

Technical Note

GRASS GIS-embedded Decision Support Framework for Flood Simulation and Forecasting

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Abstract

This study presents a spatiotemporal analysis tool, called *Shyska*. This tool allows the simulation and prediction of flash floods in semiarid basins. *Shyska* has been developed by Geographical Information System (GIS)-embedded functions, allowing the integration of hydrometeorological information from modern technologies of data acquisition in real time. A Digital Elevation Model (DEM) is used in order to obtain the relevant parameters from the integrated rainfall-runoff models. Some of its most relevant modules and methodology employed for its development are described. Case studies in basins of south-east Spain illustrate the applicability of the proposed techniques.

1 Introduction

The Spanish southeast is semiarid, and convective storms periodically produce flash flood situations. The Hydrological Information Automatic Systems (SAIH) in Spain are real-time hydrometeorological data collection networks and flood warning systems.

The coordinated integration of data provided by the SAIH with other sources of real-time information like those which are supplied by meteorological institutions (weather forecasts, radar and radar-satellite data, etc.), and local government agencies (civil protection, data showing areas at greatest risk), supply more support instruments for the taking of decisions with the aim of lessening the effects of flooding. In this case, efficient integration tools and methodologies and the presentation of information with a high degree of spatiotemporal resolution are necessary.

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In the Mediterranean basins, where flash flooding is usual, it is not enough merely to be supplied with real-time information integration and coordination between the responsible bodies. Because of the short length of time, which exists between the hydrograph peak and the associated rainfall, the warning of this type of event should be based on forecasting, both meteorological (quantitative rainfall forecasting) and hydrological. Forecasting models are needed in addition to the information integration techniques to enable the exploitation of the available spatiotemporal data for the presentation of precise and timely forecasts.

In these environments, we propose the use of a computational system named *Shyska* (García 2002a), whose characteristics will be analyzed. *Shyska* combines information from several data acquisition technologies (telemetric networks and remote sensing). This environment integrates spatially distributed and lumped topographically-based rainfall-runoff models.

2 *Shyska* System

2.1 Objectives

The *Shyska* computational system was conceived as a support tool for the taking of decisions in real time, which helps to plan strategies on a basin scale in the face of a flash flood event. The *Shyska* environment presents a structure based on the GRASS (Geographical Resources Analysis Support System) GIS, oriented to the forecasting and simulation of flows. It is made up of a series of modules, which allow the management and processing of hydrometeorological episodes in real-time coming from SAIH systems.

But the reasons which underlie the *Shyska* system go beyond the simulation and forecasting of flash flooding in real time. It is a powerful tool, which makes use of the latest technology for the treatment of information with a high spatiotemporal resolution, enabling studies of the hydrological characterization of basins, erosion and sedimentation modeling, as well as analyses of the hydrological effects of changes in land use, etc.

2.2 Overall design

The system core was developed with the Tcl/Tk language (Ousterhout 1994), using the Tix language (Lam 1995). The C language is used for the management and processing of time series and computationally intensive mathematical algorithms. Commands belonging to the GRASS GIS have been integrated, along with new spatial commands based on GIS libraries and encoded in the C language.

The *Shyska* computational system, with respect to its relationship with the GIS, is an example of an embedded integration. *Shyska* presents a modular structure. These modules are oriented to (Figure 1):

1. Data management,
2. Terrain analysis, and
3. Hydrological modeling.

Plate 17 shows an example of the system working under the Linux operating environment. The figure presents the main menu of the system, the data management submenu and inside, the selection widget for the graphic monitor and different visualizations.

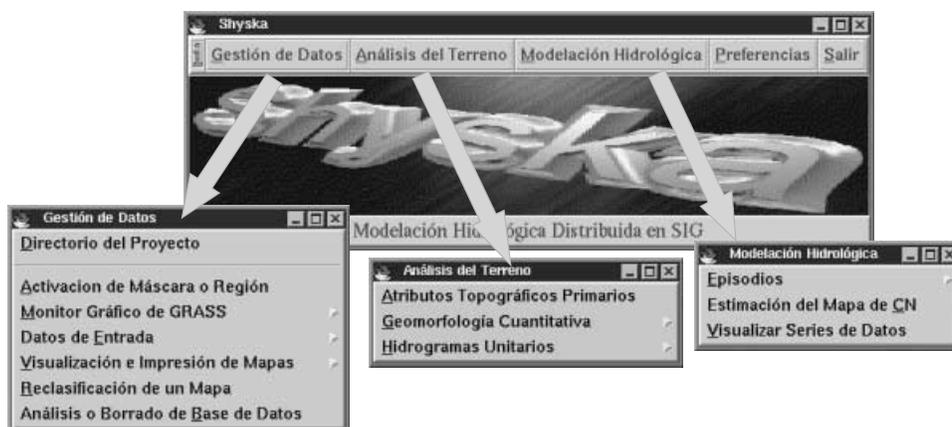


Figure 1 Shyska environment. Main menu and first level of menus

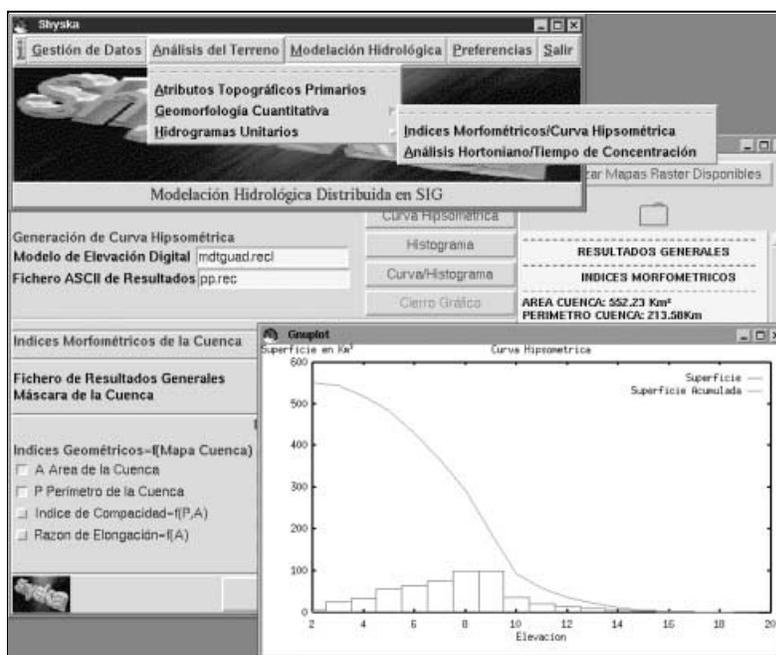


Figure 2 Estimation of morphometric indices and example of hypsometric curve estimated from DEM

Among its most relevant modules are those oriented to Digital Elevation Model (DEM) analysis. The drainage basin can be automatically extracted from one or more DEMs and morphometric characteristics estimated (Figure 2). Among the characteristics estimated under *Shyska* are: geometric indices (area, perimeter of the basin, etc.), relief indices (maximum and minimum height, etc.), and the hypsometric curve.

3 Methods

GRASS GIS-embedded techniques have been used not only for the development of the rainfall-runoff models, but also for the storage, processing and generation of the data necessary for parameterization.

The hydrological models, both those with lumped or distributed parameters, need data about land types and uses, slope, basin limits, etc. The GIS is used to analyze the different layers of information and to generate either a lumped parameter for the whole basin (or study area), or the spatial distribution of the parameter.

The basin is divided into cells and the geomorphologic analysis of one or more DEMs is carried out on a cell-by-cell basis. The geomorphologic relationships of the basin can be used as predictors of the flash flood properties. For example, the mean flow of a river can be related to the basin area or to the drainage density of the hydrographical network, and similarly, the length of the main channel can also be used in equations to define the basin concentration time.

The rainfall input is considered to be spatially distributed. In the current system, the input can be derived by an interpolation from the automatic pluviometers of the SAIH network, it directly builds rainfall fields coming from remote sensing measurements or the results of meteorological forecasts. A loss function is applied to each cell, which is treated as a hydrologic unit where a lumped model is applied. The *Shyska* system supports both distributed and lumped runoff routing methodologies.

3.1 *Geomorphologic analysis*

GIS is used to perform automatic processing of DEMs in order to derive scale properties of the drainage network and spatial distributions of parameters. From an idealized DEM, a series of hydrologically interesting topographic characteristics is obtained (drainage flow accumulation, drainage direction, slope, etc.), which are vital to derive certain parameters used in integrated rainfall-runoff models. From the drainage direction maps, the contributing basins for the stream gauging stations of the SAIH system were defined automatically. The contrasts between the limits of the basin traced manually from the printed topographical maps and the watershed extracted from the DEM have been satisfactory (García 2002a).

3.1.1 *Estimation of spatial distribution of parameters*

For the basins defined automatically from the DEM, the spatial distributions of parameters are estimated. The methodology put forward by Maidment et al. (1996) is applied. The time delay of the flow depends on the length of the flow path and the velocity in each cell. The flow velocity field is derived as a function of the flow accumulation and terrain slope maps, as well as a mean value of velocity for the whole basin. This value has been adjusted according to historical episodes. The velocity field is considered invariant with time. From the flow travel time map, the hystograph time-area is automatically obtained.

3.1.2 *Automatic extraction of the drainage network and estimation of scale properties of the channel network*

The estimation of indices and scale properties for the hydrographical network from a DEM can be summed up as a four-step process:

1. Estimation of primary topographical attributes,
2. Automatic extraction of the drainage network,
3. Automatic encoding of the network by means of Strahler's flow ordination scheme, and
4. Estimation of relevant indices and scale properties.

The extraction of the drainage network from a DEM is realized by adopting a constant threshold area. The choice of threshold area should not be arbitrary, as it affects the morphological and scale properties derived from the network, as various authors have shown (e.g. Helmlinger et al. 1993, García 2002a).

Strahler's flow orders are automatically assigned to each section of the channel corresponding to the total drainage network. In Plate 18, the module developed to carry out this analysis can be seen. From this encoded network, a series of topological indices could be obtained (drainage density, channel frequency, etc.) with this module. For each channel order the number of channels, channel length, drainage area, mean length and mean drainage area are defined.

Once the drainage network analyses have been carried out, Horton's geomorphologic relationships of area, bifurcation and length can be estimated by means of regression analysis. In addition, this module integrates different formulations to estimate the basin concentration time, even applying the formulations at cell scale.

Finally, Horton's geomorphologic relationships come into the parameter definitions for hydrological models, such as the runoff routing model proposed by Rosso (1984). This particular model is integrated in *Shyska* and will be described later.

3.2 Rainfall-runoff modeling

3.2.1 Runoff generation

The Soil Conservation Service (SCS) runoff generation method is applied at the cell scale. Using the hydrological group maps for soil uses, types, practices, management and hydrological condition, the spatial distribution of the Curve Number (CN) parameter is calculated. A modified version of the methodology presented by Srinivasan and Engel (1991) has been integrated into the *Shyska* system to estimate the CN value for each cell.

In the forecasting mode, the system integrates different tools allowing the selection of meteorological forecasts which became model inputs. A formulation is likewise presented, permitting the adjustment of the spatial distribution of CN in real time, according to the rainfall and runoff observed.

3.2.2 Runoff routing

Spatially distributed and lumped methodologies for runoff routing have been integrated into the *Shyska* system. Some of their parameters are obtained from the DEM, and the user can choose a particular runoff routing methodology when executing these models.

The flow can be routed at the basin outlet using a distributed Unit Hydrograph that presents a linear translation component (pure translation model) and a storage component (translation-storage model). Both models are based on the spatial distribution of flow velocity, as proposed by Maidment et al. (1996).

As noted earlier, the approach proposed by Rosso (1984) has also been included in the system as an option. This model is based on the combination of the Geomorphological Instantaneous Unit Hydrograph (GIUH) originally presented by Rodriguez-Iturbe and Valdés (1979) and Nash's model.

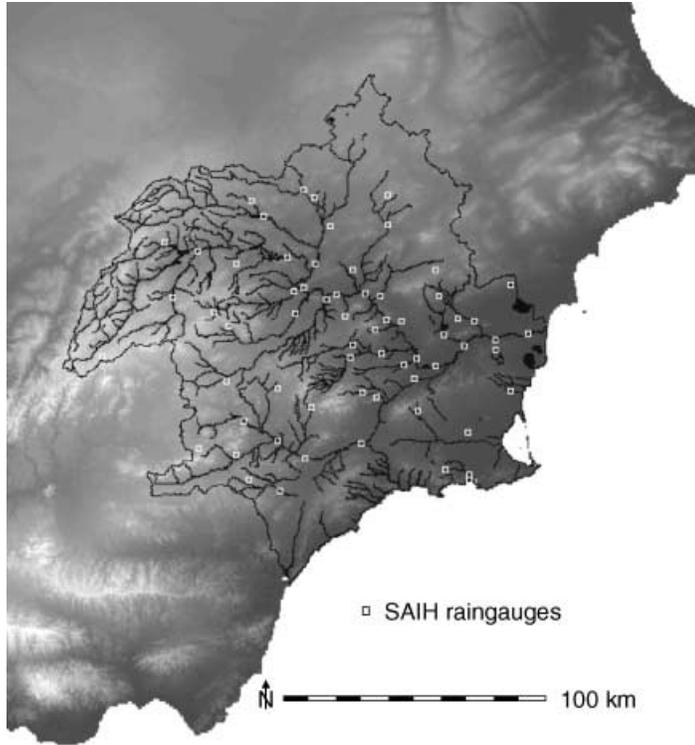


Figure 3 Location of study area and SAIH raingauges

4 Sample Applications

This section presents several case studies, describing the basin characteristics, derived parameters, and models applied.

4.1 Study basins

Different examples of the application of DEMs in the topographical parameterization of hydrological models are presented in the two basins chosen which belong to the Segura River Basin in the south east of Spain (Figure 3).

The catchments that are analyzed correspond to the Mula River Basin (169 km²), which is regulated by the La Cierva Reservoir and the Rambla Salada Basin (112 km²), which has no regulating structures.

4.2 Example of hydrological modeling

For the basins defined automatically from the DEM, the spatial distributions of the flow velocity in each cell, the flow path length (Figure 4) and the corresponding flow travel time were estimated. The area-time histograms have been calculated with those data. For the present work, in the Rambla Salada Basin, the pure translation model (T.P.) has

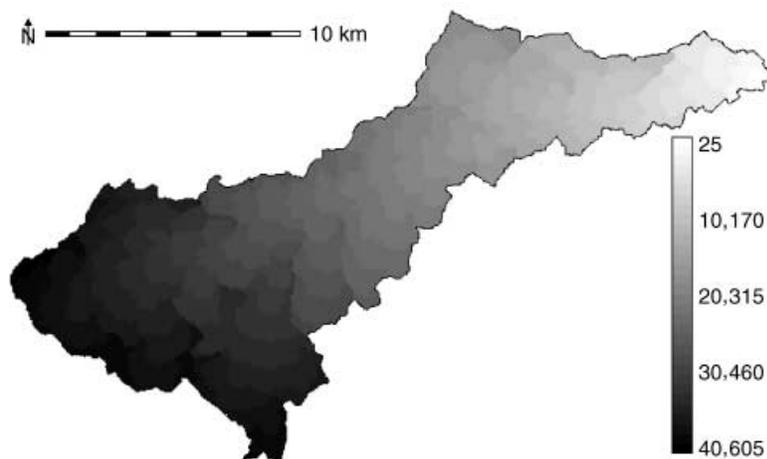


Figure 4 Spatial distribution of flowpath length (m)

been applied, while the translation-storage model (T.A.) has been adjusted for the Mula River Basin. The precipitation registered by the SAIH system in September of 1997 (episode 0997) has been taken into account in both cases.

However, it must be pointed out that the developed models have been applied to one of the study basins (Rambla Salada) for various episodes registered by the SAIH system from 1997 to 1999 (García 2002b). The model parameters were calibrated and validated, and the results so obtained were judged to be satisfactory for this particular study.

Figure 5 shows the different graphic and text results produced with *Shyska* in the simulation of episode 0997, such as the average input and effective hyetographs for the basin, the contrast between the simulated and observed runoff (hydrographs and scatterplot), the spatial distribution of the CN parameter, the numerical results (peak runoff, total volume, etc.) and the goodness of fit.

Finally, Figure 6 presents the results of the simulation of the episode recorded during the period from 05:00 hs. on 30/09/97 to 21:00 hs. on 30/09/97. This figure shows the observed (Q_{obs}) and simulated (Q_{sim}) hydrographs and hyetographs ($Prec$) in the Mula River Basin.

5 Conclusions

The advances in computational sciences and in GIS have allowed the development of spatially distributed hydrological models that operate in real time and whose functional relationships are applied at the cell scale into which the basin is discretized. Every day the demand for high resolution spatial information is greater, both for management and modeling activities. The development of techniques for the integration of spatiotemporal information is important.

In hydrometeorological warning situations in the Mediterranean basins, characterized by flash flood type events, decisions have to be taken in short periods of time. It is absolutely vital to be able to make use of systems which act as a support when taking

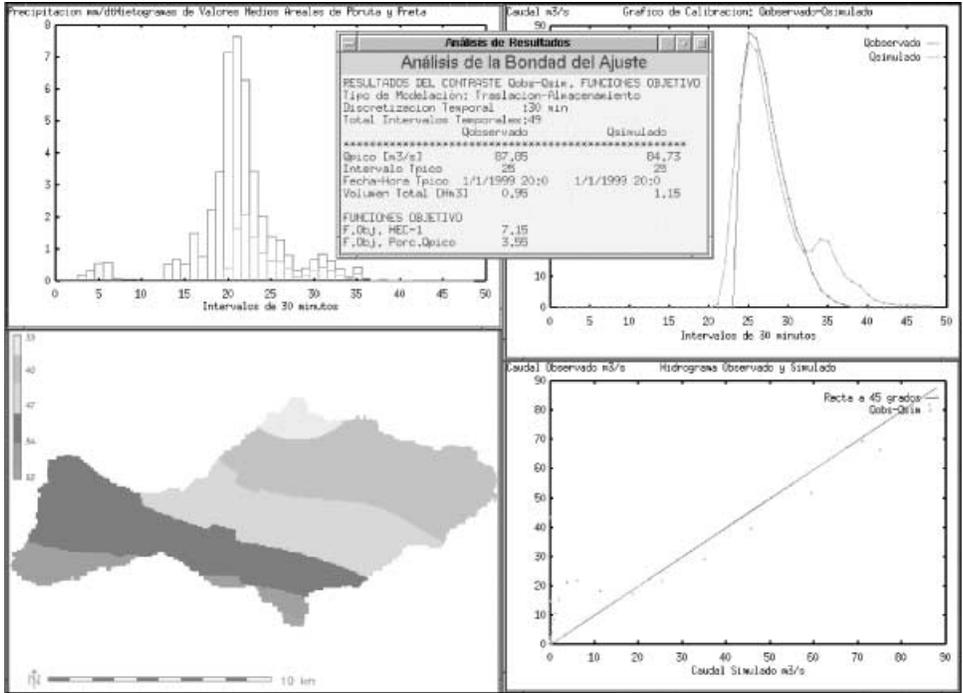


Figure 5 Example of Shyska's graphical and numerical results for the Rambla Salada Basin

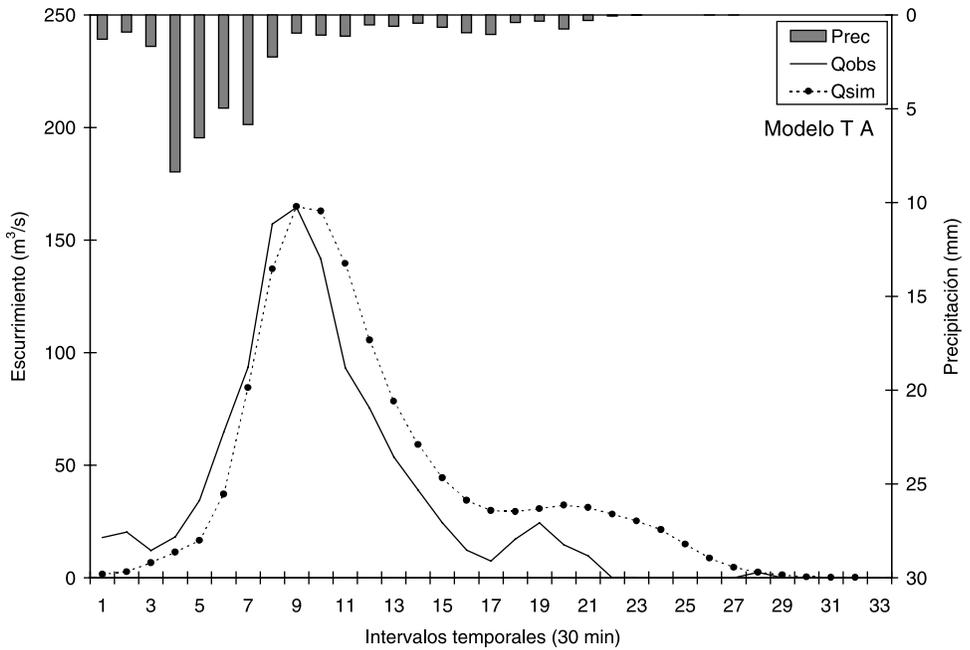


Figure 6 Observed and simulated flows in the Mula River Basin

decisions in real time. This type of system should combine the latest information treatment technologies with the most efficient simulation and parameterization techniques.

In this paper, the application of a computational system, *Shyska*, which facilitates the real time management of a flash flood event, has been presented. It is considered a support tool for decision taking by local and regional authorities, when broadcasting warnings about the potential of flash flooding, in order to lessen the effects of the flood.

In semiarid Mediterranean basins, soil moisture has a strong influence on the basin's response to a storm event. Some knowledge of the soil moisture status of the basin helps to determine the real-time parameters incorporated in conceptual models of infiltration estimation. Similarly, a spatial index which represents the aridity severity can help to guide decisions on the preceding state of humidity in the basin that is required by the models of effective rain estimation, like the runoff generation model of the SCS.

The aim in future research is to use techniques based on remote sensing, particularly for satellite images, to estimate the soil moisture status in the basin. Similarly, other innovative options will be analyzed. The aim is to develop the necessary spatial analysis computational tools and to integrate them into the *Shyska* environment. The indirect estimation of soil moisture from remote sensing will allow the initialization of the integrated runoff forecast models.

Shyska currently includes the SCS model applied to the cell scale which is discretized in the basin as its runoff production module. The integration of other methodologies which consider explicitly and in detail the soil moisture balance and the subsurface runoff, are being considered. In the current *Shyska* environment, a unitary impulse-response function is estimated for every cell independently of the other cells based on the DEM. The response at the basin outlet is found by adding all the responses from each cell by means of a spatial convolution. At present, the study and integration of new spatially distributed methodologies of runoff propagation that make intensive use of DEMs is in process. The overall goal is to improve the forecasting of the risks of extreme hydrologic events like floods.

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