frequencies of slope classes in each altitudinal gradient depends on hillslope characteristics. When HUs are homogeneous, the adjusted residuals have a clear pattern. For example, in the bottom segment, the north-facing HUs are homogeneous (group D), while the south-facing HUs have a complex morphology (group A; see residuals in figure 5). The top segment has homogeneous HUs (group C) in both slopes. In contrast, HUs in the middle segment are complex (groups A and B) and, as a consequence, adjusted residuals do not show a clear pattern (fig. 5). Characteristics of the channel network are strongly influenced by HU morphology. Homogeneous steep HU (group D) show the least complex network (only three first-order streams, tab. 5). Moreover, two of the steep HUs (13 and 14) do not contain definable channels, and 65% of the third steep HU (12) surface was occupied by inter-rill flow. In contrast, a major portion of the four homogeneous flat HU areas correspond to subcatchment areas, and have significantly lower drainage density values than those of other groups (tab. 5). Finally, complex groups (A and B) have the most complex channel network (tab. 5).

TABLE 5 - Number of first-order streams and drainage area density (average and standard error (#)) per each HUs group. Letters correspond to HUs groups of table 4

HU group	#	Drainage Area (m^2)	Drainage Density ($m\ m^{-2}$)
A	13	2,633 (508)	0.039 (0.010)
B	7	2,768 (556)	0.023 (0.003)
C	7	5,142 (1,510)	0.014 (0.003)
D	3	914 (64)	0.044 (0.010)

DISCUSSION AND CONCLUSIONS

The shape of any watershed is a result of the interaction between both large and small-scale features of the landscape (Willgoose & *alii*, 1992; De Boer, 1992). Tectonic uplift influences catchment gradient and thus drainage density. But equally hillslope and channel gradients are related to sediment transport continuity so that the catchment gradient is influenced by the hillslope gradient (Willgoose & *alii*, 1992).

Several authors (Flint, 1974; Tarboton & *alii*, 1989) have reported an inverse relationship between subcatchment area and average channel-slope. In the same way, the same relationship has been found for hillslope length versus gradient (Montgomery Dietrich, 1989). Channels in flat zones require longer areas to sustain channel processes in comparison to steep zones (Montgomery & Dietrich, 1988). Moreover, Willgoose & *alii* (1991a) using watershed model simulations found the same relationship in both topographic units. They concluded that this relationship is consistent with the theoretical results obtained by Kirkby (1987) for catchment with runoff proportional to area. However, in the present study we did not find a meaningful slope-area relationship (fig. 8).

The slope-area relationship must be higher in the hillslopes than in the channels. However, in the present study, we did not find a clear differentiation between hillslopes and channels (fig. 8). This difference is required for sediment transport continuity at the boundary, between the two units (Willgoose & *alii*, 1991b). This differentiation has been reported for field data by Patton & Schumm (1975). Willgoose & *alii*, (1991 b) using a simulation model found that this sharp differentiation between slopes and channels was not as pronounced when the catchment was far from having a dynamic equilibrium, i.e. in the beginning when the network still developing, which could be the case in WS-I. The lack of a relationship implies that pre-existent channels govern the valley erosion, which in tum governs drainage patterns in the hills and slopes, and thus spatial patterns of the channel initiation functions (Willgoose 1992). Fractures can accelerate water drainage flux, increasing the probability of channel initiation.

Since HUs configuration strongly influences drainage patterns, it is difficult to interpret the stream network at the watershed level. However, this network pattern could be clearest at HUs groups. Our results suggest that there are three different environments where both processes initiation of channels and water movement are different. The first correspond to top flat homogeneous HUs (group C), where channel initiation is related to slope-area relationships. This group had the lowest first-order drainage density values, the highest subcatchment area and a dendritic stream pattern. Secondly, heterogeneous steep HUs (groups A and B) have a greater number of first-order streams, high drainage density and a complex stream pattern. Stream networks (patterns) are strongly influenced by fractures and probably have the highest hydrological response rate. Finally, in the steep homogeneous HUs (group D), in the bottom north-facing slope, water movement is mainly by inter-rill flow. As a consequence, runoff and erosion patterns follow the hierarchical structure, and do not depend on a particular or independent topographic element (i . e. slope gradient or length slope, Moore & *alii*, 1987). Galicia-Sarmiento & *alii*, (1995) reported that the variability of the main soil physical characteristics (i.e. texture, bulk density, etc.) were explained by these three HUs group levels. García-Oliva & *alii*, (1995a) measured soil erosion by 137Cs in this watershed, found that the top ranges do not have a depositional areas closer to the main channel, while the bottom shows soil gain in these sites.

All the anterior considerations suggest that to evaluate the hydrological and geomorphological dynamics of hillslopes, must be analyzed taking into account the hierarchical structure of their relief features in its corresponding watershed.

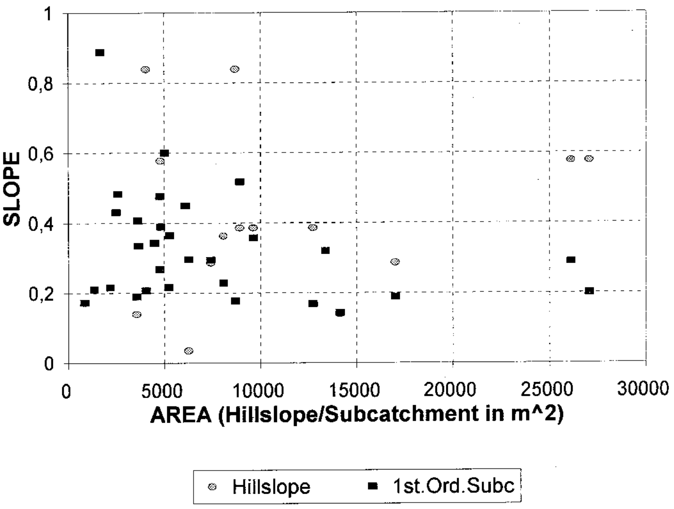

FIG. 8 - Relation between slope/HU area and slope/subcatchment area (first-order channels).

REFERENCES

BAND L.E. (1989) - *A terrain-based watershed information system.* Hydrological Proc. 3, 151-162.

BEVEN K. & WOOD E.F. (1983) - *Catchment geomorphology and the dynamic of runoff contributing areas.* Journ. Hydrology, 65, 139-158.

BULLOCK S.H. (1986) - *Climate of Chamela, Jalisco and trends in the south coastal region of Mexico.* Arch. Met. Geoph. Biocl., 36, 297-316.

BULLOCK S.H. & SOLIS-MAGALLANES A. (1990) - *Phenolony of canopy trees of a tropical deciduous forest in Mexico.* Biotropica, 21, 22-35.

CÓRDOVA C. (1988) - *Cartografía geomorfológica en escala pequeña del occidente de la República Mexicana.* Tesis de Licenciatura, Facultad de Filosofía y Letras, UNAM, México D.F., México.

DE BOER DIRK H. (1992) - *Hierarchies and spatial scale in process geomorphology: a review.* Geomorphology, 4, 303-318.

DIKAU R. (1989) - *The application of a digital relief model to landform analysis in geomorphology.* In: Raper J., Taylor & Francis (ed.), *Three dimensional applications in geographic information systems,* London, 51-77.

DIKAU R. (1993) - *Geographical Information Systems as tools in Geomorphology.* Zeit. Geomorph., N.F., Suppl.-Bd. 92, 231-239.

ENGLAND C.B. & HOLTAN H.N. (1969) - *Geomorphic grouping of soil in watershed engineering.* Journ. Hidrology, 7, 217-225.

EVERITT B.S. (1986) - *The analysis of contingency tables.* Chapman and Hall, London.

FLINT J.J. (1974) - *Stream gradient as a function of order, magnitude and discharge.* Water Resour. Res., 10, 969-973.

FORMAN R.T. & GODRON M. (1986) - *Landscape ecology.* Wiley, New York.

Galicia L., García-Oliva F. & López-Blanco J. (1995) - *Efecto de la estructura jerárquica del relieve en la distribución de las caracteristicas físicas de los suelos en una cuenca tropical estacional.* Bol. Investig. Geográf. del Inst.de Geogr. UNAM, Núm. 3, Especial de Geomorfología, 53-75, México.

García-Oliva F. (1992) - *Erosión y pérdida de nutrientes del suelo en una cronosecuencia de uso agropecuario en un ecosistema tropical estacional mexicano.* Tesis de Doctorado en Ecología, Centro de Ecología, UNAM, México.

García-Oliva F., Ezcurra E. & Galicia L. (1991) - *Pattern of rainfall distribution in the Central Pacific Coast of Mexico.* Geogr. Ann., 73-A, 179-186.

García-Oliva F., Martínez R. & Maass J.M. (1995a) - *Long term net erosion as determined by ^{137}Cs redistribution in natural and perturbed tropical deciduous forest ecosystem.* Geoderma, 63, 135-147.

García-Oliva F., Maass J.M. & Galicia L. (1995b) - *Rainstorm analysis and rainfall erosivity of a seasonal tropical region with a strong cyclonic influence in the Pacific Coast of Mexico.* Journ. App. Meteor., 34, 2491-2498.

ITC (1992) - *The integrated land and water information system. User's manual.* International Institute for Aerospace Survey and Earth Sciences (ITC). 2nd Edition, Version 1.3, Vol. 1 and 2, Enschede, The Netherlands.

Kirkby M.J. (1987) - *Modelling some influences of soil erosion, landslides and valley gradient on drainage density and hollow development.* In: Ahnert F. (ed.), *Geomorphological models: theoretical and empirical aspects.* Cremlinger-Desdelt, Catena Suppl. 10, 1-14.

López-Blanco J., Galicia-Sarmiento L. & García-Oliva F. (1996) - *Aplicación de un SIG para la caracterización morfológica y la delimitación de unidades de ladera de una cuenca tropical estacional en Chamela, Jalisco, México.* Bol. Invest. Geográf. Inst. Geogr. UNAM, Núm. Espec. 4, SIG, 39-61, México.

López-Blanco J. & Villers-Ruiz L. (1995) - *Delineating boundaries of environmental units for land management using a geomorphological approach and GIS: A study in Baja California, Mexico.* Remote Sens. Environment, 53, No. 2, 109-117.

López-Guerrero A. (1992) - *Escorrentía en paqueñas cuencas hidrológicas con Selva Baja Caducifolia en Chamela, Jalisco.* Tesis de Licenciatura ENEP-Iztacala, UNAM, México, D. F.

Lott E.J. (1985) - *Listado Florístico de México. III. la estación de Biología Chamela, Jalisco.* Instituto de Biología, UNAM, México.

Lott E.J., Bullock S.H. & Solís-Magallanes A. (1987) - *Floristic diversity and structure of upland and arroyo forest of coastal Jalisco.* Biotropica, 19, 228-235.

Lugo J. (1990) - *El relieve de la República Mexicana.* Rev. I. de Geología UNAM, 9, 82-111.

Martínez-Yrízar A. & Sarukhán J. (1990) - *Literfall patterns in a tropical deciduous forest in Mexico over a five-year period.* Journ. Tropical Ecol., 6, 433-444.

Montgomery, D.R. & Dietrich W.E. (1984) - *Where do channels begin?* Nature, 336, 232-234.

Montgomery D.R. & Dietrich W.E. (1989) - *Source areas, drainage density and channel initiation.* Water Resour. Res., 25, 1907-1918.

Moore I.D., O'Loughlin M.O. & Burch G.J. (1988) - *A contour-based topographic model for hydrological and ecological applications.* Earth Surf. Proc. Landf., 13, 305-320.

Palacio-Prieto J.L., López-Blanco J. & Ortíz-Pérez M.A. (1991) - *Evaluación geomorfológica estructural a través de modelos sombreados y pares estereoscópicos generados a partir de modelos digitales de terreno.* Investigaciones Geogr. Bol., 23, 89-101.

Patton P.C. & Schumm S.A. (1975) - *Gully erosion, Northwestern Colorado: a threshold phenomenon.* Geology, 3, 88-90.

Pelton C. (1987) - *A computer program for hill shading digital topographic data set.* Computer a. Geosc., 13, 545-548.

Romo J.M. (1989) - *Gray scale maps with a personal computer.* Computer a. Geosc., 15, 1249-1263.

Ruhe R.V. (1975) - *Geomorphology: Geomorphic Processes and Surficial Geology.* Houghton Mifflin Co., Boston, 246 pp.

Rzedowski J. (1983) - *Vegetación de México.* Ed. Limusa, México, 432 pp.

Savazzi E. (1990) - *C programs for displaying shaded three-dimensional objects on a PC.* Computers a. Geosc., 16, 195-209.

SEDUE (Non dated) - *Mapa Topográfico Escala 1:2,000 de las Cuencas de la Estación de Biología Chamela UNAM.* Plano No. 2, Subsecretaría de Ecología, Delegación SEDUE-Jalisco, México.

Solís E. (1993) - *Características fisicoquímicas de un suelo en un ecosistema tropical estacional.* Tesis Licenciatura, Fac. de Ciencias, UNAM, México.

Strahler A.N. (1964) - *Quantitative geomorphology of drainage basins and channel networks.* In: Chow V.T. (ed.), *Handbook of Applied Hydrology.* McGraw-Hill, New York, N.Y., 439-376.

Swanson F.J., Kratz T.K., Caine N. & Woodmansee R.G. (1984) - *Landform effects on ecosystem patterns and processes.* BioScience, 38, 92-98.

Tarboton D.G., Bras R.L. & Rodriguez-Iturbide I. (1989) - *Scaling and elevation in river network.* Water Resour. Res., 25, 2037-2052.

Turner M.G. (1989) - *Landscape ecology: the effect of pattern on process.* Ann. Rev. Ecol. Syst., 20, 171-197.

Ware C. (1989) - *Fast hill shading with cast shadows.* Computer a. Geosc. 15, 1327-1334.

Willgoose G.R., Bras R.L. & Rodriguez-Iturbide I. (1991a) - *A coupled channel network growth and hill-slope evolution model 2. Nondimensionalization and applications.* Water Resour. Res., 27, 1685-1696.

Willgoose G.R., Bras R.L. & Rodriguez-Iturbide I. (1991b) - *A physical explanation of an observed link area-slope relationship.* Water Resour. Res., 27, 1696-1702.

Willgoose G.R., Bras R.L. & Rodriguez-Iturbide I. (1992) - *The relationship between catchment and hillslope properties: implications of a catchment evolution model.* Geomorphology, 5, 21-37.