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

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Short title:

Abstract. An interactive digital hydro-climatologic atlas of Colombia, HidroSIG, has been developed containing distributed maps and time series of monthly and long-term average precipitation, actual and potential evapotranspiration, and river flows, as well as temperature, humidity, radiation, land use, life zones and many other 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 allows diverse hydrological and geomorphological estimations including: (*i*) extraction and estimation of geomorphological parameters of drainage channel networks and river basins from Digital Elevation Maps (DEM), (*ii*) estimation of the long term and monthly water balances and multiple hydro-climatic variables in river basins, (*iii*) estimation of extreme flows (floods and low flows) of different return periods at any site along the river network of Colombia, and (*iv*) interpolation of geophysical fields using Kriging with drift, adaptive neural networks, and triangulation with topographic drift. All results are readily available merely by 'clicking' on the requisite point. Here we describe the most relevant features of HidroSIG in terms of the methods employed 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, as well as diverse applications in hydropower, agriculture, human health, ecology and other environmental and socio-economic sectors benefit from this freely available data base and computational tool.

1. Introduction

Colombia is located in northwestern tropical South America, exhibiting a wide variety of climates and ecological environments, ranging from mountain and rainforests through savannas, tropical glaciers, and deserts. 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 local hydro-meteorological services, (*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.

With the purpose of overcoming these limitations for water resources planning and management, we have developed in-house HidroSIG, as a Geographic Information System 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, river flows (mean and extreme), and many other hydro-climatic variables. 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.

This paper aims to introduce detailed aspects of HidroSIG, proceeding 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 uses an extensive hydro-climatological data base from Colombia. More than 1,500 maps of topographic and geopmorphological parameters, multiples hydrological and climatological maps, life zones, soils and land use, 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 in a similar fashion to a Java Data Base Connection (JDBC), thus allowing exporting data to other data bases, without major code modifications. To maintain free-ware character of the software, HidroSIG is mounted on $MySQL^{®}$ (http://www.mysql.com). The client-server disposition of HidroSIG allows several users to be working simultaneously on different types of operations, avoiding concurrence issues.

2.1. Digital elevation model and river network extraction

We have used GTOPO30, a Digital Elevation Map (DEM) developed by the U.S. Geological Survey, for Colombia and neighboring countries, which provides regularly spaced elevations at 30-arc seconds (≈ 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 performed with the purpose of: checking for quality of the DEM itself; for consistency with drainage networks at finer spatial resolutions; to accounting for geologic controls; to eliminating errors; and to resolving the presence 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, located mostly in central and northwestern Colombia, and complemented with data from neighboring countries and previous studies regarding rainfall in Colombia. Kriging [*Bras and Rodríguez-Iturbe*, 1984] was used to interpolate point data on a regular 5-arcmin grid, with topography as an auxiliary variable (drift), with the purpose of incorporating the strong orographic effects of the Andes on local precipitation. Details of the data used and 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 flows

Long-term river flows were estimated for the entire river network of Colombia, using the water balance equation of a drainage basin, given by [*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 runoff leaving the basin. Total runoff $R(t)$ includes the streamflow at the basin outlet and the net integrated lateral subsurface runoff. Integrating equation (1) over long time scales gives, $\overline{R} = \overline{P} - \overline{E}$. Therefore, 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 the study, through integration of P and E over the spatial domain extracted by HidroSIG, and estimated as

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

For validation purposes, we used records from more than 200 river gaging stations throughout Colombia, and systematically compared with estimations from the long-term water balance equation, using all aforementioned evapotranspiration methods. Details of the data used and the resulting river flows map 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 [*Chow*, 1951, 1964], in combination with scaling theories to estimate statistics of annual floods in terms of mean annual flows. See details in *Poveda et al.* [2005b].

3. Results

3.1. Geomorphological and Hydrological Estimates and Visualization

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. The software was developed for our research in Colombia, but any user will be able to work with their own DEMs and data bases. 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 modelled 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 a display of HidroSIG depicting the topography of Colombia and two details of topographic analysis (aspect map, and 3-D rotation). **Figure 1.**

Figure 2 displays an example of HidroSIG's extraction of a river basin and channel network and estimated parameters of geomorphological and hydrological relevance, including the topological width function and 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 estimations developed 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 be both 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 flows 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 nearby to the Caribbean Sea, estimated through the water balance equation. **Figure 5.** Animations allow visualization of dynamical maps, with access to data corresponding to each grid point over the map. HidroSIG contains diverse tools for statistical analysis of time series, including autocorrelation function, Fourier power spectra, and correlation analysis between hydro-climatological variables and time series of macro-climatic phenomena such as ENSO.

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 [*Velez et al.*, 2002]. The interpolation module is highly interactive, and the user can provide point-data, as well as any kind of auxiliary variables and supporting information, at will. Additionally, the user can define values of any parameters required by the interpolation techniques. The software also allows the user to visualize triangulation 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 among maps and normal numerical values. Such calculator is useful in developing descriptive statistical analysis on maps and in generating new fields from indices estimated with the basic hydro-climatological data bases. 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.

With the purpose of making HidroSIG compatible with commercial geographic information systems, it includes diverse modules to import maps and vectorial files in standard formats. HidroSIG allows the users to create their own raster variables from maps originally developed in $Idrisi^{\circledR}$ format and from $DXFAutocad^{\circledR}$ vectorial files. This feature increases the amount of information the user is able to analyze 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.**

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.), were based upon interpolation of point data using Kriging with topography as an auxiliary interpolating variable. Estimation of river flows were based on the long-term water balance equation, and extreme river flows for diverse return periods used the traditional quantile analysis in combination with statistical scaling, with average flows as a scaling parameter. Estimation of water and energy balances can be performed and obtained at the click of the mouse. HidroSIG has diverse modules including 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 also contains modules to implement diverse interpolation algorithms to produce distributed fields from point data, through highly interactive procedures. It also contains a map calculator that allows manipulation and estimation among diverse maps and fields. HidroSIG has been developed during the last 10 years, and constitutes the hydrological and computational basis for a recently developed tool to study hydrological processes in real and virtual basins [*Mantilla and Gupta*, 2005]. The newly created data set and the software are original contributions of this work, which are available for the scientific community. Due to the programming language used for its development, HidroSIG is a multi-platform application and it is 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.

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Figure Captions

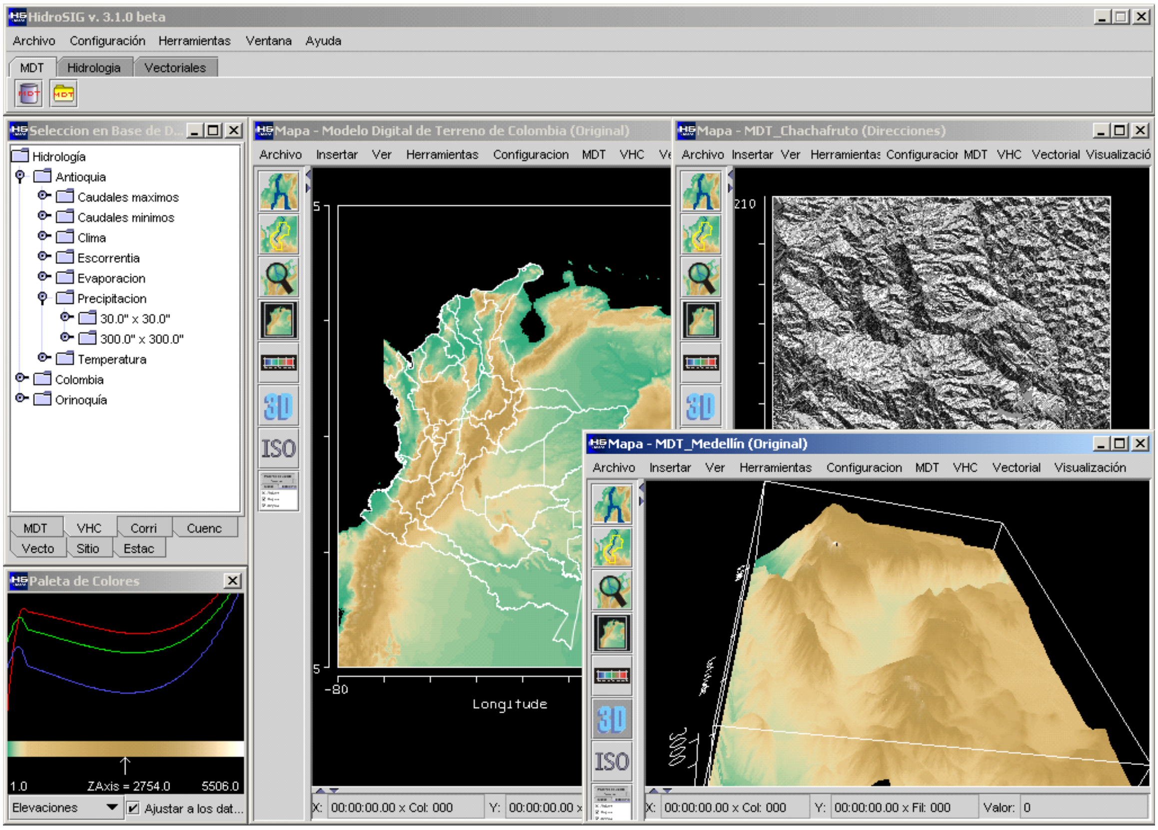

Figure 1. HidroSIG's display of diverse topographic analysis, including the Colombian topography (left), aspect map of the Chachafruto River basin in central Colombia (top right), and a 3-D rotation of the Medellin River valley topography (top bottom).

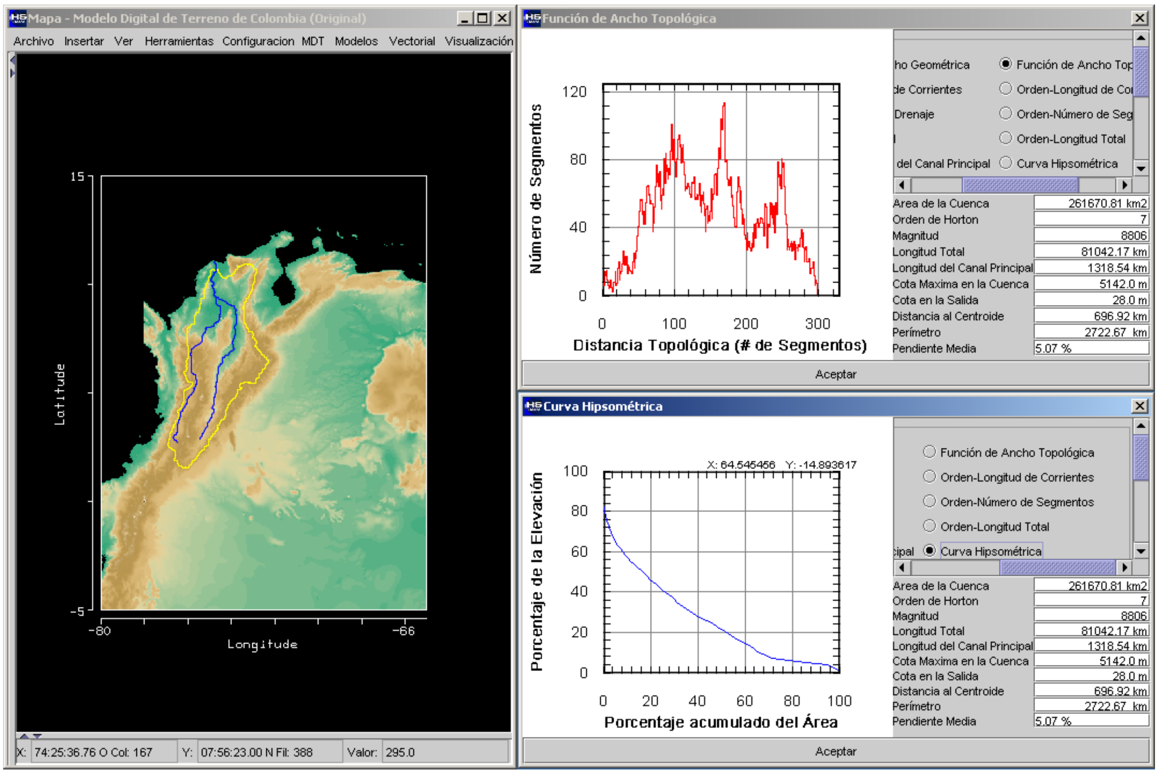

Figure 2. Example of basin extraction for the Magdalena River at a point nearby its mouth at the Caribbean Sea. The right hand panels show the topological width function (top), and the hypsometric curve (bottom) for the corresponding drainage channel network, along with results of diverse geomorphological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

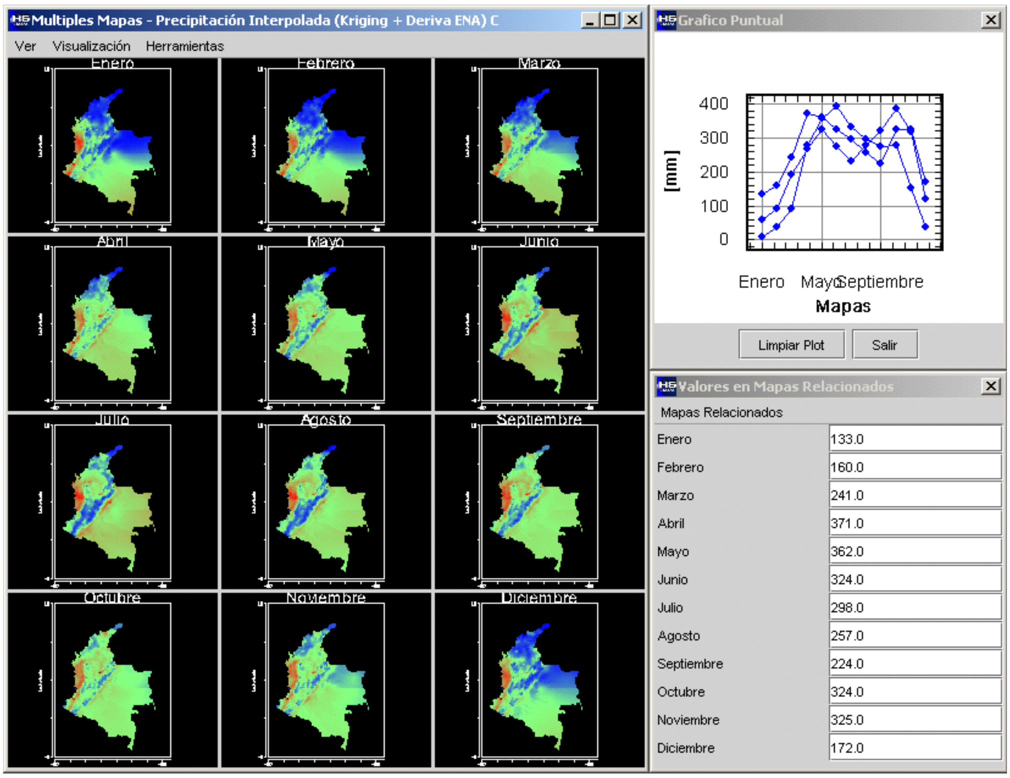

Figure 3. HydroSIG's display of the twelve maps of monthly mean precipitation for Colombia. Information of monthly precipitation at selected sites both in graphical and tabular formats are given on the right hand panels.

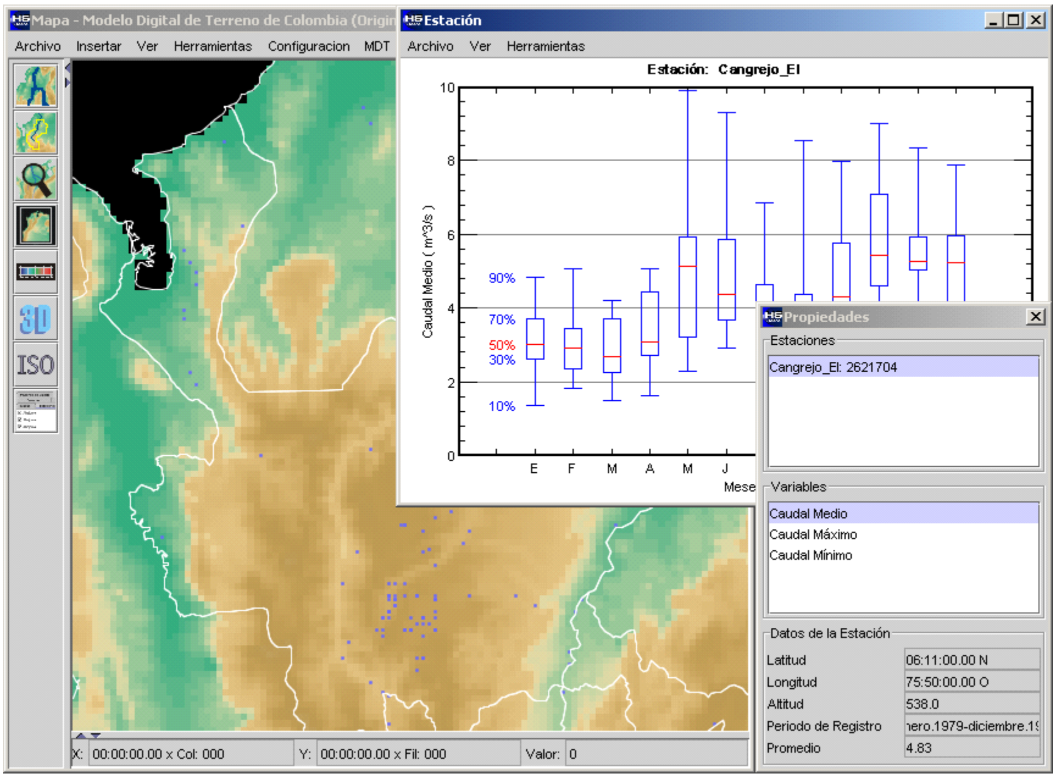

Figure 4. Time series data and reports interface depicting box-plots of monthly probability distribution functions corresponding to El Cangrejo River in central Colombia.

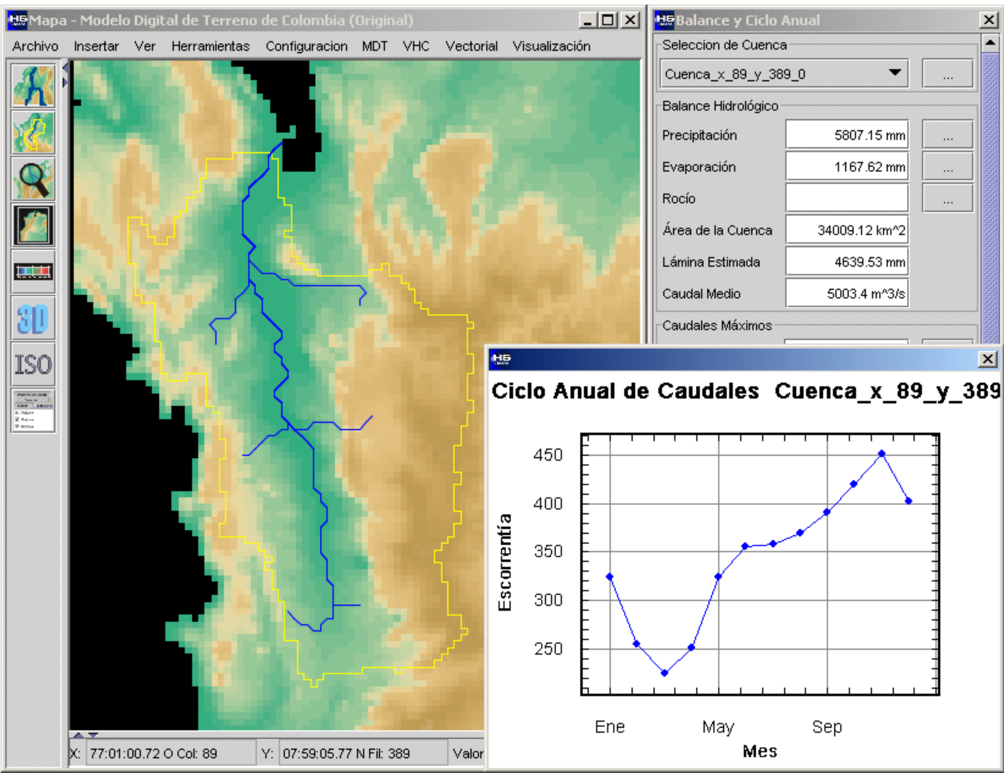

Figure 5. Annual cycle of river flows of the Atrato River along the Pacific coast of Colombia, depicting the main channel and major tributaries (left), the annual cycle of river discharges (bottom right), and estimates of the long-term water balance for the river basin, including mean annual precipitation,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

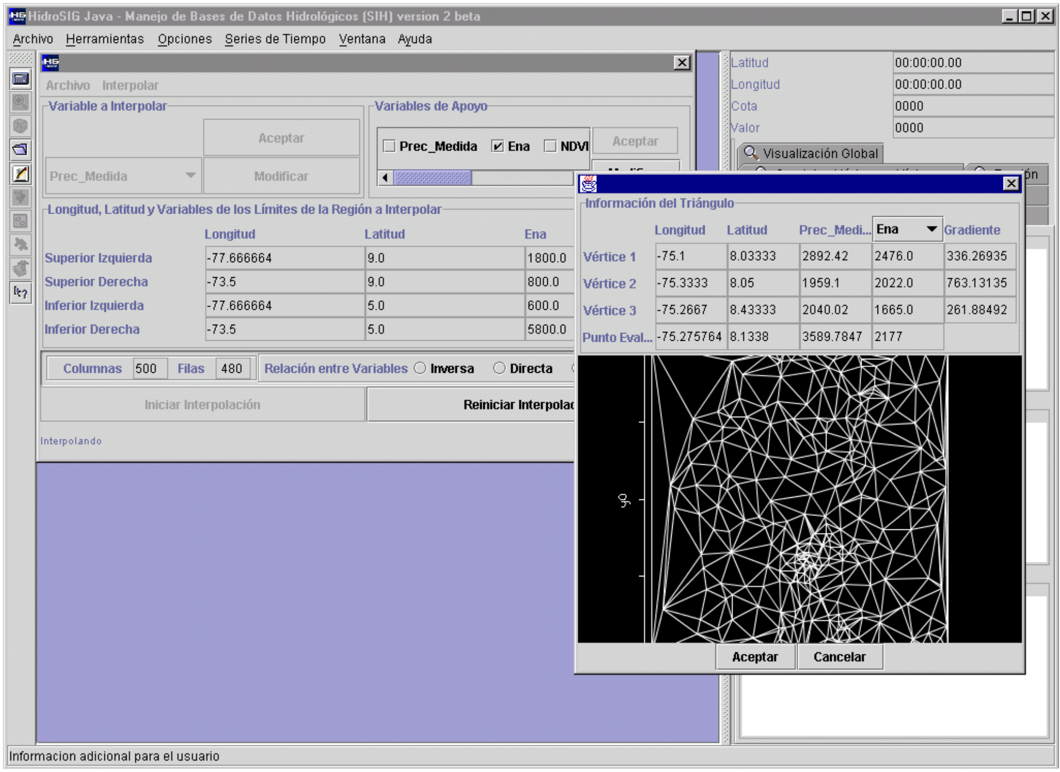

Figure 6. Interactive triangulation interface.

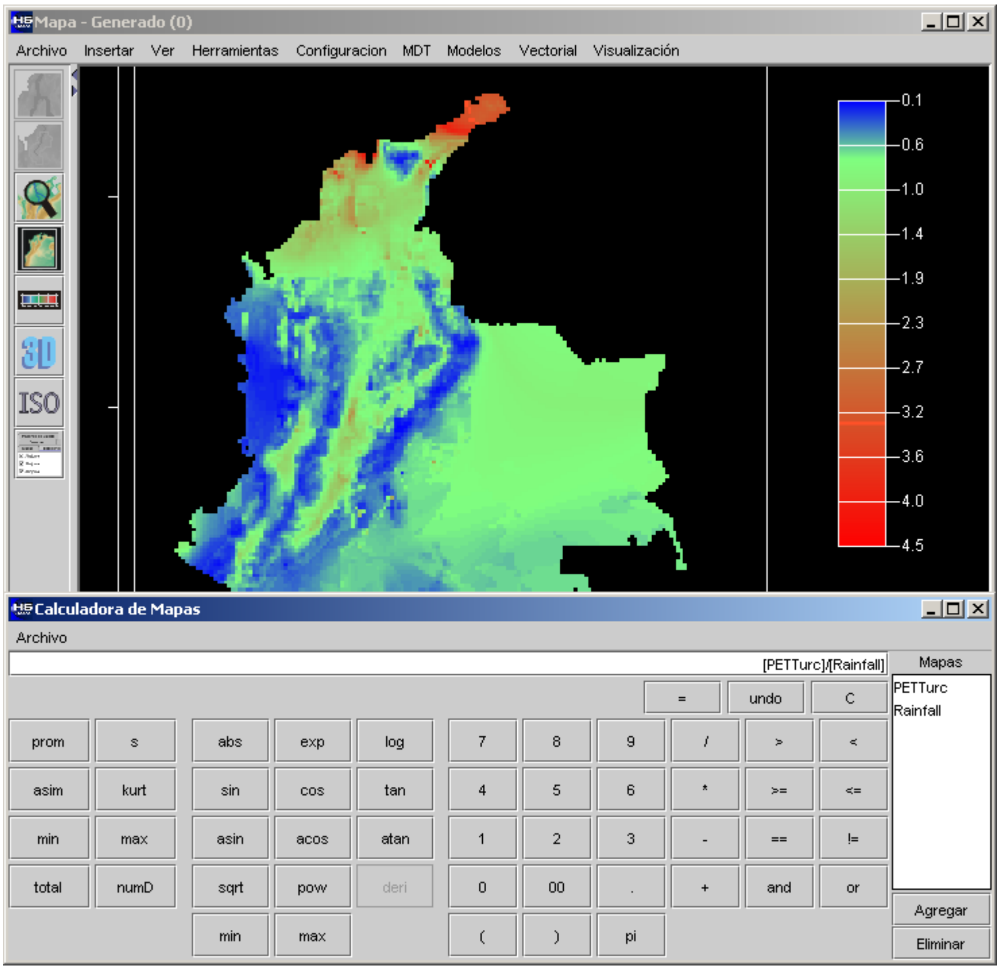

Figure 7. Map calculator showing Budykos's aridity index, defined as the ratio between mean annual potential evapotranspiration and mean annual rainfall, over Colombia.