HidroSIG: An Interactive Digital Atlas of Colombia's Hydro-climatology

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Accepted, *Journal of Hydroinformatics*

April 8, 2006

Keywords: GIS, Colombia, Hydrology, Climatology, HidroSIG, Water Resources, Floods, Water Balances

Short title:

Abstract. An interactive digital hydro-climatologic atlas of Colombia, HidroSIG, has been developed with distributed maps and time series of monthly and long-term average hydro-climatological variables, as part of a more comprehensive geographical information system (GIS) and database. Maps were developed so as to capture the spatial variability of the diverse geophysical fields resulting from major geographic, topographic and climatic controls. HidroSIG contain modules that perform diverse hydrological and geomorphological estimations including: (*i*) extraction of geomorphological parameters of drainage channel networks and river basins from Digital Elevation Maps (DEM), (*ii*) estimation of long-term and monthly water balances and other hydro-climatic variables in river basins, (*iii*) estimation of extreme flows (floods and low flows) of different return periods along the river network of Colombia by combining long-term water balance with scaling methods, (*iv*) interpolation of geophysical fields, (*v*) temporal analysis of hydrological time series including standardization, autocorrelation function, Fourier spectrum, cross-correlations analysis with macro-climatic indices, and (*vi*) simulation of rainfall-runoff processes using a hydrologic distributed model. The most relevant features of HidroSIG are described in terms of the methods used for hydrologic estimations, visualization capabilities, tools for analysis and interpolation of hydro-climatic variables in space and time, geomorphologic analysis and estimation from DEMs, and other features. Water resources planning and management and diverse socio-economic sectors benefit from this freely available database and computational tool.

1. Introduction

Colombia exhibits a wide variety of climates and ecological environments, ranging from mountains and rainforests through savannas, deserts and tropical glaciers. The country exhibits complex hydro-climatological features not only due to its tropical setting, but also due to: (*i*) topographic gradients of the three branches of the Andean mountains crossing from southwest to northeast, (*ii*) hydro-climatic and ecological dynamics of the Amazon and Orinoco River basins, (*iii*) atmospheric circulation patterns over the neighboring tropical Pacific and Atlantic oceans, and (*iv*) strong land-atmosphere feedbacks [*Poveda and Mesa*, 1997]. Water resources planning and environmental management in Colombia are challenged by such hydro-climatological complexity, amidst difficulties arising from: (*i*) lack of adequate information of relevant hydrologic variables in space and time, (*ii*) poor-quality, limited and costly data sets sold by the local hydro-meteorological service, (*iii*) lack of appropriate methodologies to predict hydrologic variables over a wide range of space-time scales in tropical environments, and (*iv*) prohibitive licensing costs of commercial geographical information systems. This situation is the rule throughout the developing world in general.

Development and application of Geographic Information System (GIS) into hydrological research and water resources planning and management constitute an exciting and fairly new field [*Maidment* , 2002]. Most commercial GIS packages are very costly in terms of license usage and/or exhibit low flexibility to accomplish certain required specific tasks. To overcome such difficulties, we have developed an in-house GIS, HidroSIG, containing an *Interactive Digital Hydro-climatic Atlas for Colombia*. HidroSIG is designed for calculating and visualizing fields of long-term average precipitation, actual and potential evapotranspiration, stream discharges (averages and extremes of different return periods), and many other hydro-climatic variables. It also is able to connect geo-spatial features to time series measurements recorded at gauging stations, to perform time series analysis of hydro-climatic records, and to estimate their interannual variability associated with El Niño/Southern Oscillation (ENSO), as well as other large-scale atmospheric phenomena. The work by *Poveda et al.* [2005b] provides a detailed account of the data sets and methods used to estimate and produce the maps of diverse hydro-climatologic fields for Colombia contained in HidroSIG.

The main contribution of this work is three-fold: (*i*) the HidroSIG system is one of the first open-source GIS software that includes an hydrological framework and can be made available for researchers and practitioners for further development under the GNU license, (*ii*) the application of the HidroGIS framework for the development of the interactive hydro-climatological atlas of Colombia that can be accessible to various research centers, public agencies and the general public, and (*iii*) the introduction of a new simple yet powerful method to estimate extreme river discharges (peak and low flows), that combines the long-term water balance equation with statistical scaling ideas.

This paper aims to introduce detailed aspects of HidroSIG and proceeds as follows. Section 2 describes data and estimation methodologies. Section 3 illustrates some results and products included in the atlas, as well as its capabilities and tools, and conclusions are drawn in the final section.

2. Data and Methods

HidroSIG was designed as a Geographical Information System (GIS, or SIG for *Sistema de Información Geográfica*, in Spanish) that allows visualization, handling and analysis of spatially distributed geophysical fields and variables, as well as time series analysis of hydrological records. HidroSIG uses an extensive hydro-climatological database from Colombia. More than 1,500 maps of topographic and geomorphological parameters, multiple hydrological, climatological, life zones, soils and land use maps, etc. Also, estimates of long-term average and extreme river flows (floods and low flows of different return periods) along the drainage network of the country, are available. In addition, HidroSIG contains information and time series of more than 7,500 gauging stations of diverse hydro-climatological variables.

HidroSIG has been developed in Java, and performs similarly to a Java Data Base Connection (JDBC), thus allowing exporting data to another databases without major code modifications. To maintain the free-ware character of the software, HidroSIG is mounted on *MySQL*® (http://www.mysql.com). The client-server disposition of HidroSIG allows that several users be working simultaneously on different types of operations, avoiding concurrence problems.

2.1. Digital elevation model and river network extraction

We have used the relevant region of GTOPO30, a Digital Elevation Map (DEM) developed by the U.S. Geological Survey, which provides regularly spaced elevations at 30-arc seconds ($\approx$ 1 km). Extraction of river networks and drainage basins from DEMs demands high algorithmic efficiency [*Band*, 1986; *Garbrecht and Martz*, 1994]. We used the steepest descent method to extract river networks from the topographic DEM, and defined a direction matrix that identifies the path of stream channels over terrain. Quality-control procedures were applied with the purpose of: (*i*) checking for quality of the DEM itself, (*ii*) checking for consistency with drainage networks at finer spatial resolutions; (*iii*) accounting for geologic controls; (*iv*) eliminating errors; and (*v*) resolving the appearance of spurious sinks or sources within the DEM, especially on low-slope terrains and flood plains. HidroSIG contains modules to estimate and display geomorphological information and parameters from DEMs, including extraction and ordering of stream channel networks according to the Strahler-Horton scheme, identification of river basin divides and areas, estimation of Horton ratios, topological and geometrical width functions, magnitudes, channel lengths and slopes, hypsometric curve, aspect maps, etc. Details of the procedures developed to extract the river network and quality-control procedures may be found in *Ramírez and Vélez* [2002].

2.2. Long-term annual precipitation

The long-term annual precipitation map for Colombia was developed using point data from more than 600 raingauges, mostly located in central and northwestern

Colombia, and complemented with rainfall data from neighboring countries and previous studies of rainfall in Colombia. Kriging [*Bras and Rodríguez-Iturbe*, 1984] was applied to interpolate point data on a regular 5-arcmin grid, using topography as an auxiliary variable (drift), with the purpose of incorporating the strong orographic effects of the Andes on local precipitation. Details of data sets the resulting precipitation map are discussed in *Poveda et al.* [2005b].

2.3. Long-term annual actual and potential evapotranspiration

Long-term actual and potential evaporation were estimated using the well known methods introduced by *Turc* [1955], *Turc* [1962], *Coutagne* [1954], *Thornwaite* [1948], *Holdridge* [1978], *Meyer* [1942], *Penman* [1948], *Budyko* [1974], *Morton* [1983], and *Cenicafé* [*Chaves and Jaramillo*, 1998]. Details of the data used and the resulting actual and potential evapotranspiration maps are shown in *Poveda et al.* [2005b].

2.4. Long-term mean river discharges

Long-term annual average river discharges were estimated for the entire river network of Colombia, using the water balance equation on drainage basins, given as [*Manabe*, 1969; *Schaake*, 1990],

$$\frac{dS(t)}{dt} = P(t) - E(t) - R(t) \;, \tag{1}$$

where $S(t)$ represents soil and ground water storage as a function of time, $P(t)$ and $E(t)$ represent basin-integrated precipitation and actual evapotranspiration rates, and $R(t)$ represents the total net runoff leaving the basin. Total runoff $R(t)$ includes the discharge at the basin outlet and the net integrated lateral subsurface runoff. Integrating equation (1) over long time scales gives $\overline{R} = \overline{P} - \overline{E}$. Thus, estimation of mean annual runoff requires basin-integrated estimates of precipitation and actual evapotranspiration. To simplify notation and due to ergodicity, one can replace time averages for expected values. Therefore, over bars will be dropped hereafter. The equation $Q = A[P - E]$ is taken as the methodological basis of our study, through integration of P and E over the spatial domain extracted by HidroSIG, and therefore Q is estimated as,

$$Q \cong \sum_{i,j \in A} (P_{i,j} - E_{i,j})\, \Delta_{i,j}, \tag{2}$$

where $\Delta_{i,j}$ denotes the area of the (i, j)-th pixel in the DEM. For validation purposes, discharge records from more than 200 river gauging stations throughout Colombia were systematically compared with estimations from the long-term water balance equation, using all the aforementioned evapotranspiration methods. Details of the data used and the resulting river flows maps are discussed in *Poveda et al.* [2005b].

2.5. Estimation of floods and low flows

Our methodological approach to estimate peak flows for different return periods was based on the classical quantile analysis in combination with scaling ideas. Statistical parameters of annual floods were estimated using the mean annual flow field as a scaling parameter. Thus, annual floods $Q_{max}(T_r)$, were estimated for a given return period ($T_r = 1/p$, the inverse of the exceedance probability), as [*Chow*, 1951],

$$Q_{max}(T_r) = \mu_{Q_{max}} + k(T_r, \gamma)\sigma_{Q_{max}}, \tag{3}$$

where $\mu_{Q_{max}}$, and $\sigma_{Q_{max}}$ are the mean and standard deviation of annual floods, and $k(T_r, \gamma)$ is the frequency factor, which is a function of the return period and possibly of other parameters that are generically represented in γ. For different probability distribution functions (PDF) assigned to annual floods, the functional form of k is different [*Chow*, 1951, 1964]. We chose the lognormal distribution, which is a particular case of the family of Log-Stable distributions whose structure is consistent with the theory of multi-scaling [*Zolotarev*, 1986]. The frequency factor for the lognormal distribution may be found in *Chow* [1964, p. 8-25].

As a fundamental assumption of this work, we used a power law to relate the statistical parameters of annual floods of different river basins with their mean annual flows, Q, expressed in terms of the long-term water balance equation as,

$$\mu_{Q_{max}} = \alpha_\mu Q^{\theta_1} = \alpha_\mu [A(P - E)]^{\theta_1}, \tag{4}$$

$$\sigma_{Q_{max}} = \alpha_\sigma Q^{\theta_2} = \alpha_\sigma [A(P - E)]^{\theta_2}. \tag{5}$$

where the *pre-factors* α_μ and α_σ, and the *scaling exponents* θ_1 and θ_2, are fitted from observed data. The rationale for using the mean flow as the scaling parameter for the distribution of floods may be appreciated from equations (4) and (5). Basin area alone does not represent the scale of the phenomena in view of the climatic differences, represented by P and E. Using information of more than 200 river gauging stations, we estimated pretty stable scaling exponents of $\theta_1 = 0.82$ and θ_2=0.648. See detailed results in *Poveda et al.* [2005b].

3. Results

3.1. Geomorphological and hydrological estimates and visualization

HidroSIG was developed for our research in Colombia, but a data import module allows the user to cast climatological data and DEMs from usual formats into an HidroSIG database and use any estimation tool. It possesses special tools to estimate and analyze hydro-climatological variables and time series. The software allows an interactive visualization of raster, at-station, and vector information contained in a large server-client database. HidroSIG utilizes the VisAD Java Library to generate and handle graphical objects. This library consists of a set of classes that provide interactive visualization of numerical data. Complete information on VisAD and its applications can be found at http://www.ssec.wisc.edu/ billh/visad.html. HidroSIG's main interface allows the simultaneous visualization and usage of several two or three-dimensional maps at any spatial resolution, in combination with VisAD. Visualization of the maps can be modified interactively through zooming, rotations, and movements of maps. Color palettes can be interactively adjusted. All information associated with every map and the corresponding data at-a-station are available at the "click" of the mouse. The user can estimate distances and visualize spatial gradients of any variable through any transect. Figure 1 shows the display of HidroSIG with the topography of Colombia and details of topographic analysis, including aspects map and 3-D rotation. **Figure 1.**

Figure 2 displays an example of HidroSIG's extraction of a river basin and its channel network, as well as results of estimations of relevant geomorphological and hydrological parameters, including the topological width function and the hypsometric curve of the Magdalena River basin near its mouth to the Caribbean Sea. **Figure 2.**

Figure 3 shows average monthly rainfall maps for the twelve calendar months over Colombia (left), and the annual cycles of precipitation (figure and table) at some chosen site (right hand panels). **Figure 3.**

3.2. Analysis tools

3.2.1. Analysis of hydro-climatic variables. Most calculations performed by HidroSIG rely on the spatial coverage of gauging stations. The user can analyze and store results of the space-time distribution of an unlimited number of hydro-climatic variables. Such information can contain spatially distributed fields (raster formatted maps), and time series of data at-a-station. Figure 4 shows an example of box plots for the annual cycle of river discharges at El Cangrejo River in central Colombia, a result which comes up by just clicking at the desired site or gauging station along the channel network. **Figure 4.** Results from the long term and monthly water balance are shown at any desired site along the drainage channel network of Colombia. Figure 5 shows results for mean monthly river discharges of the Atrato River at a station close to the Caribbean Sea, estimated through the water balance equation. Animations within the software allow visualization of dynamical maps, with access to data from each grid point over the map. **Figure 5.**

3.2.2. Interpolation. HidroSIG contains a module to implement diverse interpolation techniques, including Kriging, and other algorithms based on neural networks, linear triangulation, and a combination of both. Some of the methodologies rely on auxiliary support variables to improve interpolation performance. Interpolation methods allow regionalization of interpolating variables, as is the case of adaptive neural networks, and triangulation with topographic drift [*Vélez et al.*, 2002b]. The interpolation module is highly interactive, as the user can provide point-data, as well as any kind of auxiliary variables and supporting information. Additionally, the user can define values of any parameters required by the selected interpolation technique. The software also allows to visualize results in order to detect possible erroneous basic information and possible interpolation problems. The final result is a raster file that can be visualized by HidroSIG (Figure 6). **Figure 6.**

3.2.3. Map Calculator. HidroSIG incorporates a map calculator to perform arithmetic, statistical and logic operations between raster maps. The map calculator is useful in developing descriptive statistical analysis on maps and in generating new fields from indices estimated with the basic hydro-climatological databases. It is worth noting that all types of analysis performed by HidroSIG are totally independent from map scale and resolution. In such a manner, integration of variables or operations performed using the map calculator can be performed on maps having different sizes and spatial resolutions.

HidroSIG includes diverse modules to import maps and vectorial files in standard formats, thus making it compatible with most commercial GIS. It allows the user to create their own raster variables from maps originally developed in *Idrisi*® format and from *DXFAutocad*® vectorial files. This feature increases the amount of information that can be analyzed with the software. Figure 7 shows a display of Budyko's aridity index, defined as the ratio between mean annual potential evapotranspiration and mean annual rainfall, over Colombia.

Figure 7.

3.2.4. Temporal analysis. In addition to diverse spatial types of analysis, HidroSIG has a complete module to perform time series analysis, and to deploy temporal information from gauging stations at diverse timescales, including daily, monthly, annual, and interannual timescales. It deploys time series of hydro-climatic variables by choosing the gauging station from a list of diverse variables including river discharges, rainfall, temperature, radiation, etc. Gauging stations are selected either by code number, name, geographic coordinates, or by selecting them from the maps themselves. HidroSIG allows to deploy time series at desired time resolutions, to estimate the annual cycle (box plots), to estimate and show graphical results of standardized monthly records, to estimate the Fourier power spectrum, and the autocorrelation function of any time series. Also, the software performs and shows graphical lagged cross-correlation analysis between any standardized hydro-climatic variable with diverse macro-climatic indices such as the Southern Oscillation Index (SOI) and others, with the purpose of quantifying their statistical association at interannual timescales.

Additionally, HidroSIG contains a module that runs a hydrological distributed model including land surface-atmosphere interaction processes, which are described in *Vélez et al.* [2002a]. The model simulates the water balance at daily and monthly timescales at any site along the drainage network. For instance, Figure 8 compares the annual cycle of simulated (red bars) and observed (black bars) river discharges for the

Canteras, Monteria and Rionegrito Rivers, using such a distributed hydrological model. Results show a good performance of the model in simulating monthly river discharges. **Figure 8.**

A recent development of HidroSIG by one of the co-authors (coined as *Cuencas*) contains a module to estimate peak flows resulting from intense storms, through rainfall-runoff routing on hills and channels in real and virtual basins [*Mantilla and Gupta*, 2005].

4. Conclusions

We have developed HidroSIG, as an interactive hydro-climatological atlas of Colombia. The maps incorporate dominant climatic, geographic and topographic controls. Estimations of main hydro-climatological fields (precipitation, actual and potential evapotranspiration, radiation, etc.), are based upon interpolation of point data using Kriging with topography as an auxiliary interpolating variable. Estimation of river discharges are based on the long-term water balance equation, and extreme river flows for diverse return periods are estimated through the traditional quantile analysis in combination with statistical scaling, with the average flow field as the scaling parameter. Estimation of water and energy balances can be performed and obtained at the click of the mouse. HidroSIG has diverse modules for detailed geomorphological analysis from DEMs, including extraction of river basins and channel networks, and estimation of geomorphological parameters of hydrological relevance.

HidroSIG contains modules for visualization of in-situ data and distributed fields, as well as modules for time series analysis of hydrological records. It implements highly interactive procedures for interpolation of distributed fields from point data using diverse methods. It also contains a map calculator that allows manipulation and estimation among diverse maps and fields.

The newly created data sets and the software are available for the scientific community and the general public. Currently, the Ministry of Mining and Energy of Colombia is using HidroSIG to re-asses the hydropower generation capacity of the country, by estimating average river discharges in selected sites. Several regional public environmental agencies in Colombia are using HidroSIG for diverse tasks of water resources planning and management.

Due to the programming language used for its development, HidroSIG is a multi-platform application and freely distributed under GNU license (http://www.gnu.org). It requires at least 800 MB of hard disk storage and between 256 MB and 512 MB of RAM memory. Detailed information can be found in http://cancerbero.unalmed.edu.co/∼hidrosig/index.php.

Acknowledgments. This work has been supported by UPME from the Ministry of Mining and Energy of Colombia, by COLCIENCIAS, and by DIME of Universidad Nacional de Colombia at Medellin. We thank the two anonymous reviewers for helpful comments.

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Received ________________________

This manuscript was prepared with AGU's LaTeX macros v5, with the extension package 'AGU++' by P. W. Daly, version 1.6b from 1999/08/19.

Figure Captions

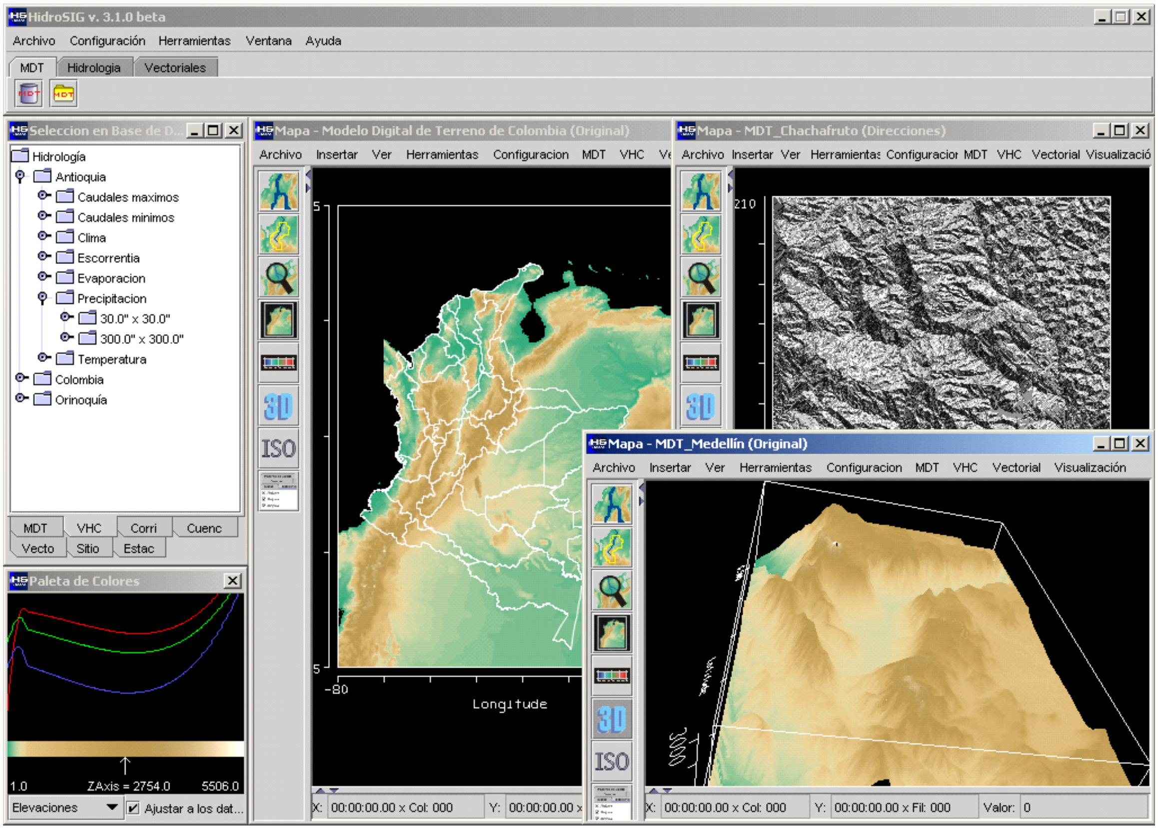

Figure 1. HidroSIG's display of diverse topographic analysis, including the Colombian topography (left), aspect map of the Chachafruto River basin in central Colombia (top right), and a 3-D rotation of the Medellin River valley topography (top bottom).

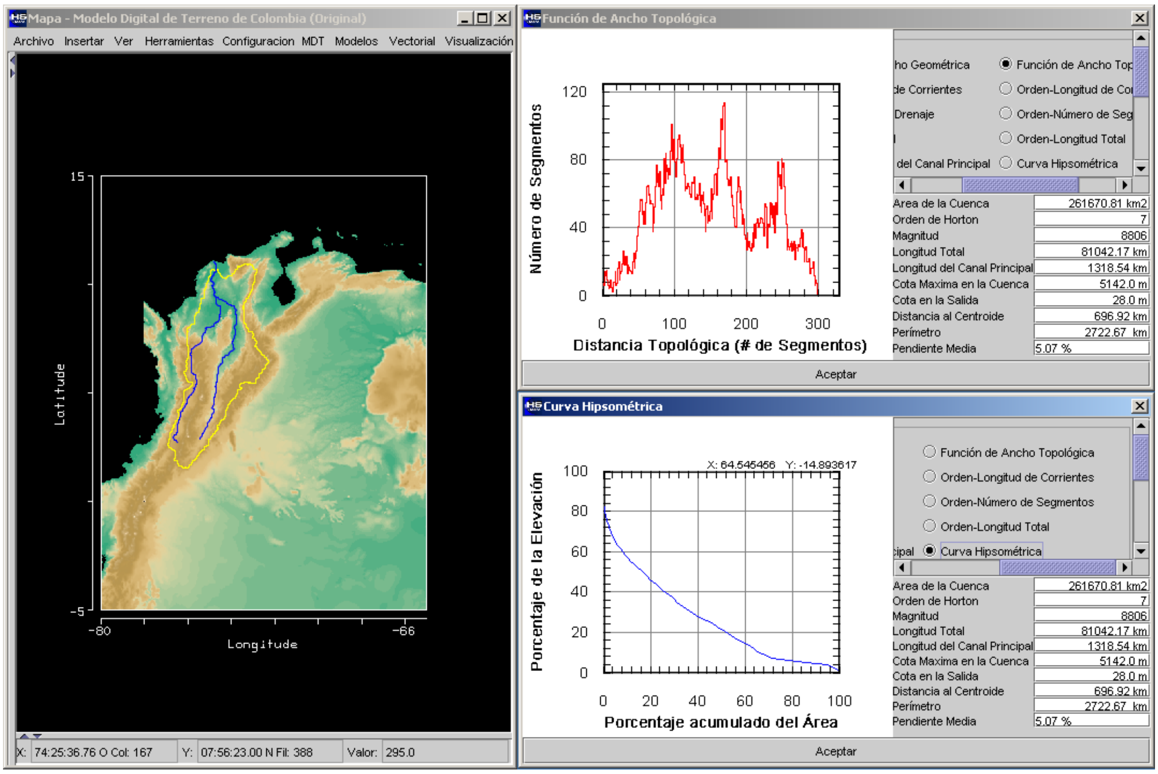

Figure 2. Example of basin extraction for the Magdalena River at a point nearby its mouth at the Caribbean Sea. The right hand panels show the topological width function (top), and the hypsometric curve (bottom) for the corresponding channel network, along with results of diverse geomorphological parameters.

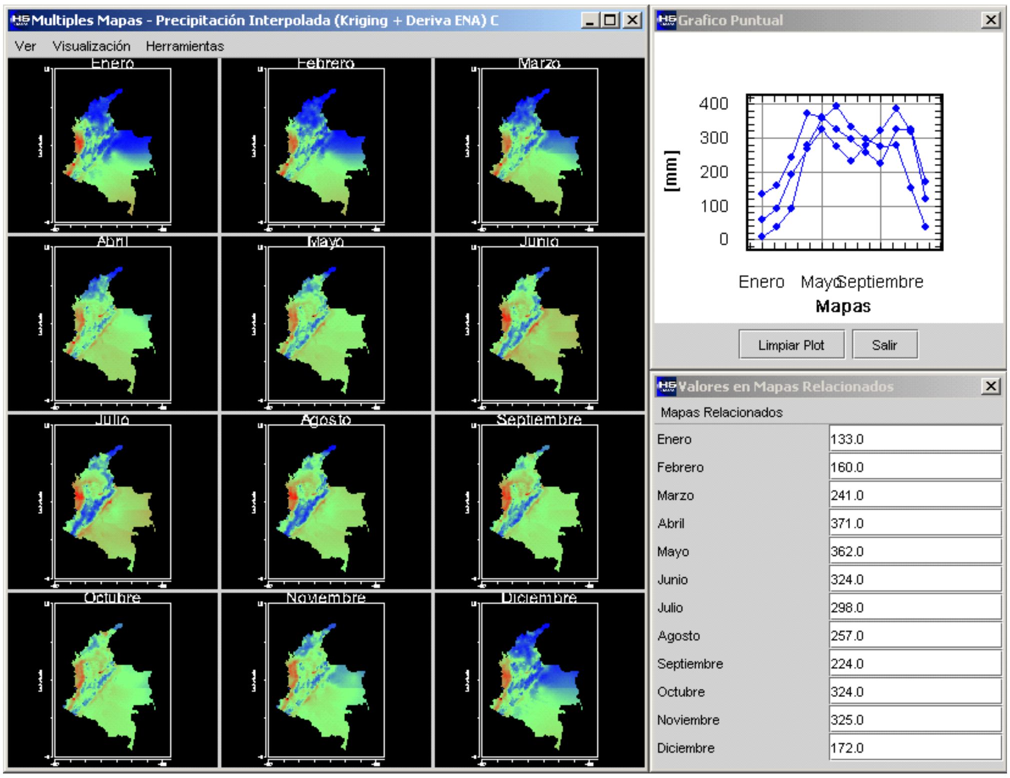

Figure 3. HydroSIG's display of the twelve maps of average monthly precipitation over Colombia. Data on monthly precipitation at selected sites are given on the right hand panels, both in graphical and tabular formats.

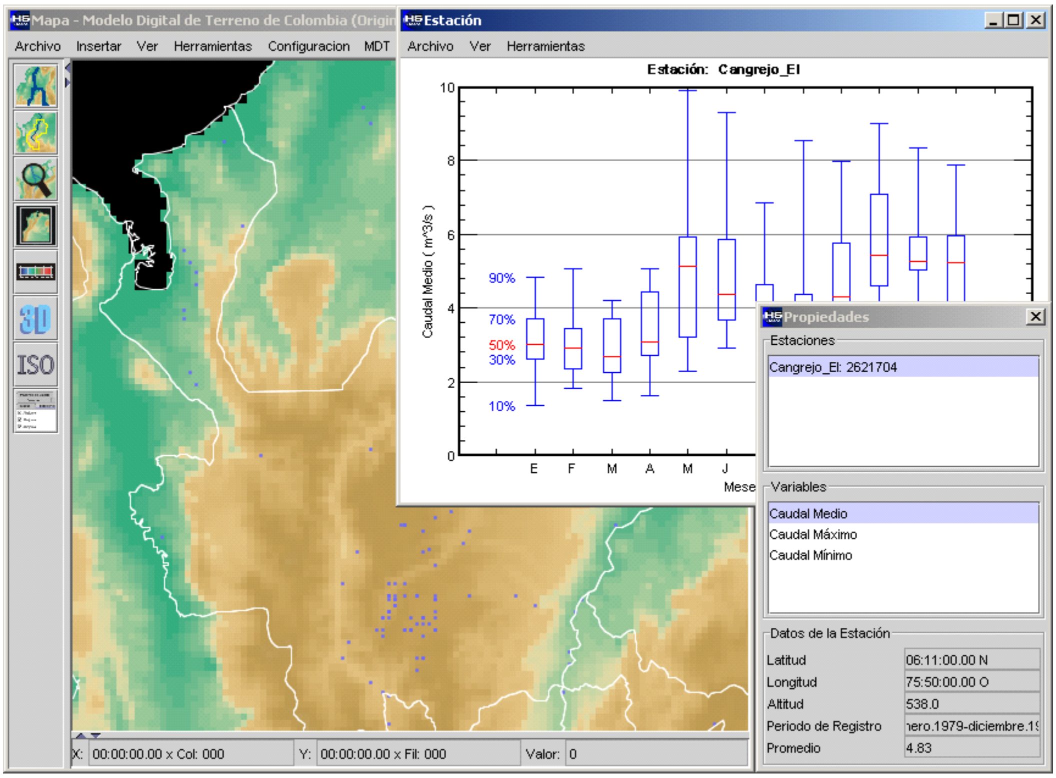

Figure 4. Time series data and report interface depicting box-plots of monthly probability distribution functions corresponding to El Cangrejo River in central Colombia.

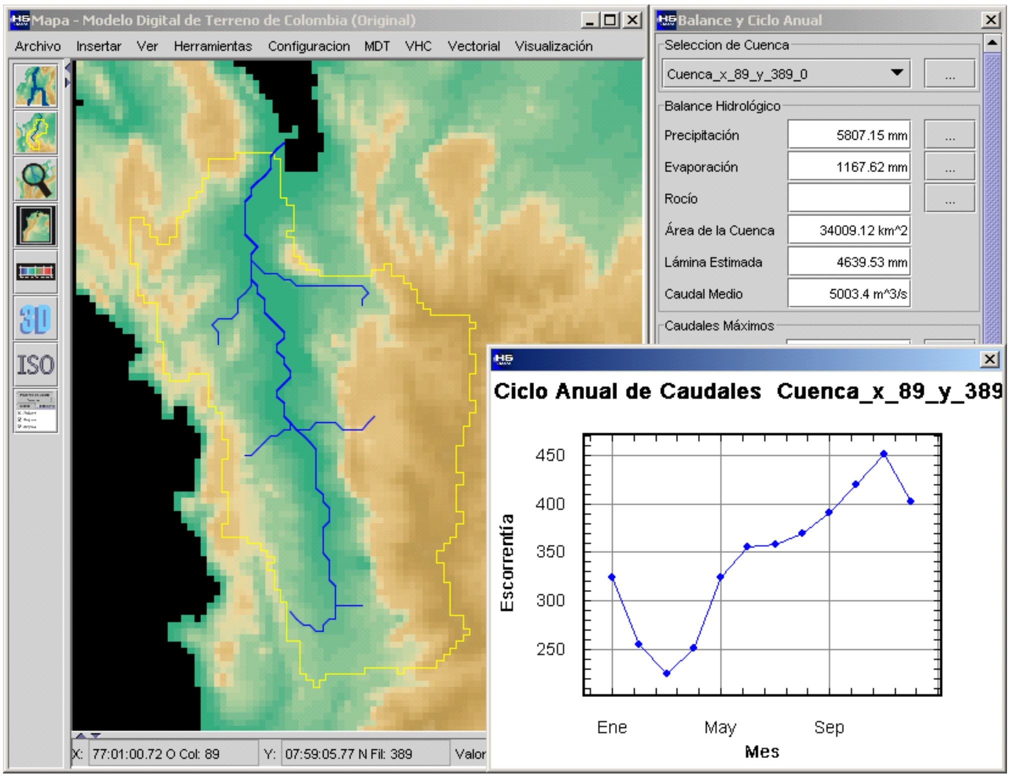

Figure 5. Annual cycle of river flows of the Atrato River along the Pacific coast of Colombia, depicting the main channel and major tributaries (left), the annual cycle of river discharges (bottom right), and estimates of the long-term water balance for the river basin, including mean annual precipitation, mean annual actual evapotranspiration, river basin area, mean annual river runoff and discharge (top right).

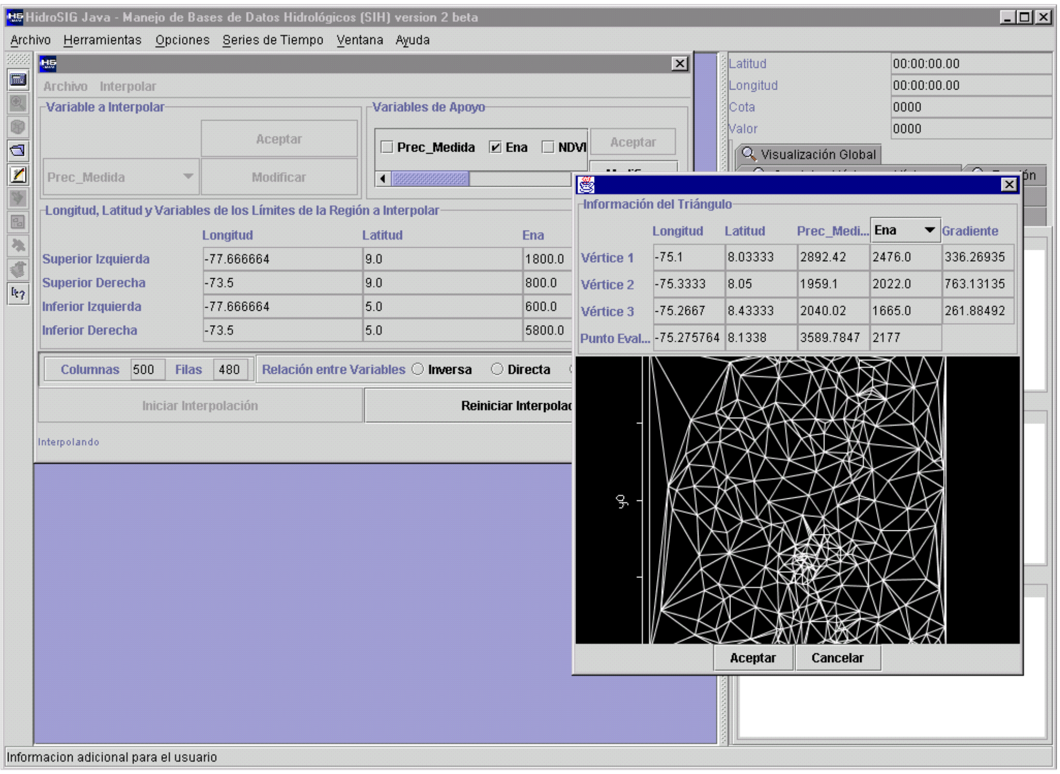

Figure 6. Interactive triangulation interface.

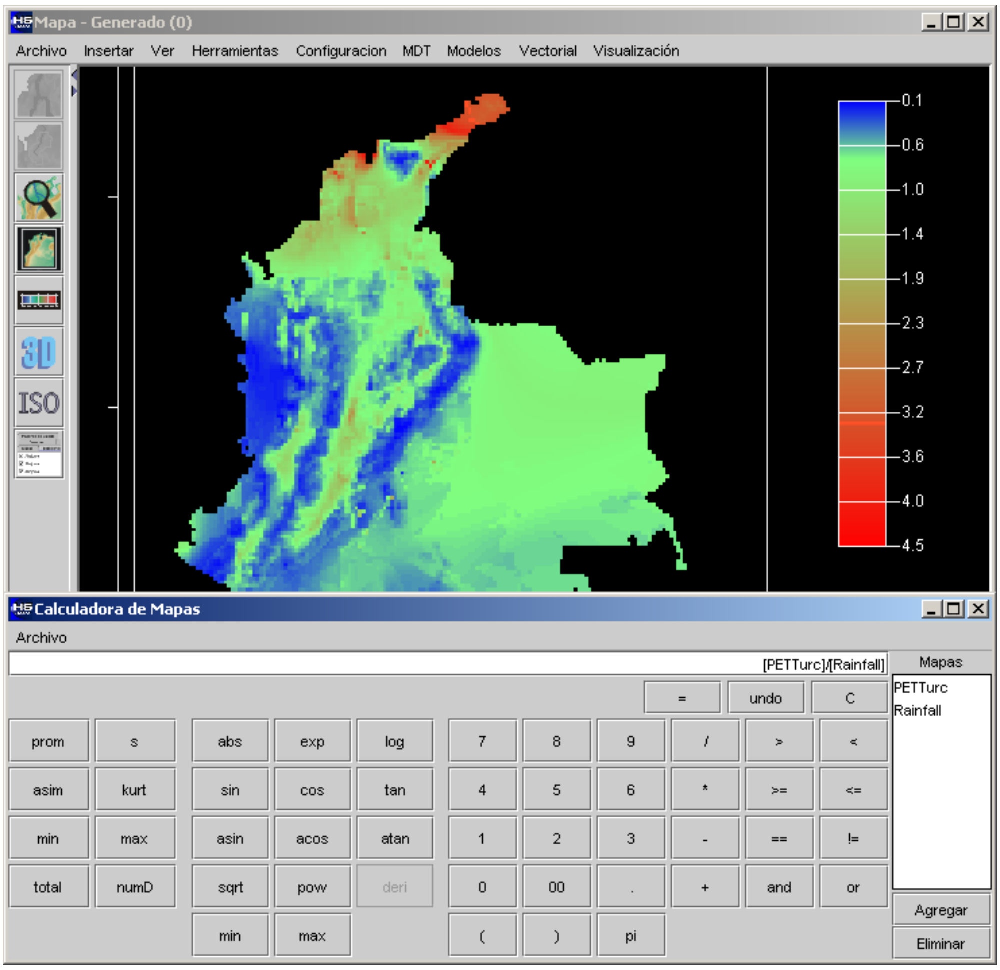

Figure 7. Map calculator showing Budykos's aridity index, defined as the ratio between mean annual potential evapotranspiration and mean annual rainfall, over Colombia.

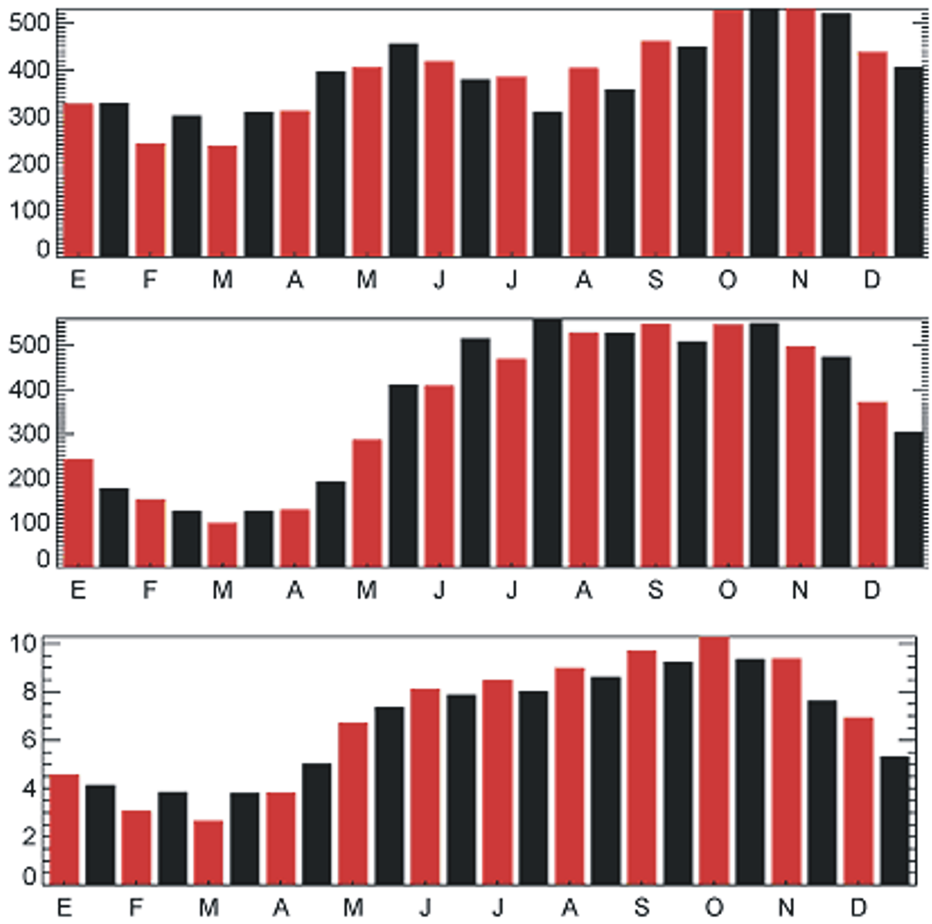

Figure 8. Comparison of simulated (red bars) and observed (black bars) annual cycles of river discharges for the Canteras, Monteria and Rionegrito Rivers.