

Mediterranean Storms

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AN INVESTIGATION ON FLOOD GENERATION MECHANISMS BY COUPLING DISTRIBUTED MODELS AT DIFFERENT TIME SCALES

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ABSTRACT

A spatially distributed hydrologic model has been developed for the simulation of runoff in the Agri river basin in Southern Italy. This model is an extension of WetSpa (De Smedt et al., 2000). It works on a daily and hourly time step. Runoff generation is estimated from the rain intensity and soil moisture status, and is calculated using a default runoff coefficient, which depends upon slope, land use and soil type. Runoff is routed through the basin along flow paths determined by the topography of the catchment using a diffusive wave transfer model. Used parameters are slope, flow velocity and dissipation characteristics along the flow path. The daily model evaluates the evolution of the soil moisture content, while the hourly model simulates the actual runoff events, using the moisture condition calculated by the first module as input. The model has been tested on two different flood events. In the first case, characterised by dry soil conditions prior the event; good results are obtained using a simplified method in which redistribution of soil moisture between cells is not taken into account. In the second one, due to consistent antecedent precipitation, significant throughflow makes the process more complex, and has to be accounted for in the model.

1 INTRODUCTION

Hydrological modelling of surface runoff at basin scale provides useful knowledge for water resources management. Classical techniques, as the rational method or the Soil Conservation Service curve number approach, are still widely used in practice. Estimating runoff on the basis of the soil water storage capacity, permeability, vegetation (surface coverage), and geophysical characteristics is more accurate. Similar considerations have been introduced with regard to derivation of the probability distribution of floods (e.g. Fiorentino and Iacobellis, 2001).

Physically based models offer a better understanding of the simulated processes, and they are becoming more and more popular, as for instance the Topmodel (Beven and Kirkby, 1979; Beven, 1991).

The WetSpa (Yongbo, 1999; De Smedt et al., 2000) is a physically based model, it has been successfully used to simulate the hydrological processes in small basins, such

as the Barebeek catchment (67.8 km²) in Belgium. In this study a modified version of WetSpa was adapted to simulate the surface runoff in a subcatchment of the Agri river basin at Tarangelo (507 km²), in the region of Basilicata, Italy.

2 THEORY

The hydrological processes are simulated in a grid based schematisation of a river basin. The computation of the runoff for each cell of the grid is carried out by the following equation:

$$V = CP \frac{(\theta_t - \theta_0)}{(\theta_s - \theta_0)}, \quad (1)$$

where V is the amount of surface runoff [L], P the net precipitation [L] (rainfall minus interception), θ_t the soil moisture content, θ_s the saturated soil moisture content, θ_0 the residual soil moisture and C is defined as default runoff coefficient (tab. 1). Runoff coefficients were collected from the literature (Kirkby, 1978; Browne, 1990; Mallants & Feyen, 1990, and Pilgrim & Cordery 1993). Table 1, generated by Yongbo (1999), links values of the runoff coefficient to slope, soil type, and land-use classes, and was exploited in this work.

Land Use	Slope (%)	sand	loamy sand	sandy loam	silty loam	silt	loam	sandy clay loam	silty clay loam	clay loam	sandy clay	silty clay	clay
Forest	<0.5	0.03	0.07	0.1	0.13	0.17	0.2	0.23	0.27	0.3	0.33	0.4	0.4
	0.5-5	0.12	0.13	0.15	0.17	0.19	0.22	0.25	0.28	0.32	0.36	0.4	0.45
	5-10	0.17	0.19	0.21	0.23	0.25	0.27	0.29	0.32	0.35	0.39	0.4	0.5
	>10	0.23	0.27	0.3	0.33	0.37	0.4	0.43	0.47	0.5	0.53	0.6	0.6
Grass	<0.5	0.03	0.07	0.1	0.13	0.17	0.2	0.23	0.27	0.3	0.33	0.4	0.4
	0.5-5	0.07	0.09	0.12	0.15	0.18	0.21	0.24	0.28	0.32	0.36	0.4	0.45
	5-10	0.15	0.15	0.16	0.18	0.2	0.23	0.27	0.31	0.36	0.42	0.5	0.55
	>10	0.2	0.21	0.22	0.24	0.26	0.29	0.33	0.37	0.42	0.47	0.5	0.6
Crop	<0.5	0.23	0.27	0.3	0.33	0.37	0.4	0.43	0.47	0.5	0.53	0.6	0.6
	0.5-5	0.27	0.31	0.34	0.37	0.41	0.44	0.47	0.51	0.54	0.57	0.6	0.64
	5-10	0.33	0.37	0.4	0.43	0.47	0.5	0.53	0.57	0.6	0.63	0.7	0.7
	>10	0.45	0.49	0.52	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.8	0.82
Bare Soil	<0.5	0.33	0.37	0.4	0.43	0.47	0.5	0.53	0.57	0.6	0.63	0.7	0.7
	0.5-5	0.37	0.41	0.44	0.47	0.51	0.54	0.57	0.61	0.64	0.67	0.7	0.74
	5-10	0.43	0.47	0.5	0.53	0.57	0.6	0.63	0.67	0.7	0.73	0.8	0.8
	>10	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82	0.85	0.9	0.92
Imper- vius Area	<0.5	0.32	0.35	0.37	0.39	0.42	0.44	0.46	0.49	0.51	0.53	0.6	0.58
	0.5-5	0.35	0.37	0.38	0.4	0.42	0.45	0.47	0.5	0.52	0.55	0.6	0.62
	5-10	0.4	0.41	0.41	0.42	0.44	0.46	0.49	0.52	0.55	0.59	0.6	0.69
	>10	0.44	0.44	0.45	0.47	0.48	0.51	0.53	0.56	0.59	0.63	0.7	0.72

Table 1. Default runoff coefficient for different land covers, slope and soil type.

3 SOIL MOISTURE STORAGE

The soil moisture storage is the actual quantity of water held in the soil water belt at any given instant, usually applied to the soil layer of root depth. Based on different soil

water contents, the moisture storage can be roughly divided into saturation capacity, field capacity, and residual soil moisture. In the model, soil moisture storage varies continuously depending on rainfall, evapotranspiration, interflow and groundwater recharge. For each grid cell, the soil moisture storage is expressed by a water balance equation:

$$S_{t+\Delta t} = S_t + F_t - E_t - RI_t - RG_t \quad (2)$$

where: $S_{t+\Delta t}$ is the total water content in the soil profile at time $t+\Delta t$ [L], S_t the total soil water content at time t [L], F_t the infiltration amount into the soil during time t [L], E_t the actual evapotranspiration from the soil during time t [L], RI_t the lateral in and out subsurface flow of the soil during time t [L], and RG_t the groundwater recharge during time t [L]. The interflow is not redistributed cell by cell but stored in a conceptual linear reservoir which simulates the subsurface flow at the outlet.

4 SURFACE FLOW ROUTING

When handling flood routing modelling, the generated runoff needs to be routed at the hourly scale through the basin to compute the discharge at the outlet. The diffusive wave approximation simulate both overland flow and channel flow:

$$\frac{\partial Q}{\partial t} = D \frac{\partial^2 Q}{\partial x^2} - c \frac{\partial Q}{\partial x} \quad (3)$$

where Q is the discharge [L³/T], D the wave damping coefficient [L²/T], c the wave celerity [L/T], x the distance along the flow path [L] and t the time [T]. The wave transport parameters c and D depend upon flow velocity, flow depth and terrain characteristics. The flow velocity is determined by the Manning equation:

$$v = \frac{1}{n} R^{2/3} \sqrt{i} \quad (4)$$

where R is the hydraulic radius [L], n the roughness coefficient [L^{-1/3}T], and i the slope, c and D are given as

$$c = \frac{3}{2} v \quad (5) \quad \text{and} \quad D = \frac{vR}{2i} \quad (6)$$

By assuming that the hydraulic radius is a static terrain characteristic that does not change during a flood event, it follows from eqns (5) and (6) that c and D depend on position only. In such a case, De Smedt et al. (2000) proposed an approximate solution of the diffusive wave equation in the form of a response function, relating the discharge at the end of a flow path to the available runoff at the beginning of the flow path:

$$Q = V \frac{(1+t_0/t)}{2\sqrt{2\pi}\sigma} \exp\left[-\frac{(t-t_0)^2}{2\sigma^2}\right] \quad (7)$$

where t_0 is the average flow time [T], and σ the standard deviation of the flow time [T].

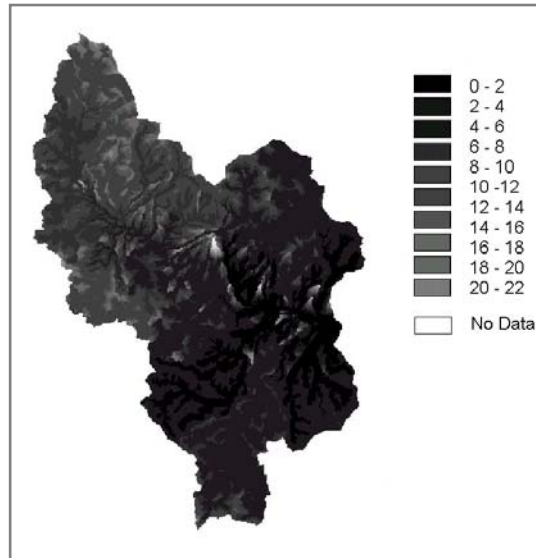


Figure 1. Map describing the flow time of the Agri river Basin in hours.

Hence, the flow routing consists of tracking the runoff along its topographic flow path, such that a response function is obtained for every grid cell to the outlet of the catchment. This routing response serves as an instantaneous unit hydrograph and the total discharge is obtained by convolution of the flow response of all grid cells.

The response function is obtained using ArcView scripts, developed to extract topographic, topologic and hydrologic information from digital spatial data of a hydrologic system.

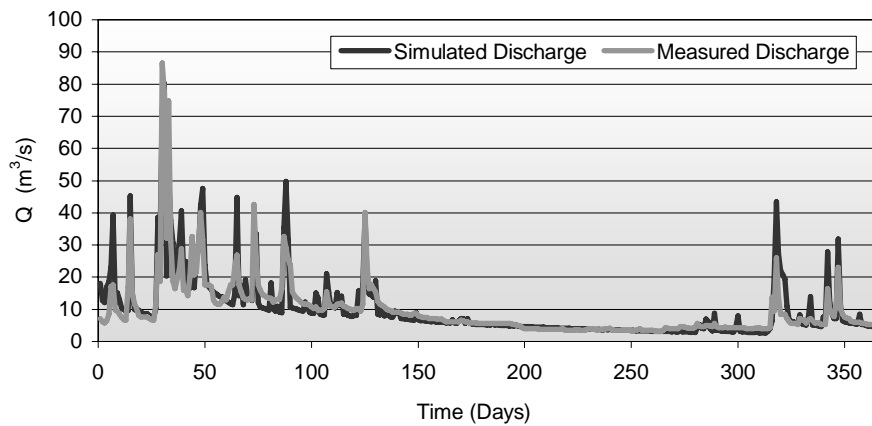


Figure 2. Comparison between observed and simulated daily discharge (year 1954).

5 RESULTS

Using the model at daily scale, daily soil moisture maps and the river discharge at the outlet were obtained. These results have been used as inputs for the model at the hourly scale in order to describe the initial conditions in the watershed for each simulated event. As is shown in figure 2, the fitness between observed and predicted discharge is sufficiently good.

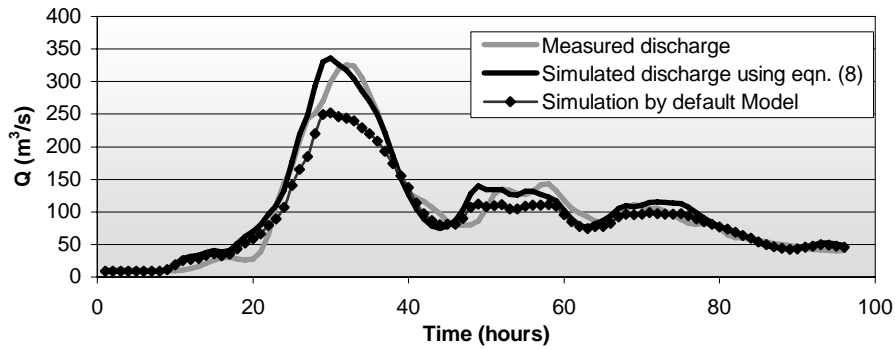


Figure 3. Simulation at hourly scale (event measured 9-13 march 1951).

The model used with hourly time step performs well without any arrangement in case of initial dry soil conditions. Yet, the hydrograph peak was significantly underestimated in the case of an event with prior high humidity soil conditions. By comparing this event to the other one, it is evident to note that in this case great part of the basin surface showed soil water content greater than the field capacity. Hence, the suspicion arises that in presence of significant antecedent rainfall the subsurface flow cannot be neglected. In fact, the main results of this flow are subsurface discharge at the outlet and increasing soil water content along the flow path in the downstream direction. This latter phenomenon is not taken into account in the model.

This problem could be faced by using an additional sub-model suitable to account for subsurface flow antecedent to and occurring during the event. This issue will be considered in a next work.

To the aim of better supporting these interpretations, we simply considered that the subsurface flow is directed to the cells with a higher value of flow accumulation, and that these cells are more likely to be saturated during an event. Then we mimicked this effect by reducing artificially the soil depth of cells by a decreasing function of their flow accumulation value. Accordingly, as a first order of approximation, we wrote:

$$d(i,j) = d(i,j) / (1 + 4 (Facc(i,j) / \max(Facc))^{0.2}) \quad (8)$$

where: $d(i,j)$ is the soil depth at the point (i,j) of the grid, $Facc(i,j)$ is the value of the flow accumulation at the point (i,j) and $\max(Facc)$ is the maximum value of the flow accumulation reached at the outlet.

As a result of eqn(8) runoff is more easily generated in the areas close to the river network. Thus, a generation mechanism similar to Dunne's one is somehow modelled.

The goodness of the approximation is shown in the figure 3, where the hydrograph achieved by introducing eqn (8) into the model is compared to the default one.

6 CONCLUSION

The model studied gives us a method to interpret the hydrological processes; it represents a useful instrument to control the variation of the soil condition, which influences the hydrological answer of a basin. The main outputs of the model are river flow hydrographs and spatially distributed hydrological characteristics as soil moisture, evaporation rates, infiltration rates, groundwater recharge, surface water retention or runoff, etc. The model is especially useful to simulate the effects of topography, soil type, and land-use or soil cover on the hydrologic behaviour of a river basin. The approximation done reduces the computational complexity and is well done in the case of dry soil condition. It is also shown that in humid climates where the water content is likely to be higher, spatially redistribution of the subsurface runoff should be taken into account.

REFERENCES

- Beven, K.J., and Kirkby, M.J., A physically-based variable contributing area model of basin hydrology. *Hydrol. Sci. Bull.*, 24(1), 1979, pp. 43-69.
- Beven, K.J., Spatially distributed modelling: Conceptual approach to runoff prediction. *Recent Advances in the Modelling of Hydrologic Systems*, ed. D.S. Bowles and P.E. O'Connell, Kluwer Academic, 1991, pp. 373-387.
- Browne, F.X., Stormwater management, Standard Handbook of Environmental Engineering, ed. R.A. Corbitt, McGraw-Hill, New York, 1990, pp. 7.1-7.135.
- De Smedt, F., Yongbo, L., and Gebremeskel, S., Hydrologic modelling on a catchment scale using GIS and remote sensed land use information, *Risk Analysis II*, ed. C.A. Brebbia, WIT press, Southampton, Boston, 2000, pp. 295-304.
- Fiorentino, M. and Iacobellis, V., New insights about the climatic and geologic control on the probability distribution of floods, *Water Resources Res.*, 37(3), 2001, pp. 721-730.
- Kirkby, M.J. (ed.), Hill Slope Hydrology, John Wiley & Sons, Ltd., 1978, 235 pp.
- Mallants D., and Feyen J., Kwantitatieve en kwalitatieve aspecten van oppervlakte en grondwaterstroming (in Dutch), Volume 2, Catholic University Leuven, Leuven, Belgium, 1990, 96 pp.
- Naden, P.S. Spatial variability in flood estimation for large catchment: The exploitation of channel network structure. *J. Hydrol. Sci.* (37), 1992, pp. 53-71.
- Pilgrim, D.H. and Cordery, I., Flood runoff, *Chapter 9 of "Handbook of Hydrology"*, McGraw-Hill, New York, 1993, pp. 9.1-9.42.
- Yongbo, L. GIS-based spatially distributed hydrological modeling of the Barebeek catchment, MSc. Dissertation Water Resources Engineering, Free University Brussels, Brussels, Belgium, 1999, 86 pp.