A real-time flood forecasting system based on GIS and DEM

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Abstract A real-time operative decision support computer system named *Shyska* is presented. The system applies the potential of GIS to processing information to different space–time scales. It integrates spatially-distributed hydrological models, oriented to runoff simulation and prediction, using topographical attributes extracted from a DEM. Its final aim is to assist Hydrological Information Automatic Systems (SAIH) in Spain, facilitating information management and use in real-time during alert and flash-flood situations typical of Mediterranean environments. *Shyska* has been applied to semiarid basins in southeast Spain, using pluviometric information from telemetric networks and the products of remote sensing, presenting satisfactory results. The sensitivity of results, both the spatial distribution of geomorphological and hydrodynamic parameters, to DEM resolution is investigated.
Key words DEM; distributed hydrological models; flash flood forecasting; GIS; Spain

INTRODUCTION

The integration of real-time hydrometeorological data collection networks (such as the flood-warning Hydrological Information Automatic Systems—SAIH—systems) with meteorological forecasts and pluviometric information from remote sensing provides instruments for flood forecasting and protection. Warning of flash flooding, typical of the study area in southeast Spain, based on hydrological forecasting allows the adoption of real-time reservoir operation strategies and reduces flood damage. For efficient use of remote sensing information with high space–time resolution, spatially distributed rainfall–runoff models should be used (Schultz, 1997).

This paper presents the application of a decision support structure, named *Shyska*, developed with GIS-embedded functions, which:

(a) Efficiently combines information from different sources presenting considerable time–space variability, both supplied by SAIH systems and from remote sensing (rainfall field products of radar satellite technology).
(b) Integrates spatially distributed and hybrid hydrological models, topographically based, oriented to real-time simulation and forecasting.
(c) Automatically extracts from the Digital Elevation Model (DEM) the relevant parameters for formulating the hydrological models used.

In this paper we try to answer questions which arise when working with topographically based models: Are the distributed parameters taken from the DEM affected by cell size? Is it possible to identify the scale-invariant properties, characterized by the spatial distributions of parameters?

METHODS

When a flood event occurs in a semiarid environment, the hydrological processes implicated may be reduced to production and propagation of runoff at the basin outlet. The rainfall excess production model is based on the US Soil Conservation Service (SCS) Runoff Model (Soil Conservation Service, 1971), modified for application at the level of the cells into which the basin is subdivided. The hydrological transfer functions correspond to distributed unit hydrograph (UH) models, where the runoff generation threshold area concept is not applied, as its parameters are estimated for each cell into which the basin is subdivided.

A Pure Translation (PT) model is applied, in which the translation of the net rainfall from each cell to the basin outlet is carried out using the area–time curve for the basin. If the isochrones in the basin are traced at time intervals Δt, the incremental area in the ith isochrone will be $\Delta A'_i$. The UH ordinates for an event of duration Δt may be estimated (Maidment *et al.*, 1996) as $U(i\Delta t) = \Delta A'_i/\Delta t$.

If a combination of a linear channel followed by a linear reservoir is considered the expression of IUH (Maidment *et al.*, 1996), it will be given by the following combined translation–storage (TS) model:

$$u(t) = 0 \qquad \text{for } t < T_s \tag{1}$$

$$u(t) = 1/T_r \cdot \exp[-(t - T_s)/T_r] \qquad \text{for } t \geq T_s \tag{2}$$

In this model, total flow time (T) from the cell is translation time in a linear channel, T_s plus residence time in a linear reservoir, T_r. The constant relationship for the whole basin, between T_r and T is the β parameter for the model. The direct runoff hydrograph is estimated according to a spatial convolution equation, as follows:

$$Q(t) = \sum_{j=1}^{J} \Delta A_j \int_0^t \mu(t - \tau) I(\tau) \mathrm{d}\tau \tag{3}$$

The basin studied is the Rambla Salada basin. This medium sized semiarid basin (112.65 km^2), with a particularly torrential regime, belongs to the Segura River basin in the southeast of Spain. It is part of the SAIH-SEGURA system managed by the Confederación Hidrográfica del Segura (CHS, Spain) river authority.

EFFECTS OF DEM RESOLUTION ON DISTRIBUTED PARAMETERS

The length of the flow path from each cell to the basin edge is defined as the sum of the flow distances through each cell. Figure 1 shows the cumulative frequency distributions for (a) the land slope and (b) the flow length. For medium to steeper slopes the resolution rises as the slope increases, the opposite happening with gentle slopes. Figure 1(b) indicates that when the resolution rises, the flow length increases: observations which are consistent with other studies.

The cumulative area distribution curve is a log-log plot of the percentage of pixels in the basin presenting an upstream contribution area greater than or equal to a specified value. This curve may be divided into three regions (Fig. 2(a)), according to the physical explanation given by Perera & Willgoose (1998); Region I (small

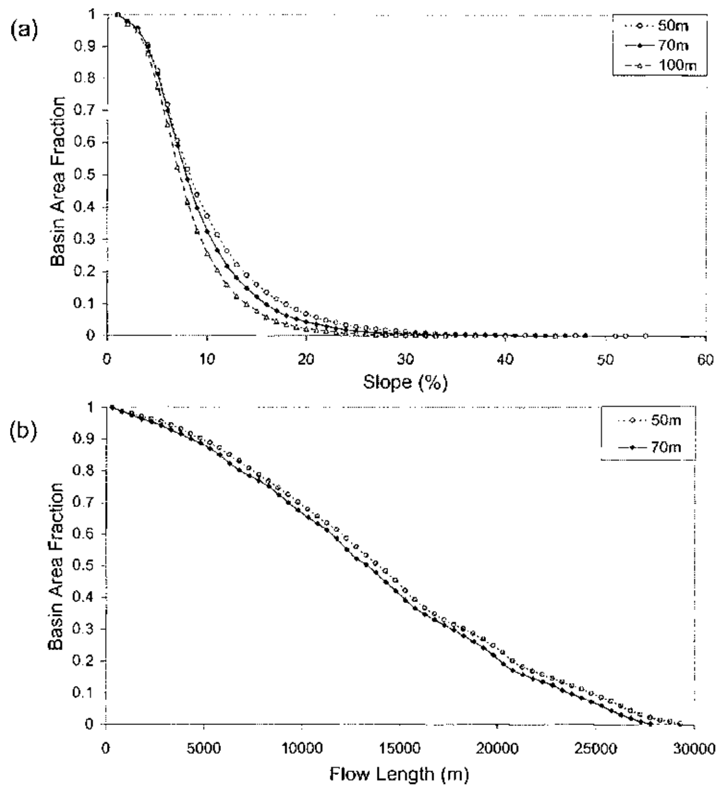

Fig. 1 Cumulative frequency distributions: (a) slope and (b) flow length.

drainage areas) represents the flow aggregation pattern on hillslopes; Region II represents the part of the basin dominated by fluvial erosion (these processes are predominant in this basin); and Region III corresponds to the lower sections of the river network, near to the basin outlet. Region II obeys the power law distribution (Perera & Willgoose, 1998) as, $A(a \geq a^*) \propto (a^*)^{\phi}$ where ϕ is the scale exponent. For the basin studied, $\phi \approx -0.43$ is obtained for 50 m and 70 m DEM resolutions, and $\phi \approx -0.45$ for 100 m. The invariance of the scale observed in the cumulative area relationships for Region II are explained in the fractal properties of rivers. Other authors (Rigon *et al.*, 1993; Perera & Willgoose, 1998) have deduced similar values.

The flow velocities are spatially distributed and invariable in time and with discharge, so a constant velocity is assigned to each cell. It is estimated as (Maidment *et al.*, 1996):

$$V_i = V_{\mathrm{mean}} \frac{s^b A^c}{(s^b A^c)_{\mathrm{mean}}} \tag{4}$$

where s is the local slope, A is the area draining to cell i, V_{mean} the mean basin velocity and $(s^b A^c)_{\mathrm{mean}}$ is the mean value of the area–slope term for the whole basin. Coefficients b and c were set equal to 0.5. It can be seen that the estimated velocity is within a valid variation range. The velocity frequency distributions suggest that this parameter is practically insensitive to DEM resolution. If the cumulative frequency

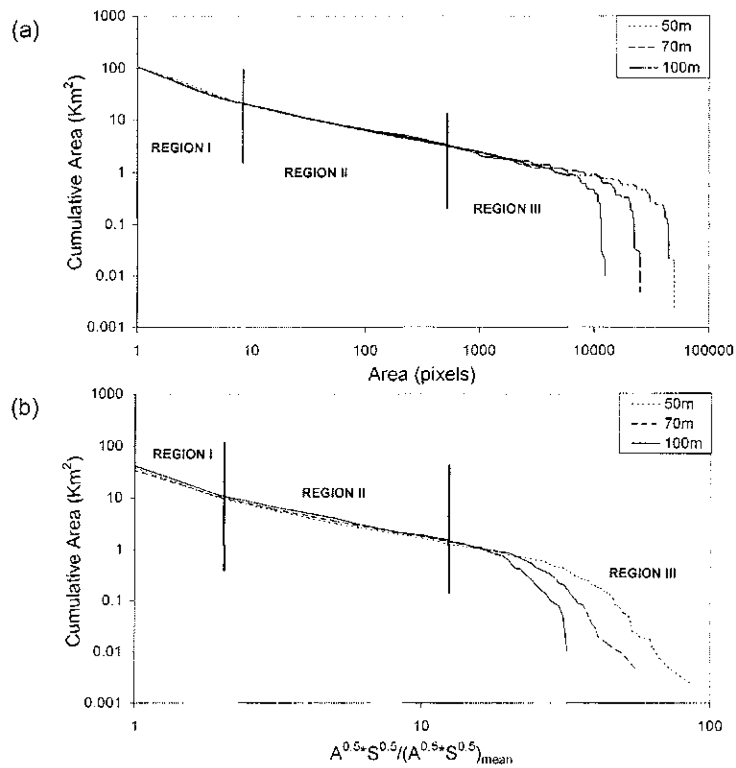

Fig. 2 Frequency distribution analysis: (a) cumulative drainage area and (b) term of $A^{0.5} \times S^{0.5}/(A^{0.5} \times S^{0.5})_{mean}$.

distributions for the term $A^{0.5} \times S^{0.5}/(A^{0.5} \times S^{0.5})_{mean}$ are represented on a log-log graph, (plotted in Fig. 2(b) for the three DEM resolutions analysed), three regions may be identified: Region II follows a power law, with exponent ≈ -1.061 for all three scales. A^cS^b type distributions have been suggested by several authors (Montgomery & Dietrich, 1992), to identify the drainage network from DEM acting as a threshold area depending on slope.

Flow travel time from each cell to the basin outlet is estimated as the sum of the partial flow times through the cells that make up the flow path. The spatial distribution of the travel time is clearly influenced by the DEM resolution, because travel time combines the scale effects on flow length and velocity.

HYDROLOGICAL RESULTS: SIMULATION AND PREDICTION MODES

The analyses were based on episodes registered by the SAIH-SEGURA network. The distributed flow routing methodology described above was used, considering $\beta = 0.2$ for the TS model. A flow time field (Fig. 3) was worked with, estimating with $V_{mean} = 30$ m min^{-1} and a valid distributed velocity range (1, 300) m min^{-1}.

In simulation mode, stationary curve number (CN) parameters are used. In episode 0299 (27 February 1999 06:00 h–28 February 1999 20:00 h), both information from

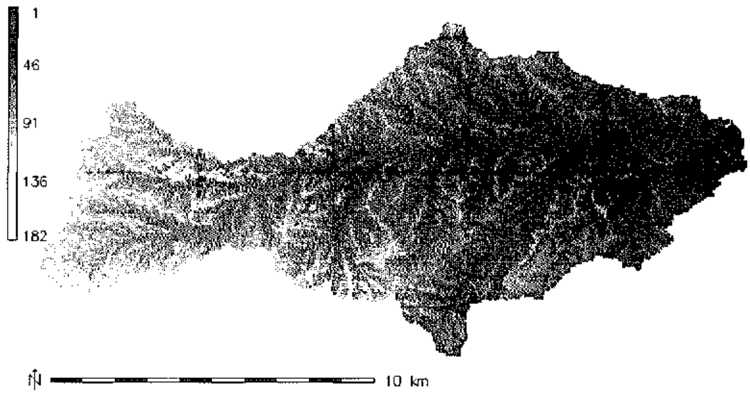

Fig. 3 Reclassified flow time map (min) of Rambla Salada basin. DEM 50 m.

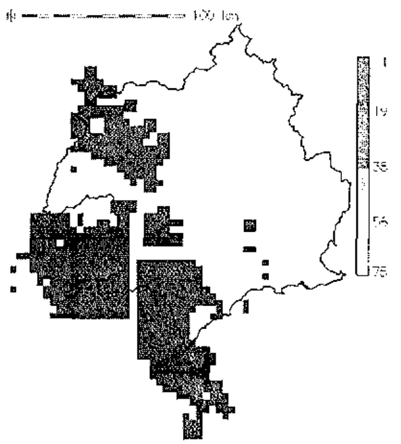

Fig. 4 Radar-RAINSAT image of Segura River basin (08:20 h GMT 27 February 1999).

automatic SAIH raingauges and radar-RAINSAT rainfall fields (Fig. 4) is available. The total rainfall volume is adjusted from radar-RAINSAT data to the corresponding SAIH. It has been noted that the hydrograph timing is significantly better when radar-RAINSAT data are used, due to its high spatial resolution (16 km^2), however, the general shape of the simulated hydrograph is more faithful to the observed hydrograph when SAIH data are used for this episode.

In prediction mode, the CN spatial distribution is updated in real time in accordance with existing hydrometeorological information by means of a state–space formulation. The integration of rainfall forecasts allows the system to be used to reproduce different scenarios and select those that may represent the best decisions. Episode 0299 was analysed, applying the TS model up to different forecasting lead times (K). The peak time was 21:00 h 27 February 1999 (time step 31). Figure 5(a) presents the flow prediction results considering only SAIH data, assuming rainfall forecasts (Pb) equal to those which took place in the last time interval with data (Pk), and considering that rainfall has ceased ($Pb = 0$). In Fig. 5(b) various lead time SAIH data were used adjusting the CN spatial distributions; then radar-RAINSAT rainfall

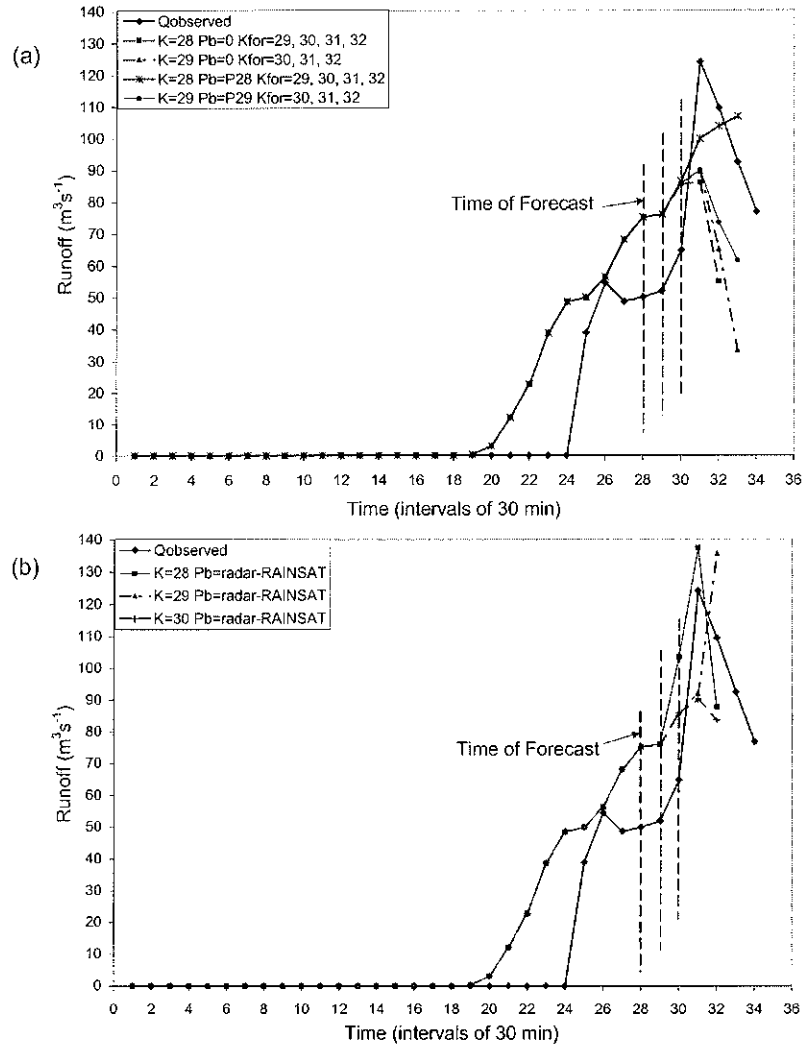

Fig. 5 Hydrological forecasting: (a) from SAIH data and (b) from radar–RAINSAT.

fields were integrated in (K_{for}) forecasting time intervals. A substantial improvement in predictions was observed, compared with Fig. 5(a). The radar-RAINSAT fields are not exactly precipitation forecasts, but they were used to demonstrate their integration with other types of information (such as SAIH telemetric information) in real time.

CONCLUSIONS

Hydrologically oriented GIS based structures, such as that proposed, are the ideal framework for the integration of remotely-sensed information and the use of DEM to derive information for hydrological models. It has been shown that both the slope and the flow length are affected by spatial discretization (cell size) of the basin. The same does not occur with the spatial flow velocity field, which presents invariance properties with the DEM scale, based on the behaviour of the cumulative drainage area curves.

The single-episode forecast improvement when radar-RAINSAT rainfall fields were used cannot be generalized; more episodes need to be analysed. Finally, it is to be underlined that in flash-flood forecasting, meteorological prediction is essential, necessitating collaboration between meteorologists and hydrologists.

Acknowledgements The author thanks the Confederación Hidrográfica del Segura and the Instituto Nacional de Meteorología of Spain, for providing data for this study.

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