Tridimensional-Temporal-Thematic Hydroclimate Modeling of Distributed Parameters for the San Miguel River Basin

María del Carmen Heras Sánchez[1], José Alfredo Ochoa Granillo[1],
Christopher Watts Thorp[1], Juan Arcadio Saiz Hernández[1], Raúl Gilberto Hazas Izquierdo[1],
and Miguel Ángel Gómez Albores[2]

[1] Universidad de Sonora, Blvd. Luis Encinas y Rosales, Col. Centro, C.P. 83000,
Hermosillo, Sonora,
Mexico

[2] Centro Interamericano de Recursos del Agua, Universidad Autónoma del Estado de México, Carretera Toluca-Atlacomulco, km. 14.5, C.P. 50110, Toluca, Estado de México,
Mexico

carmen@acarus.uson.mx, ochoa@correo.geologia.uson.mx, watts@correo.fisica.uson.mx, jsaiz@dicym.uson.mx, rhazas@difus.uson.mx, magomeza@uaemex.mx

Abstract. A geographic database (GDB) for the San Miguel river basin has been built by integrating data from multiple sources for analysis and graphical representation of diverse physiographic features and hydroclimate phenomena such as rainfall, temperature, soil-evaporation and topography, among others. This database allowed us to combine digital maps and images along with thematic information and spatially-referenced vector data. Moreover, further geographical referencing and validating processes enabled us to accurately represent continuous data through discrete data structures which fit the mathematical models used in representing the physical phenomena at the study site. In this paper we discuss some significant progress on models generated for the analysis of existing records for a season with measurable rainfall at the San Miguel river basin during the period from June 1st to September 30th of 2005.

Keywords. GDB, GIS, digital elevation model, river basin, e-geoscience, modeling, mapping.

Modelación tridimensional-temporal-temática de parámetros hidroclimáticos distribuidos en la cuenca del Río San Miguel

Resumen. Se construyó una Base de Datos Geográfica (BDG) de la Cuenca del Río San Miguel, Sonora, México, que integra datos de diversas fuentes, con el propósito de analizar y representar gráficamente, fenómenos climatológicos y fisiográficos como precipitación, temperatura, suelos, topografía, uso del suelo, geología, entre otros. Se agregaron también imágenes de satélite, información tabular, gráficas, estadísticas e información vectorial espacialmente referenciada al sitio de estudio. La conformación de la BDG requirió rigurosos procesos de validación, debido a que las estructuras de datos representan valores continuos en sistemas discretos (como los computacionales), lo que hizo necesario realizar estudios de referenciación y validación geográfica, con lo que se lograron modelos matemáticos y gráficos que representan con precisión los fenómenos físicos de interés en el sitio de estudio. En este trabajo se presentan algunos avances de la modelación de la precipitación registrada en la cuenca del Río San Miguel, correspondiente al periodo del 1ro de Junio al 30 de Septiembre del 2005.

Palabras clave. BDG, SIG, modelo digital de elevación, Cuenca, río, e-geociencias, modelación, mapeo.

1 Introduction

As originally devised [1], a GDB encompassing the San Miguel river basin, Sonora, Mexico, has been built. Among its primary components, the digital elevation model (DEM) allowed us to model the target basin. Using the model outcome, we redefined the polygon for the study area and calculated the physiographic parameters for both the river basin and the main river bed. Furthermore, a series of digital cartographic by-products containing thematic information such as geologic, hydrology and soil use, among others, was generated. The latter is indispensable for any further hydrological and tridimensional modeling.

The application used to perform the simulations and modeling was Idrisi version 16, Taiga edition. We have integrated data from several sources, mainly from INEGI[1] and hydrometereological stations (HS) distributed along the basin. The integrating methods previously discussed [1] allowed us to proceed with confidence in a proper validation and referencing of our GDB.

The GDB design required substantial computing power. It was implemented by means of a server with 16 GB in memory and 4TB of mass storage. The server was acquired and set up with the material and technical support of Telemetry and Geographic Information System Applications Development Centre at the Mines and Civil Engineering Department and the High-Performance Computing Area (ACARUS) at the Sonora University (Universidad de Sonora).

2 Overview of Study Area

The San Miguel river drainage basin is located in the northern central part of the state of Sonora, Mexico, as depicted in Fig.1, the main runoff contributors being the Cucurpe, Opodepe and Rayón municipalities (see Fig.2).

Due to more precise hydrographic modeling outcomes, the polygon enclosing the study area was reevaluated. The Universal Transverse Mercator (UTM) geographic coordinate system coordinates for the new polygon vertices are as follows: a(482,805,3408152), b(583812,3408152), c(482805,3236102) y d(583812,3236102. It has an area of 17,378.25 km^2 and a perimeter extending 546.11 km. Moreover, as a consequence of the study area polygon revaluation, the DEM image resolution is different from the one previously calculated [1].

Image spatial resolution is indicative of the pixel size expressed in terms of dimensions on the terrain. Even though a pixel is a graphic element, it is commonplace to refer to the pixel size with regards to the grid cell size in a raster file. Pixel size and cell size are used interchangeably to refer to a grid primary building block [2].

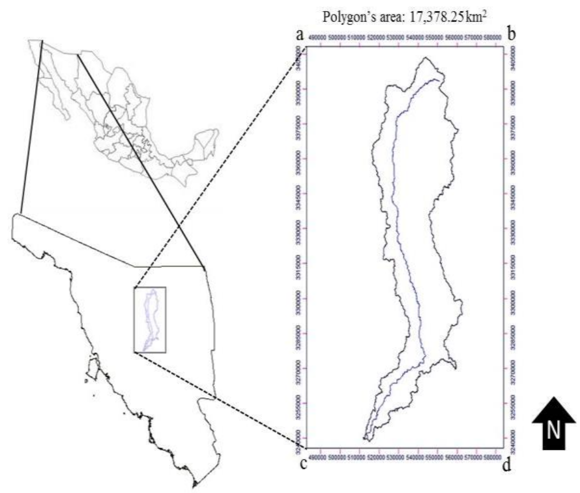

Fig. 1. Study area

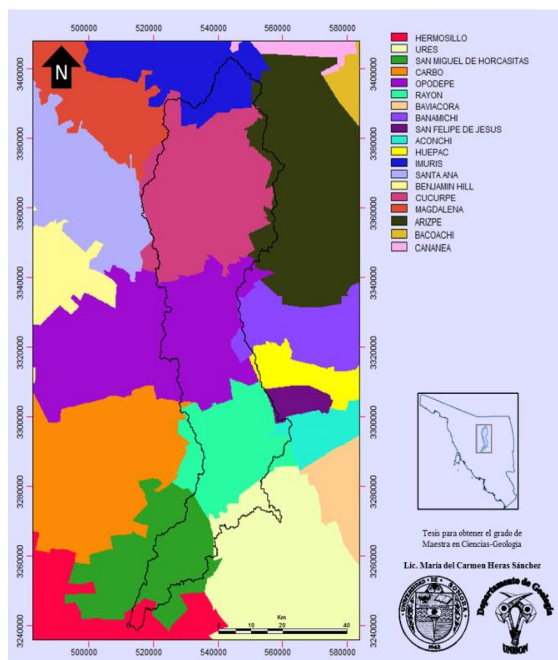

Fig. 2. The San Miguel river drainage basin surrounding municipalities

[1] Instituto Nacional de Estadística, Geografía e Informática (National Institute for Statistics, Geography and Informatics), Mexican federal government agency for the collection, classification and distribution of geographical information.

GIS systems (Geographic Information Systems) do not assume that pixels are square since spatial resolution is determined by X and Y coordinates' scope and the number of rows and columns forming the grid [3]. Using data of UTM12N and the WGS84 ellipsoids, the cell dimensions for our study area were defined as follows:

- spatial resolution X: Xmax-Xmin/number-of-columns=583812-482805/3741=27;
- spatial resolution Y: Ymax-Ymin/number-of-rows=3408152-3236102/5550=31;
- cell spatial resolution X and Y for DEM=27X31.

Therefore, spatial resolution means that the fine details of an image are distinctively resolved: the smaller terrestrial areas are represented by a given pixel, the finer details can be picked up, and greater spatial resolution is achieved [4].

For thematic information images, a lower resolution was utilized. In fact, the pixel dimensions are three times those of DEM model due to greater detail and precision required for the latter.

The cell spatial resolution X and Y for thematic information is 81X93.

3 Calculation of Physiographic Parameters

Proper physiographic dimensioning for the basin and for the river bed allows us to refer them to the geographic space they occupy. The river basin itself is a physiographic unit where measurable climatic phenomena occur, and it possesses distinctive soil use, vegetation, lithology, underground and surface hydrological characteristics, among others.

The Idrisi application includes algorithms required to calculate physiographic parameters of the river basin and the river bed. Such algorithms can either be accessed through the drop-down menus or as command line statements, or as part of the hydrogeomatic "Water Cycle" module developed by researchers at the Hydrogeomatic Lab from the Water Resources Inter-American Centre (CIRA) at the Engineering School of the Autonomous University of the State of Mexico

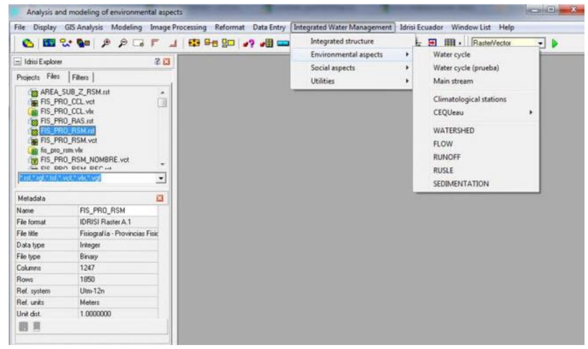

Fig. 3. Water cycle menu on Idrisi16, Taiga edition

(Universidad Autónoma del Estado de México), Mexico [5]. This module (see Fig.3) automates several required processes to carry out the calculations using the DEM model.

3.1 San Miguel River Basin Physiographic Parameters

Basin characteristics such as precipitation play a leading role in estimating the hydrologic cycle component behavior. Llamas [6] defines the basin main physical characteristics regarding the river bed and the drainage basin. Table 1 shows the main physiographic parameters for the study area.

Table 1. Physiographic parameters of the San Miguel river basin

Field	Calculated parameter	Value
A_km2	Basin area (km^2)	4,034.7
P_km	Perimeter (km)	717.76
Em_m	Mean basin height (amsl)	972.20
Pm_g	Mean basin slope (degrees)	10.9
Pm_p	Mean basin slope (percentage)	19.92
Kc	Compactness shape ratio	3.19
Rci	Circularity ratio	0.1

The basin form is determined from the circularity and compactness coefficients. The Gravelius compactness coefficient is the dimensionless ratio of the smoothed perimeter of the basin to the circumference of a circular area, which equals to the area of the basin. For our study area, the compactness ratio was equal to

$$K_c = \frac{1}{2\sqrt{\pi}}\frac{P}{\sqrt{A}} = \frac{1}{2\sqrt{\pi}}\frac{717.76}{\sqrt{4034.27}} = 3.19 \tag{1}$$

where *P* is the basin perimeter and *A* is the basin area. For elongated basins, such as that of San Miguel, the coefficient typically exceeds 3. Circular basins would approach a coefficient value of 1. Basins have an infinite variety of shapes, and the shape supposedly reflects the way in which runoff will "bunch up" at the outlet. A circular basin would result in runoff from various parts of the basin reaching the outlet at the same time. An elongated basin having the outlet at the end of the major axis and having the same area as the circular basin would cause the runoff to be spread out over time, thus producing a smaller flood peak than that of a circular basin.

On the other hand, the circularity coefficient is defined as the ratio of the basin area to the area of a circle whose perimeter is equal to the perimeter of the basin. For our study area, the circularity coefficient was equal to 0.1, see Equation 2.

$$R_{ci} = \frac{4\pi A}{P^2} = \frac{4\pi\, 4034.27}{717.76^2} = 0.1 \tag{2}$$

P and *A* are equal as above. A coefficient close to 1 indicates a basin resembling a circle; whereas for $R_{ci} < 1$ the basin approaches an elongated form, such as in the present case.

Another important physiographic parameter is an empirical cumulative distribution function

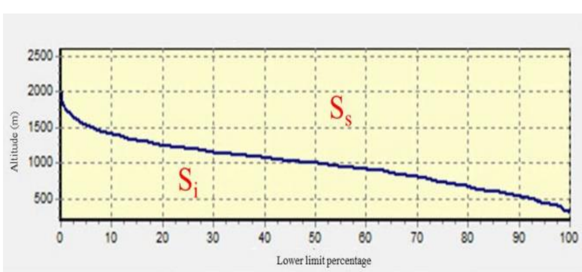

Fig. 4. Hypsometric curve of the San Miguel river basin

termed as a hypsometric curve, which assesses the erosive potential for a given basin.

The hypsometric curve precisely reflects the overall behavior of elevation within a basin and is directly related to evapotranspiration and precipitation distribution, among others. For the San Miguel river basin, the altitude was classified in 500m bins. Total area for each class was calculated and the percentages of the resulting areas compared to the basin area were calculated. S_s and S_i correspond to the areas over and under the hypsometric curve. The hypsometric ratio for the San Miguel river basin is calculated by Equation 3.

$$R_h = \frac{S_s}{S_i} = 2.08 \tag{3}$$

According to Llamas [6], the hypsometric ratio is an indicator of the dynamic equilibrium within a basin. When $R_h = 1$, the basin is at equilibrium; if $R_h < 1$, the basin is a young one with high erosive potential; when $R_h > 1$, we would have an old, also called sedimentary, basin. Such is the case of the San Miguel basin.

3.2 Physiographic Parameters for the Main River Bed

The physiographic parameters for a river bed define measurable characteristics such as its length and main axis length, which allow us to calculate the profile and river bed sinuosity, among others. For our study area, the river bed physiographic parameters are given in Table 2.

The longitudinal profile is a graph showing different river bed elevations from the watershed to the river bed's mouth. The profile for the San Miguel main river bed is shown in Fig.5.

Table 2. Main river bed parameters of the San Miguel river

Field	Calculated parameter	Value
Lc_km	Main river longitudinal river bed length (km)	228.18
La_km	Longitudinal axis length (km)	158.12
Emx_m	Main river maximal basin height (amsl)	290.00
Sc	Main river mean slope(degrees)	1.02

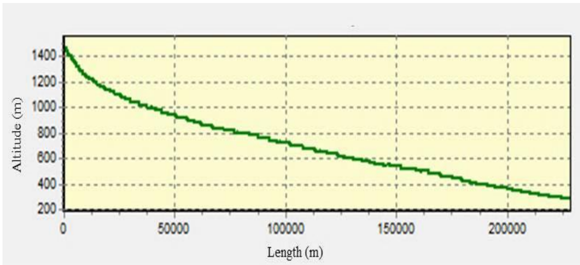

Fig. 5. Main topographic profile of the San Miguel river

In order to obtain the sinuosity index, we calculate the ratio of the main river longitudinal river bed length (Lc) to the length of a straight line between the highest and lowest elevation points (La) (see Fig.6).

For our study area, the sinuosity index is (Sh = Lc / La) = 228.18/158.12 = 1.44.

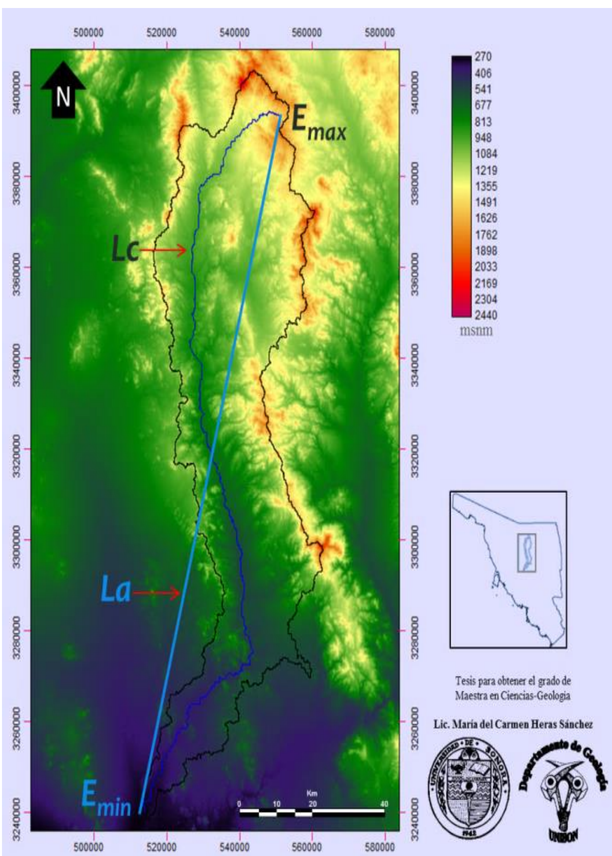

Fig. 6. Main river bed parameters of the San Miguel river

4 Cartographic Products Generated from DEM Model and Thematic Information

One of Idrisi modules, "composer", allowed us to integrate different cartographic elements, for instance, the coordinate system with a myriad of graphic information records in a layered fashion, so it is possible to switch any one of them ON or OFF and modify its appearance, scale, color palette, etc. We highlight some of these products for the study area.

Fig.7 shows concurrent vegetation varieties within the study area. The map is composed from land use images, vegetation records, class legends, the San Miguel river watershed limits, and corresponding UTM grid coordinates.

Fig.8 shows the lithology of the area with vegetation information.

In order to achieve results such as those portrayed in Fig.7 and 8, it was necessary to perform a careful analysis of the existing elements in the original raster images and obtain a correct classification of vegetation types (Fig.7), as well as rock types (Fig.8).

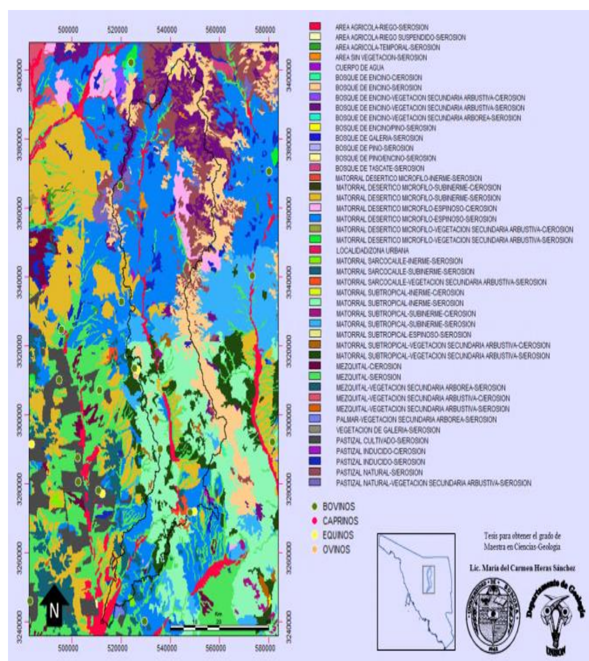

Fig. 7. The San Miguel river basin soil use

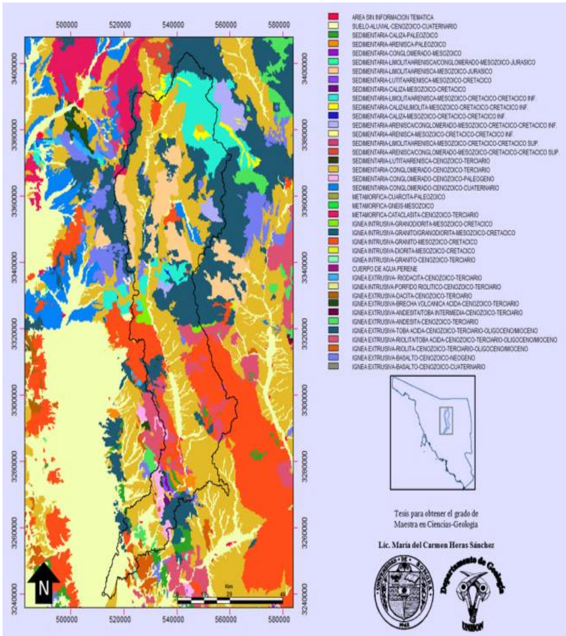

Fig. 8. The San Miguel river basin geology: lithology

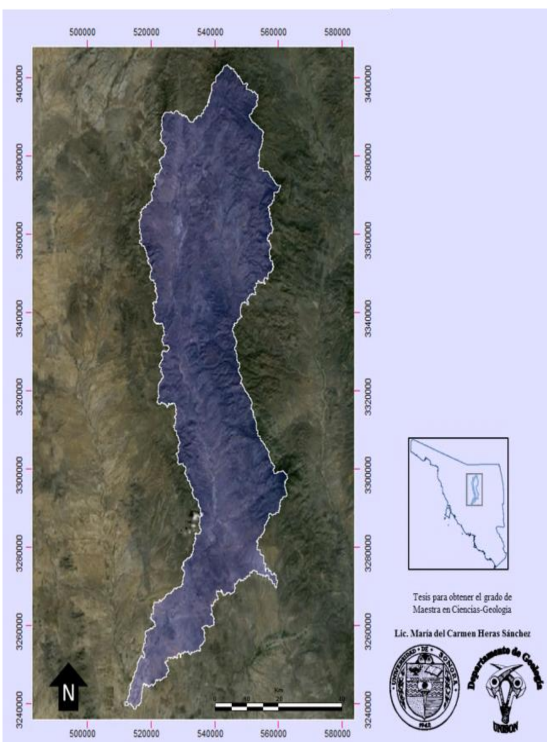

Fig. 9. The San Miguel river basin image overlaid on Google Earth image

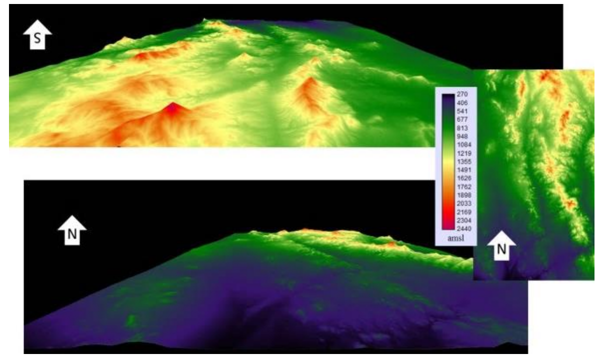

Fig. 10. Study area: tridimensional images with north and south orientation

For our GDB, we reclassified the images according to the methodology proposed earlier [1] for themes such as physiography, geology, hydrology, topography, soil use and potential soil use. For each theme, we further classified images according to sub-themes: for instance, the image in Fig.7 is a derived image from soil use, and the image in Fig.9 is a derived image from the geology theme.

To make Fig.9, a cut out Google Earth ® image was further georeferenced before being superimposed by the San Miguel river watershed contour.

Using DEM models, it is also possible to obtain 3D models such as panoramic views, visibility analysis, illumination analysis, relief maps, among others. We present a few examples.

Fig.10 shows panoramic views of the study area polygon. At the top, the orientation is southward, whereas at the bottom it has a northward orientation. The terrain orientation and inclination could be modified to accomplish greater raised relief, as well as the exaggeration factor for the highest elevations. In the image, the highest elevations correspond to an intense pink according to the chosen palette. Each color represents a given height in meters above the mean sea level (AMSL).

Relief maps are rather illustrative; one of them is shown in Fig.11. They result from a process in which the terrain illumination is derived from the DEM model; then the Idrisi "illuminate" module separates the color scheme into its blue/green/red components, transforms these into hue/lightness/saturation bands, and reassembles

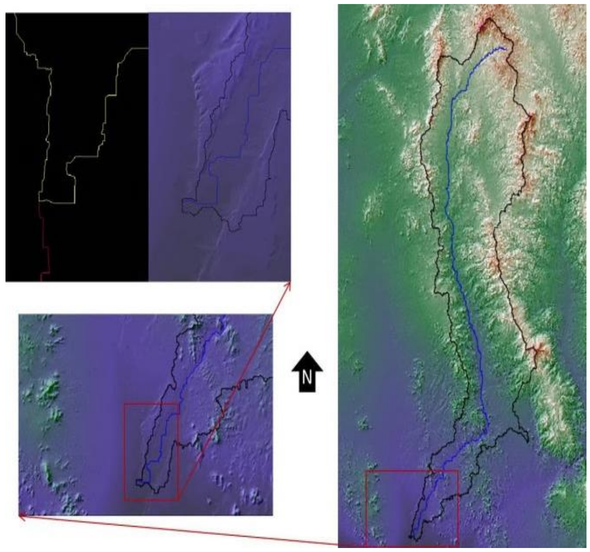

Fig. 11. Study area: runoff and land relief images

them, replacing the lightness image with either a hillshade model or any other byte-level image. This typically produces visually dramatic results in which a single image contains two different pieces of information. It is necessary to specify both the sun azimuth (0 – 360°) and elevation angle (0 – 89°) to be used in the creation of a hillshading image.

5 Measurable Rainfall at the San Miguel River Basin during the Period from June 1st to September 30th of 2005

5.1 Temporal-Thematic Hydrometeorological Information Preprocessing

The GDB includes the cumulative daily values of rainfall from June 1st to September 30th 2005. Those cumulative values are calculated from the thematic tabular files generated at each of the 8 hydrometeorological stations (HS) and stored as text files following the naming conventions outlined in [1]. The rainfall database comprises a total of 122x8 records generated during the study period. For demonstrative purposes, precipitation was accumulated in four periods per month. This reduced the number of files to 16. The dates included in each period are listed in Table 3.

Table 3. Cumulative periods for precipitation analysis

Cumulative period	Actual dates
0106	06/01-06/07
0206	06/08-06/15
0306	06/16-06/23
0406	06/24-06/30
0107	07/01-07/07
0207	07/08-07/15
0307	07/16-07/23
0407	07/24-07/31
0108	08/01-08/07
0208	08/08-08/15
0308	08/16-08/23
0408	08/24-08/31
0109	09/01-09/07
0209	09/08-09/15
0309	09/16-09/23
0409	09/24-09/30
0409	09/24-09/30

5.2 Hydrometeorological Stations Digitizing Process and Space-Temporal Image Generation

Once the HS files were in place, we used the DEM file for reference and took advantage of the Idrisi DIGITIZE command to situate the stations within the San Miguel river basin DEM model. Its outcome was a vector file (see Fig.12). As can be seen from Fig.12, available climatic data are scattered and localized, since they are collected at remote, yet permanent HS stations. Therefore, forecast methods are utilized to spatially distribute the climatic data. We then subjected the resulting HS vector file to a Thiessen polygon-based interpolation process and surface interpolation based on point data. The latter step produced images as well as vectors depicting areas, which can then be used in time series analysis and thematic-temporal model simulations for a given phenomenon under examination. As in the case

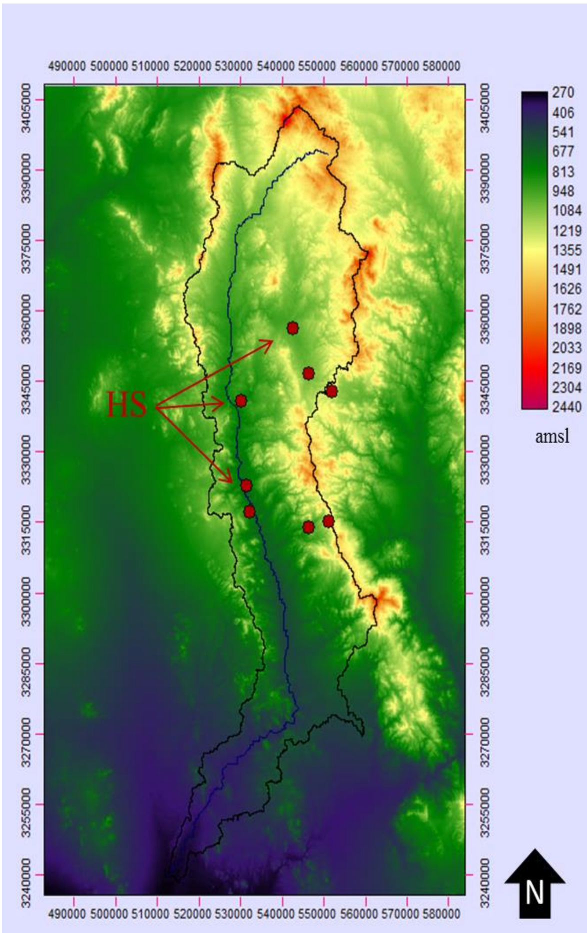

Fig. 12. The San Miguel river basin HS locations

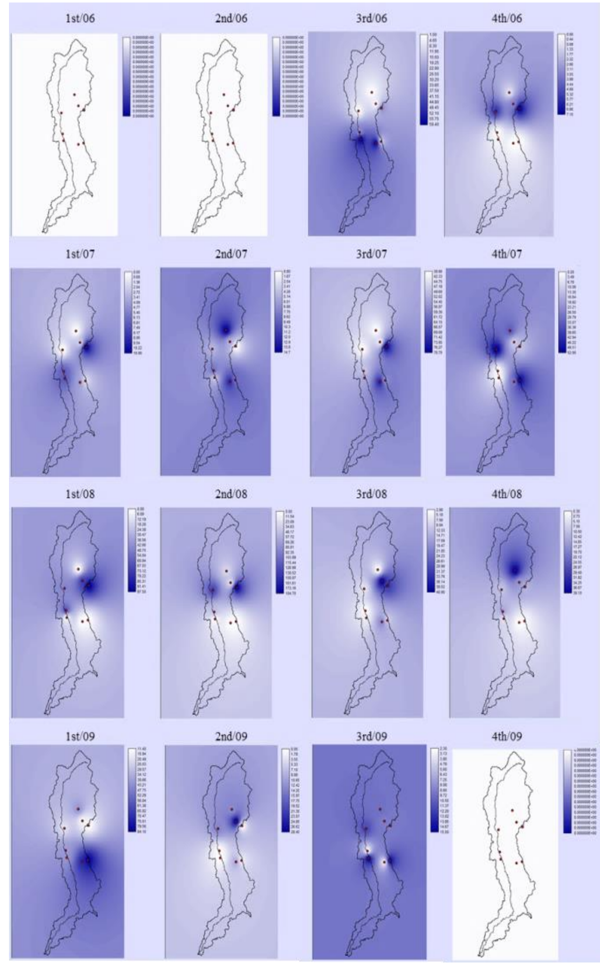

Fig. 13. Weekly cumulative precipitation of the San Miguel basin

of precipitation information, we also generated 16x8 georeferenced double precision binary files during the study period, see Fig.13.

Each one of the images representing accumulated precipitation for a given interval within the study period has been obtained applying Idrisi interpolation subroutine using a full surface from point data. The interpolation procedure can be either a distance-weighted average or a potential model. With both models, the exponent associated with the distance weight is user-defined. For this particular sequence, the DEM was interpolated with a distance weight exponent of 2.0.

As a result, we obtain rainfall estimation for each pixel making up the image. The further a given pixel is from an HS location, the lower its estimation will be. We also generated the interpolation for the cumulative precipitation for the whole period (see Fig.14).

The minimum and maximum cumulative precipitation for the study area were obtained for each interval within the study period, as well as the cumulative total for each HS (see Tables 4, 5 and Fig.15).

As can be seen from Tables 4 and 5, in the first and second weeks of June as well as the fourth week of September, there was no precipitation. Likewise, HS number 131 shows the lowest cumulative precipitation record for the study period, whereas HS 134 shows the highest record.

The graph in Fig.15 shows the cumulative precipitation per interval for the whole study period (for date reference, see Table 3). The maximum cumulative precipitation was recorded within the period of August 8th-15th as evidenced on 0208 bin of the histogram.

5.3 Thiessen Polygons

Idrisi THIESSEN subprogram constructs Thiessen polygons around a set of points, the hydrometeorological station locations in this instance. Thiessen polygons divide space such that each location is assigned to the nearest

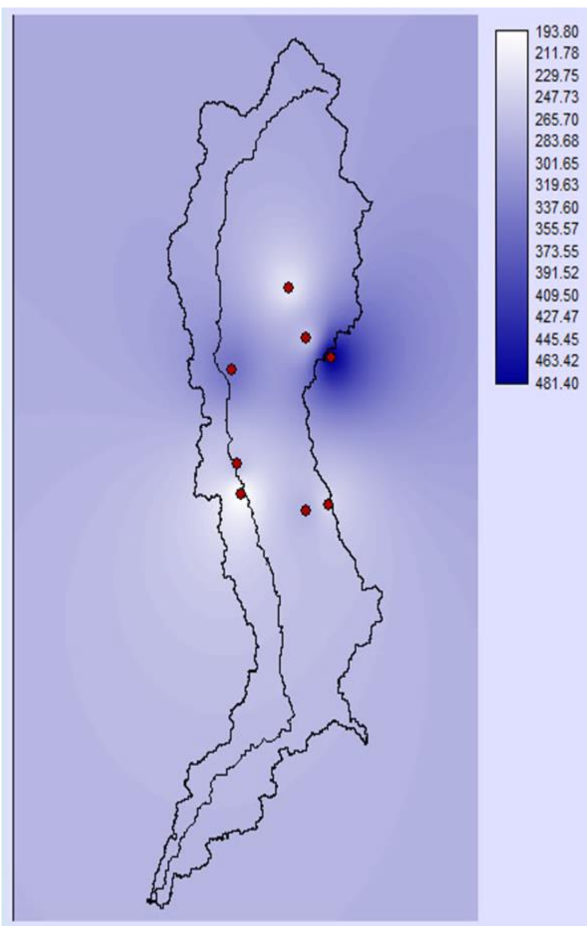

Fig. 14. Cumulative precipitation of the San Miguel river basin

Table 4. Minimum and maximum precipitation by cumulative period

Cumulative period	Minimum precipitation (mm)	Maximum precipitation (mm)
0106	0.0	0.0
0206	0.0	0.0
0306	1.0	59.4
0406	0.0	7.1
0107	0.0	10.9
0207	0.8	14.7
0307	39.9	78.7
0407	0.2	52.8
0108	0.0	97.5
0208	0.0	184.7
0308	2.8	40.9
0408	0.3	39.1
0109	11.4	84.1
0209	0.0	28.4
0309	2.3	15.5
0409	0.0	0.0
0409	0.0	0.0

Table 5. Cumulative precipitation recorded by HS

HS ID	Cumulative precipitation recorded
130	267.4
131	193.8
132	280.4
134	481.4
135	266.9
143	226.6
144	348.2
146	424.7

control point [7]. The polygons define the regions which are dominated by each point. Division of space into polygons of this nature is also known

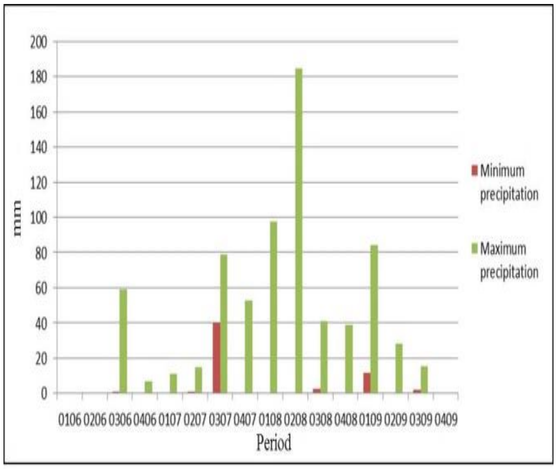

Fig. 15. Minimum and maximum precipitation by cumulative period

Table 6. Thiessen polygon-based cumulative mean precipitation of the San Miguel river basin's

HS ID	CMP: Cumulative mean precipitation (mm)	PA: Polygon area (m^2)	CMP*PA
130	267.4	224508598	60033599105.2
131	193.8	506368280	98134172664.0
132	280.4	1015546329	284759190651.6
134	481.4	85469418	41144977825.2
135	266.9	176211936	47030965718.4
143	226.6	1364510087	309197985714.2
144	348.2	461170260	160579484532.0
146	424.7	200521678	85161556646.6
Sum		4034306586	1086041932857.2
Basin cumulative mean precipitation			269.2

as Voronoi Tessellation [8]. It is assumed that each station represents the enclosing polygon area; therefore, the mean precipitation for the area corresponds to the cumulative precipitation for the corresponding station. Thus the mean precipitation for the basin is obtained by summing the product of the cumulative precipitation for each station times the area of the corresponding polygon, and then dividing by the total basin area:

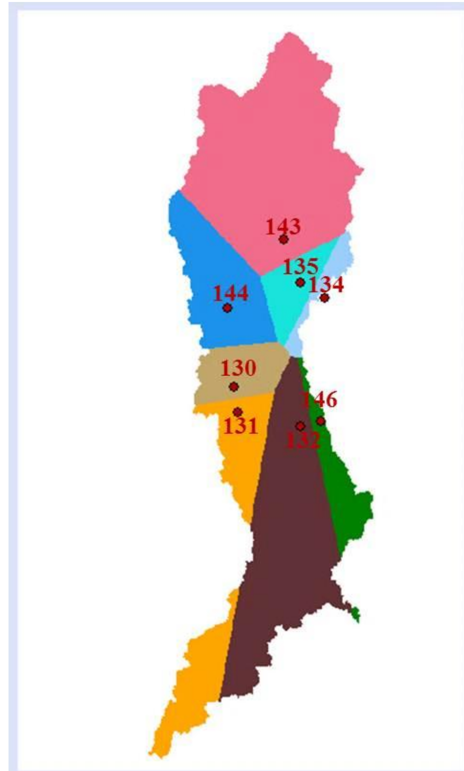

Fig. 16. Thiessen polygons and HS locations for the San Miguel river basin

$$P = \frac{\sum p_n a_n}{A} \tag{3}$$

where P is the basin mean precipitation, p_n is each station's cumulative precipitation, a_n is the area of each polygon, and A is the basin total area.

Table 6 shows the results of the computations, and Fig.16 shows the polygons distribution around the basin. As ican be seen in Table 6, the basin cumulative mean precipitation for the study period was 269.2 mm.

6 Conclusions

We assembled the GDB integrating data from multiple sources for hydrological modeling and numerical analysis purposes. Also, we devised a strategy for structuring, identifying, handling and increasing or improving the GDB information. An iterative digitizing and georeferencing process was formulated to match remotely collected hydroclimate data with DEM and thematic images. Spatial resolution calculations which allowed us to redefine the polygon enclosing the study area were performed. Moreover, as a consequence of the study area polygon revaluation, the DEM image resolution was fine-tuned to improve the geographical information representation.

As is evidenced by the cartographic examples shown above, care and detail taken in structuring the GDB allowed us to easily integrate thematic and model information and perform the different analyses presented. Visually appealing models render explicative maps which facilitate an assorted choice of analyses such as terrain tendencies, illumination models, and hydroclimatic time series, among others.

Thematic information generated in this way can be used for decision-making strategies in further engineering projects, soil and other resource utilization planning, as well as future human settlement reordering within a hydrological basin.

7 Acknowledgements

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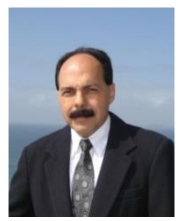
María del Carmen Heras Sánchez received her M. Sc. in Geology (Suma Cum Laude) from University of Sonora. She graduated as an Engineer in Informatics from the Technological Institute of Hermosillo. Since 2001, she has been a director of the high performance computing area of the Unison (ACARUS) and a professor of computer sciences and information system programs at the University of Sonora. She is a leader of such projects as the program of high performance technological development, training and qualification programs in high performance computing, scientific visualization laboratory, among others. She also collaborates in other projects like the national laboratory of supercomputing grids for supporting e-science and other grid initiatives in Mexico. She is a member of the Mexican Joint Research Unit and CONACYT Special Council for E-infrastructures, coordinator of the Consultative Council of Supercomputing at the University of Sonora, and has presided at northwest supercomputing symposiums in 2008 and 2006. She attended and lectured at national and international congresses and academic events related to high performance computing.

José Alfredo Ochoa Granillo received a M.Sc. in Geology from the University of Sonora. His fields of interest are hydrogeology and hydrological and geological mapping. He has been a professor at the Department of Geology at the University of Sonora since 2001. He is a specialist in cartography of groundwater, hydrology-surface Geological at INEGI and in Northwestern Regional Hydraulic CNA. Since 1991 he has worked as a consultant in the fields of geology, hydrology, geohydrology, and risk evaluation in addition to environmental impact assessment in mining areas. He is a member of the following professional associations: Association of Mining Engineers, Geologists of Metallurgists of the Mexican Republic (AIMMGE), International Society for Photogrammetry and Remote Sensing (ISPRS), Mexican Geological Society (SGM), and Mexican Hydrologic Resource Association.

Christopher John Watts Thorp has been a researcher at the Department of Physics of the University of Sonora since 2002. He supervised 3 Ph.D. and 16 M.Sc. students. He is author of publications in 6 national and 45 international journals, chapters in 5 national and 4 international books as well as publications in proceedings of 10 national and 21 international scientific meetings.

Juan Arcadio Saiz Hernández is a Civil Engineer from the University of Sonora and Ph.D. from the Polytechnic University of Madrid, Spain. He is a professor at the Department of Civil and Mining Engineering at the University of Sonora, Mexico, a member of the National System of Researchers of the National Council of Science and Technology of Mexico. He has directed and advised 10 graduate theses. He is author of articles in such journals as Hydrology and GIS and Digital Image Processing as well as book chapters.



Raúl Gilberto Hazas Izquierdo is currently an associate professor in the Electronics Technology Engineering Program at Physics Research Department of the University of Sonora. He received an M.S. degree in Electrical and Computer Engineering from SUNY Buffalo. His interests are digital electronics, computer architecture, high-performance computing, and digital signal processing.

Miguel Ángel Gómez Albores is a research professor at the Inter-American Center of Water Resources of the Autonomous University of the State of Mexico (CIRA-UAEMEX. Since 2009 he has been coordinator of Mexico IDRISI Resource Center. He received a Master's degree and a Ph.D. in Water Science. His area of research is geographic information of systems water-health.

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