Distributed GIS Environment to Detect Geomorphometric Characteristics in Geo-Images

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Abstract. We present an approach to detect geomorphometric characteristics in a Distributed GIS Environment. The application is focused on providing support during the decision-making process. It is oriented to generate DEM classifications (landform and topographic ruggedness) and drainage density. Spatial analysis is computed by Spatial Analyzer Module. The approach involves the following raster layers: slope, profile curvature and plan curvature (primary attributes), which have been built to identify the intrinsic properties of the landscape. The landform is considered to evaluate the probable water movement and concentrations. We use a *multi-valued raster* to integrate the primary attributes of DEM to generate the landform classification layer in order to find the terrain characteristics of the water movement. The topographic ruggedness is used to express the amount of elevation difference between adjacent cells of DEM. The topographic ruggedness is presented by means of Terrain Ruggedness Index (TRI). The drainage density layer is used to represent the amount of hydrologic linear objects. The GIS-application has been implemented into ArcMap module of ArcInfo system. Also, the GIS-application is oriented to partially solve problems related to natural disasters, by means of GIS-simulations.

1 Introduction

An increasing number of Geographical Information System (GIS) applications rely on computer networks and the World Wide Web for accessing their resources, being both datasets and software operations [1]. Digital Elevation Models (DEM) are playing an increasingly important role in many technical fields GIS development, including earth and environmental sciences, hazard reduction, civil engineering, landscape planning, and commercial display [2]. Furthermore, DEM has been incorporated in geomorphometric analysis. This is the measurement of geometry of the landforms[1] to analyze distribution and concentration of certain spatial objects and has traditionally been applied to watersheds, drainages, hillslopes and other groups of terrain objects.

We usually note that DEMs are directly computed from the elevation model and

[1] Landform is the result of various processes acting on the surface has also the function of a static boundary condition for processes in geomorphology, hydrology, meteorology and others.

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secondary compound attributes, which involve combination of primary attributes and constitute physically the spatial variability of specific processes that are presented in the landscape [3], while *primary attributes* include slope, aspect, plan and profile curvature. Most of these topographic attributes are computed from directional derivatives of a topographic surface. The slope affects the overall rate of movement downslope. The *Profile curvature* impacts the acceleration and deceleration of the water flow. Therefore, it influences in the erosion and the deposition processes. The *Plan curvature* affects convergence and divergence of the water flow [4].

This type of analysis should be support the decision-making process in different areas such as risk prevention, urban planning, agriculture, etc. By using the distributed environment the users can make queries to retrieve the spatial data from different GIS sites.

In this work, we propose a method to perform geomorphometric analysis implemented in a distributed GIS. In Section 2, we present the architecture of the GIS-application. Description of SAM and its functionality is described in Section 3. Section 4 sketches out the results, and our conclusions are outlined in Section 5.

2 Architecture of GIS-application

This GIS-application presents a client-server architecture. This tool contains the following modules: Enterprise GIS, Communication Module, Spatial Analyzer Module, Spatial Database and XML Administration Module. See Fig. 1.

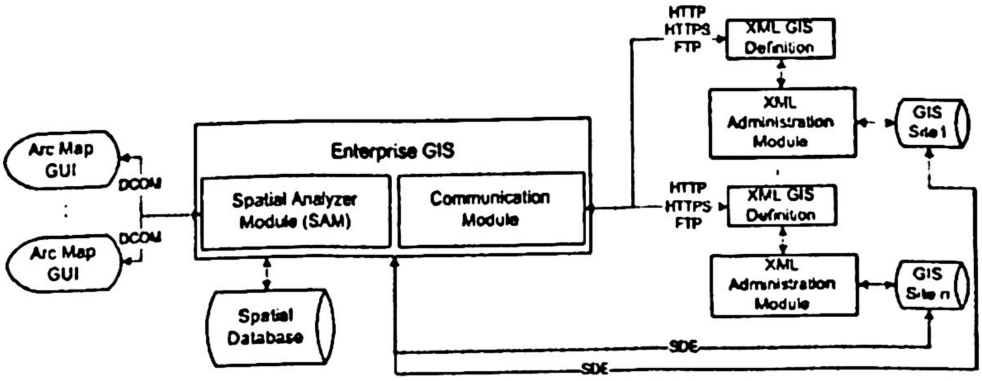


Fig. 1. Architecture of GIS-Application

The functional mechanism of the GIS-application is the following: ArcMap users need to make a request. This request is sent by DCOM technology to the communication module into the Enterprise GIS. This module processes the request and sends the parameters via HTTP or HTTPS protocols. In the remote GIS site, the XML administration module verifies the initial XML definition and queries the local XML definition to locate and compare the *qualitative* and *quantitative* characteristics of the spatial data such as scale, projection, spatial reference, resolution, representation type, thematic, DBMS type and attribute data. If the XML definition matches with the local XML definition, the spatial data (DEM) will be recovered and sent by means of the Spatial Database Engine (SDE) mechanism. The geographic data are stored in the spatial database in which they will be analyzed by SAM. In the following sections, we will describe the most important issues on the GIS-application such as spatial database, communication module and spatial analyzer module.

2.1 Spatial Database

GIS-application contains a geographic database, which has been designed and implemented by *Geodatabase*. It is a storage mechanism provided by ArcInfo, which is focused on generating independent geographic depositories [5].

The spatial database is a special environment that models the characteristics of the geographic phenomena. *Geodatabase* provides a topological model that is integrated by *class of elements*. This model is similar to the spatial coverage. The *Geodatabase* model is supported by an object-oriented relational database. On the other hand, it is considered as a *hybrid* between object-oriented and relational techniques. By using this technology, users can access to the spatial and descriptive attributes from different sources by means of the SDE [6]. This hybrid mechanism defines an open interface to database system and allows handling geographic information in an intrinsic way. In this case, the behavior of the spatial objects is defined by the system. The entities are represented as spatial objects with properties, behaviors and relationships between them. The spatial database has been designed using the ArcInfo system. All these components are involved in the analysis to determine landform and topographic ruggedness. The spatial data that match with the XML specification are retrieved and stored in the spatial database. The model of this depository has been developed in *Unified Modeling Language* (UML), which generates COM objects. These objects implement the behavior and the schema in which the objects are created, stored, and handled into the spatial database.

2.2 Communication Module

It is usual that the spatial analysis involves a lot of data sources. These data sources are located in different sites that belong to different organizations. For instance, in the case of flooding areas, the analysis involves data of superficial water volume, geology, infrastructure, etc. All these resources are not located in the database of a single organization. To solve this problem, many efforts have been made to interoperate multi-vendor and distributed GIS. One of the alternatives is GML [7][8] - a specification developed by the OPC for the transferring and the storage of geographic information based on XML -. However, this OPC recommendation is not yet supported by the majority of the commercial GIS. Therefore, it is difficult to find a solution for the problem in short term, because it is necessary that GIS vendors agree in the construction of translators from its data proprietary representations to a standard.

The problem to interoperate a multi-vendor and distributed GIS can be divided into three parts: (1) Localization of the required data to perform a spatial analysis; (2) Remote access to the relevant data, and (3) Transformation of different data representations. In this work, we propose a partial but useful solution that treats the first two problems. We have been able to get rid of the first component of the problem, because in many cases the GIS involved in analysis are distributed. However, all of them use the same technology provider (this scenario is usual in a government).

To locate the required data and to perform a spatial analysis, we include a module called XML Administration Module. This module is responsible to obtain the geo-information to know if a particular data source is relevant in a particular spatial analysis [9]. The architecture is shown in Fig. 1. The obtained geo-information is then codified in a XML document. Fig. 2 depicts an example of the contents of the XML document. Part of the information is queried from the GIS and other part is manually loaded by the GIS administrator.

```xml
<?xml version="1.0"?>
<Spatial_Data>
  <Descrption>
    <Layer_Name>topo</Layer_Name>
    <Theme>DEM</Theme>
    <Elab_By>GeoLab-CIC-PN</Elab_By>
    <Elab_Date>02/08/2004</Elab_Date>
    <Last_Update>02/08/2004</Last_Update>
    <Type>Raster</Type>
    <Resolution>10</Resolution>
  </Description>
  <Geographical_Properties>
    <Projection>UTM 13</Projection>
    <Datum>NAR_D</Datum>
    <Units>METERS</Units>
    <Spheroid>GRS1980</Spheroid>
    <Boundary>
      <Xmin>397041.431</Xmin>
      <Xmax>685954.665</Xmax>
      <Ymin>2432826.985</Ymin>
      <Ymax>3097482.722</Ymax>
    </Boundary>
    <Scale>1:50000</Scale>
  </Geographical_Properties>
  <DBMS_Properties>
    <Provider>ArcInfo</Provider>
  </DBMS_Properties>
</Spatial_Data>
```

Fig. 2. A XML document containing a DEM description

The communication module, located into the enterprise GIS, queries the XML documents of the different sites to display its information to the user [10]. In this way, the users can select the information sources, which are relevant to their analysis.

The communication between the enterprise GIS and the XML Administration Modules can be made using different standard protocols such as HTTP, FTP or HTTPS, if a secure transaction is needed.

When the data sources are selected, the Communication Module uses the SDE to retrieve the spatial data.

3 Spatial Analyzer Module

SAM is a special module, which has been designed to perform the spatial analysis procedures. SAM uses geographic data to make the spatial analysis. This module has been implemented using Arc Macro Language (AML) to ensure portability between computer platforms executing ArcInfo 7.0 or later. The analysis consists of using different spatial data related to the case of study. SAM contains two components: *Analysis Block*, which is composed of a set of processes to make data analysis; *List of Procedures* that stores the sequence of steps to execute the processes, and List of Resources that contains the *spatial* and *attributive* data description, which can be queried using the network. (See Fig. 3).

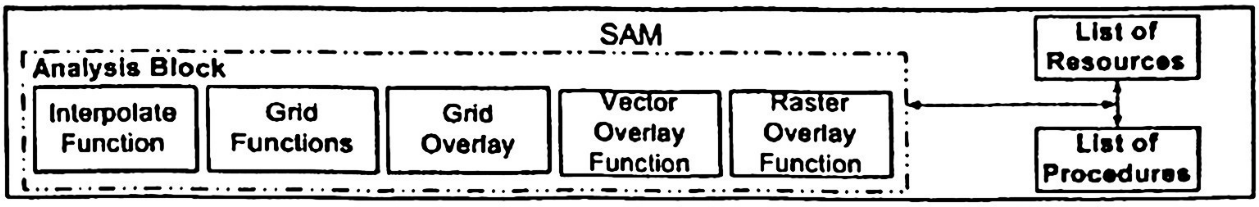


Fig. 3. Schema of SAM

3.1 Analysis Block

It contains the functions to perform the spatial analysis. The functions are the following:

1) *Interpolate Function.* The method used is a minimum curvature spline in two dimensions from a set of points. For computational purposes, the entire space of the output grid is divided into blocks or regions of equal size. They are represented in a rectangular shape. Eqn. 1 describes the spline function that has been used [11]:

$$S(x,y) = T(x,y) + \sum_{j=1}^{N} \lambda_j R(r_j), \qquad (1)$$

where j= 1, 2... N; N is the number of points; λ_j are the coefficients obtained from the system of equations, which computes the point coordinates; $R(r_j)$ is the distance from the point (x,y) to the j^{th} point.

To use this function, it is necessary to provide the set of points and tolerances, which depend on the specific case of study.

2) *Grid Generator.* It is used to process some analyzed data, especially in density map generation. The vector grids are regular of *m* x *m* magnitude in which *m* is the cell size. The cell magnitude in the grid is determined by the phenomenon under study characteristics (scale and covered area). Two alternatives can be used to generate the grids. First, specifying the initial and terminal grid coordinates ((x_0, y_0), (x_1, y_1)) respectively and establishing the number of required divisions for the grid. The second alternative is to specify the initial coordinate (x_0, y_0), cell size, number of columns and rows in the grid [12].

3) *Grid Functions.* They contain the set of functions for cell analysis, which includes operations of the map algebra and functions to compute primary topographic attributes such as slope, aspect, plan and profile curvature and upslope contributing area.

- *Map Algebra Functions:* They consist of the set of functions for cell analysis that includes operations of the map algebra. In this case the functions are considered to compute the square root (*SQRT*) and square (*SQR*) respectively in the input grid [13].
- *Slope Function* (*CALC_SLOPE*): Slope identifies the maximum rate of change in

value from each cell to its neighbors. An output slope grid can be computed as percent slope or degree of slope. Conceptually, the slope function fits a plane to the z-values (altitudes) of a 3 x 3 cell neighborhood around the processing or center cell. The direction of the plane (x,y-values) faces is the aspect for the processing cell. The slope for the cell is computed from the 3 x 3 cell neighborhood by using the average maximum approach [14]. This function is described with more detailed in [2]. The formulas to compute the slope are the following:

$$Rise\_Run = \sqrt{\sqrt{dz/dx} + \sqrt{dz/dy}}, \tag{2}$$

$$Slope = A\tan(Rise\_Run) * 57.29578, \tag{3}$$

where dz/dx and dz/dy are calculated by using a 3x3 window as described in Eqn. 4 and 5:

$$dz/dx = ((a + 2d + g) - (c + 2f + i))/(8 * X\_mesh\_spacing), \tag{4}$$

$$dz/dy = ((a + 2b + c) - (g + 2h + i))/(8 * Y\_mesh\_spacing), \tag{5}$$

• *Curvature Functions:* These functions compute the curvature in a DEM. The curvature functions can be used to describe the physical characteristics of a drainage basin to understand erosion and runoff processes. Two types of curvatures can be obtained by using SAM: 1) *Profile curvature* (*CALC_PROFILE_CURVATURE*) is the curvature of topography from a cross-section view (perpendicular to contour lines). 2) *Plan curvature* (*CALC_PLAN_CURVATURE*) is the curvature of topography from a map view (following contour lines). The curvature of a surface is computed by a *cell-by-cell*. For each cell, we use a fourth-order polynomial of the form [14]:

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I, \tag{6}$$

Eqn. 6 is used to fit a surface composed of a 3 x 3 window. The coefficients from A to I are calculated from this surface. The relationships between the coefficients and the nine values of elevation for every cell numbered are shown in Fig. 4 and described in [13]. The output of the *CURVATURE* function is the second derivative of the surface (i.e., the slope of the slope), which is defined in Eqn. 7.

$$Curvature = -2(D+E)*100, \tag{7}$$

4) *Raster Overlay Function.* This operation has been designed to generate *multi-valued raster*, which can be used to combine different geo-images. It is to count rasters with more than one attribute and assign values to these attributes for each raster elements [12]. The representation schema of the data structure is depicted in Fig. 5. It is important to note that two rasters can only be overlaid if they have the same geometry.

5) *Vector Overlay Function.* This function has been designed to make *topological overlays*, which can be used to identify areas of risk. A set of operations has been defined, and applied to the spatial analysis. This is made to establish the conditions and to combine different information layers, by means of logical operators. These functions combine spatial and attributive data. The implemented operations for topological overlay in this application are: intersection, union and identity [15].

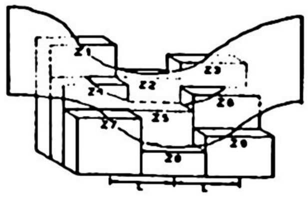


Fig. 4. Elements to compute the curvature

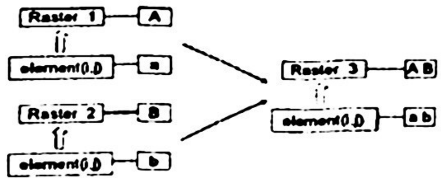


Fig. 5. Data schema of multi-valued rasters

3.2 List of Procedures

List of procedures stores the set of functions for each one of the analysis processes, and it describes the required data type and the constraints. In this paper we propose two processes: Ruggedness Index and Landform Clasification. SAM has a wide range of applications, not only to make *geomorphometric analysis* but also to perform the detection of *landslide* and *flooding* areas [16].

3.2.1 Topographic Ruggedness

Topographic Ruggedness is represented by means of Terrain Ruggedness Index (TRI). TRI is a measurement developed by Riley to represent the amount of elevation difference between adjacent cells of a DEM [17]. The process essentially computes the difference in elevation values from the center cell and the eight cells surrounding it immediately. This process squares each of the eight elevation difference values to make them all positive and averages the values (squares). Therefore, TRI is derived by taking the square root of this average, and it corresponds to the elevation average change between any point into a grid cell and its surrounding area. The authors of the TRI propose the classification for the values obtained by the index (see Table 1). The pseudo-code [17] to generate TRI layer is presented as follows:

```
program TRI {
 de-Input Grid;   tmp1-Standard elevation difference;
 tmp2-TRI;  tmp3- adjust TRI range;   ri-Output grid
 tmp1(X,Y):=((SQR(dem(x,y)-dem(x-1,y-1))+ (SQR(de(x,y)-de(x,y-1))+
   SQR(de(x,y)-de(x+1,y-1))+(SQR(de(x,y)de(x+1,y))+(SQR(de(x,y)-de(x+1,y+1))+
  (SQR(de(x,y)-de(x,y))+(SQR(de(x,y)-de(x-1,y+1))+ (SQR(de(x,y)-de(x-1,y)))
 tmp2(X,Y):=SQRT(tmp1(x,y))
 tmp3(X,Y):=If(tmp2(x,y)>=5000) then tmp3(x,y):=5000  Else tmp3(x,y):=tmp2(x,y)
 if(0>=tmp3(x,y)<= 80)then ri(x,y):=1;if(81>=tmp3(x,y)<=116)then ri(x,y):=2;
 if(117>=tmp3(x,y)<=161)then ri(x,y):=3; if(162>=tmp3(x,y)<=239)then ri(x,y):=4
 if(240>=tmp3(x,y)<=497)then ri(x,y):=5;if(498>=tmp3(x,y)<=958) then ri(x,y):=6
    if(959>=tmp3(x,y)<=5000)then ri(x,y):= 7 )}
```

Table 1. Terrain Ruggedness Index Classification

TRI	Interval (m)	Represent
1	0-80	Level terrain surface
2	81-116	Nearly level surface
3	117-161	Slightly rugged surface
4	162-239	Intermediately rugged surface
5	240-497	Moderately rugged
6	498-958	Highly rugged
7	959-4367	Extremely rugged surface

3.2.2 Landform Classification

Primary and *secondary attributes* have been used to classify DEM into different landforms. A method by Pennock described in [4] was implemented to automatize the classification. The slope, profile curvature and plan curvature are used to classify eleven different landforms (see Table 2). The landform classification is considered to evaluate the probable water movement and concentrations. Watershed is an area that drains water and other substances to common outlet as concentrated drainage. This area is normally defined as the total area flowing to a given outlet or pour point [4]. These areas are detailed by *WATERSHED* function (Arc/Info). The following pseudo-code has been designed to generate the *landform classification*:

```
program LFC{
 dem- Input Grid; slope- slope; profcurv - profile curvature;
 plancurv - plan curvature;  watershead - watershead area
 otgrd0  - Aux grid; otgrd1  - Aux grid; landform- landform classification
 slope:=CALC_SLOPE(dem);
 profcurv:=CALC_PROFILE_CURVATURE(dem);
 plancurv:=CALC_PLAN_CURVATURE(dem);
 otgrd0:=OVERLAY(profcurv, plancurv)
 otgrd1:=OVERLAY(slope, watershead);
 landform:=OVERLAY(otgrd0, otgrd1);  }
```

Table 2. Classification of landform elements for a DEM

Landform Elements	Acronym	Slope	Profile Curvature	Plan Curvature	Watershead
Divergent Shoulder	DHS	>0	>0.1	>0.1	NA
Planar Shoulder	PSH	>0	>0.1	>0.1 >-0.1	NA
Convergent Shoulder	CSH	>0	>0.1	>0.1	NA
Divergent BlackSlope	DBS	> 3.0	>-0.1 <0.1	>0.1	NA
Planar BackSlope	PBS	> 3.0	>-0.1 <0.1	>0.1 >0.1	NA
Convergent BackSlope	CBS	> 3.0	>-0.1 <0.1	>0.1	NA
Divergent FootSlope	DFS	>0	>-0.1	>0.1	NA
Planar FootSlope	PFS	>0	>-0.1	>0.1 >0.1	NA
High Catchment Level*	HCL	< 3.0	>-0.1	NA	> 500

3.2.3 Drainage Density

Drainage density is defined as the total length of channels divided by area and measured the degree to which a landscape is dissected by channels [18]. To generate the drainage density layer, it is necessary to build a regular grid of 1 km^2 per cell [19]. By using this layer, we can construct the centroid layer. Later, the drainage layer is intersected with the grid layer. For each cell of the grid the lengths by area unit are added into centroid layer. The centroid layer is interpolated and the drainage density layer is obtained. The pseudo-code to generate the *drainage density* is described as follows:

```
program DD{
  hdr - Hydro Net; grd-Grid Layer; cent- centroids layer;
  int-Intersection layer  dd - Drainage density layer;
  grd:= GENERATE-GRID(hdr,1 Km);
  int:=intersection (hdr,grd);
  cent:= frecuency-by-cell(int)  dd:= interpolate (cent)  }
```

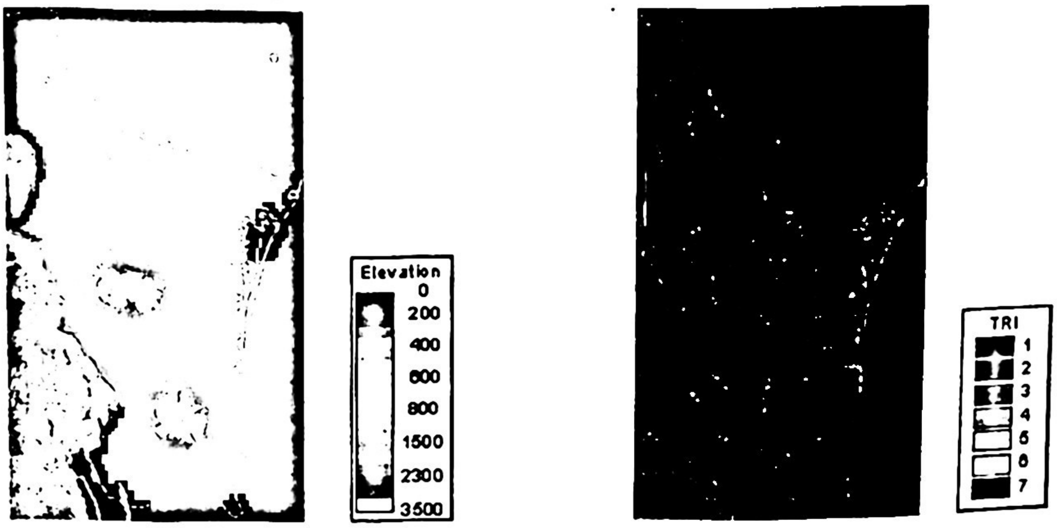
3.3 List of Resources

This mechanism stores the description of the remote and distributed GIS sites. This description is used to retrieve the spatial data from different spatial databases. Thus, the users are able to select the cartographic digital products list. This list provides a general view of the qualitative and quantitative characteristics of the spatial data.

4. Results

By using SAM, we construct *terrain ruggedness index* and *landform classification* layers. Some results of this approach are presented in this section. The methods have been applied to Tamaulipas State, Mexico covered by DEM at two resolutions, 10 x 10 m and 100 x 100 m generated in GEOLAB, interpolating line contours.

Fig. 6a shows the original DEM (100 meter resolution) composed of 8000 rows and 2478 columns. The minimum value is 0 m, maximum value is 3496, mean value of this layer is 227.40 m and the standard deviation is 498.469. Fig. 6b depicts the *terrain ruggedness* layer constructed by SAM, and the TRI classification of this area. The *TRI* layer has the following values; mean is 2.386 m and the standard deviation is 2.457. This means that Tamaulipas State has slightly rugged areas in its territory. The extremely rugged areas are principally concentrated at the southwestern part of Tamaulipas State. Fig. 7 presents a fragment of the terrain ruggedness classification.



a) b)

Fig. 6. a) Digital Elevation Model with resolution of 10 m, b) Terrain Ruggedness layer.

Fig. 7. Fragment of ruggedness layer

To test the landform classification, we use two DEMs of the same area in two resolutions: 1) 1925 rows and 2410 columns (10 meter resolution), 2) 190 rows and 239 columns (100 meter resolution); see Fig. 8. In Fig. 8a we appreciate the DEM prior to classification. Fig. 8b and 8c depict the landform classification of the DEM. The differences between these figures are due to the resolutions. Fig. 8b has more level of detail than Fig. 8c. The favorite value in both classifications is *Planar Back Slope*, this means that the terrain is mainly planar (this is its semantics).

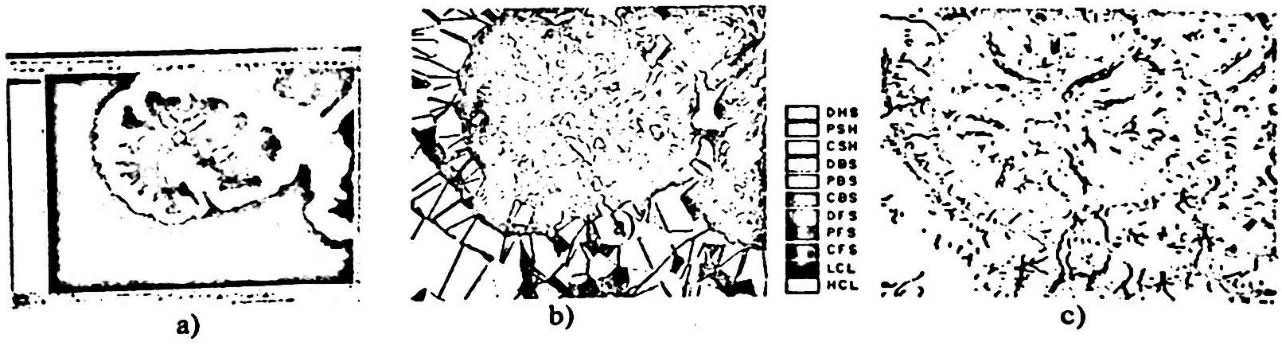


Fig. 8. a) DEM with resolution of 10 m, b) Landform classification of DEM with resolution of 10 m, c) Landform classification of DEM with resolution of 100 m

Fig. 9a shows the hydrological layer, this layer contains all streams of Tamaulipas State (1:200,000). The drainage density layer is depicted in Fig. 9b. The mean value of this layer is 24857, which is nearly to the lower value. The concentrations are represented in blue scale, the dark blue represents higher concentrations and light blue represents the lower concentrations. We can see the highest concentrations of drainage are situated in the south coast, near Tampico City, while the lowest densities are presented in the northwestern part of Tamaulipas State. Fig. 10 presents a fragment of the drainage density layer.

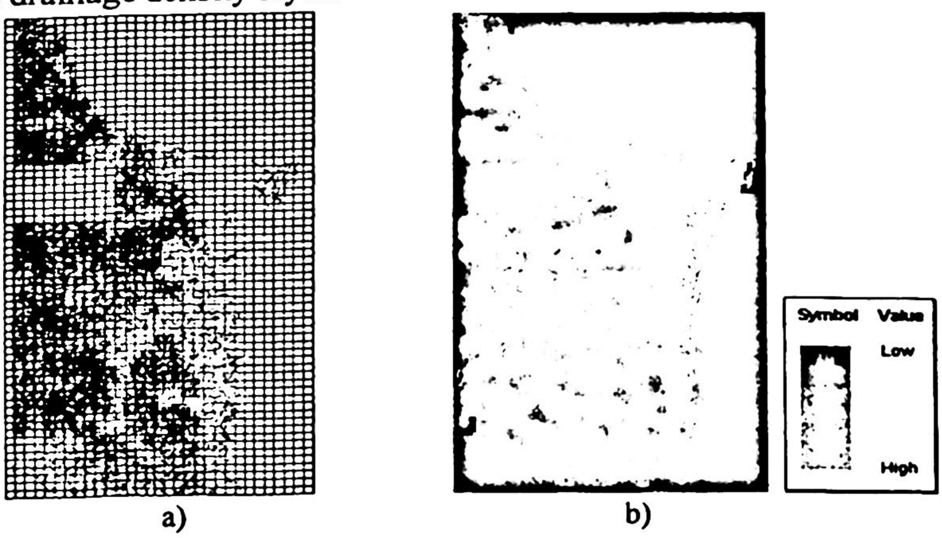


Fig. 9. a) Hydrological Layer, b) Drainage Density

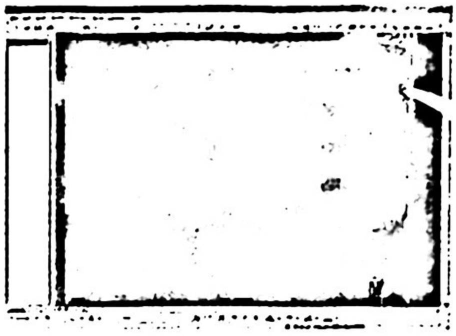


Fig. 10. Fragment of drainage density layer

5 Conclusions and future works

In this work, we present a Distributed GIS-application oriented to perform spatial analysis. The analysis is processed by Spatial Analyzer Module integrated into GIS-application to analyze *spatial characteristics* of terrain. SAM generates primary attributes of DEM to detect landform elements in raster image data. In this approach, spatial and attributive data are used to generate raster. The mechanisms implemented in the *List of Procedures* can be modified and extended to apply in the analysis of different phenomena.

We propose a XML description, which can be used as a standard to partially solve the spatial data integration problem. This approach is an alternative to retrieve spatial data in a distributed environment, because the XML definition that has been designed to represent a *spatial semantics* of the geographical objects can be used to find solutions related to the spatial interoperability.

The geomorphometric analysis is traditionally performed by using the methods based on topographic map-processing in manual way. Our approach significantly decreases the amount of time and effort required to quantify selected terrain characteristics. Other methods are designed to evaluate additional characteristics, which are different to the properties proposed in our approach. However, these methods can be integrated into SAM. The geomorphometric analysis facilitates the extraction-information of the spatial properties that can be used in other cartographic processes such as hydrological balance, automatic map description, map generalization, etc. Moreover, the *landform, drainage density* and *ruggedness classification* approaches are used to identify flooding areas and the path of the hydrological flows. Also, we can catch the *semantics*, which is represented by a set of properties that involves the DEM. Future works related to our research, are oriented to change the architecture of the GIS-application, for new technologies, which are focusing on solving interoperability and heterogeneity issues in spatial data. Also, we will attempt to define GML descriptions and represent the spatial data by means of SVG format.

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