



The effects of soil properties on floods in the Agri basin (southern Italy)

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Abstract

The spatial distribution of soil properties is directly involved in the fluctuation of soil moisture conditions and in the runoff generation mechanisms. In this work, the influences of the physical characteristics of the contributing area to the peak flow were widely investigated with the aim of understanding the influences of each physical parameter.

The study was conducted by means of a hydrological distributed model (Manfreda et al. [7]), applied on the study area of the Agri river basin at Tarangelo (507 km²), in the region of Basilicata, Italy. Two different time scales were used: the first with higher temporal resolution (1-hour) dedicated to the superficial routing, the latter at daily scale used for local water balances and subsurface flow evaluation. Using the model at daily scale, daily soil moisture maps and the river discharge at the outlet are obtained. These results were used as input for the model at the hourly scale in order to describe the initial conditions in the watershed for event simulations.

The simulation was carried on by using a synthetic hourly rainfall series generated by using the IRP model proposed by Veneziano & Iacobellis [9]. By using the rainfall-runoff model it was possible to simulate a large number of extreme events and consequently evaluate the relative contributing area to the peak flow. Specifically, every cell of these areas was classified for its vegetational, pedological and morphological characteristics with the aim of interpreting the relationship between physical properties and potential contribute to flow peaks.

1 Introduction

The hydrological modelling of surface runoff at basin scale provides knowledge and tools necessary in water resources management. Models are increasingly used in hydrology in order to simulate changes in catchment management, extend data sets (such as flood series), evaluate the impacts of external influences (such as climate or land use change) and interpret in a complete way the hydrological processes. In technical literature many simulation models are

available; the skill is in selecting the best one balancing data requirements against the cost of model implementation.

In this study a spatially distributed model is used for runoff simulation of the Agri river basin in Southern Italy. The proposed model is compound by two modules working respectively on daily and hourly time step. The runoff generation depends on the rainfall intensity and soil moisture status, and is evaluated by means of a variable runoff coefficient. The daily module is finalized to the modelling of the soil moisture content, while the hourly module reproduces the total runoff at the event scale using as initial condition the soil moisture estimated by the first module.

The runoff estimation, based on the soil water storage, permeability, vegetation (surface coverage), and geophysical characteristics of basins, is therefore more accurate. The paper is mainly focussed on the investigation of the interactions between climate, soil and vegetation, as well as on their hydrological role on the flood generation mechanisms, suggested by Fiorentino & Iacobellis [4].

2 Hydrological model

The hydrological processes are simulated in both modules in a grid-based schematisation of a river basin (cell size 80 m for the hourly module and 240 m for the daily module). The computation of the runoff for each cell of the grid is carried out by the following equation (De Smedt et al. [2]):

$$R_t = P_t C \frac{(\theta_t - \theta_0)}{(\theta_s - \theta_0)} \quad \theta_t < \theta_s \quad (1)$$

where R_t is the amount of surface runoff occurring during the time-step Δt [L], P_t the net precipitation during Δt [L] (rainfall minus interception), θ_t the soil moisture content at time t , θ_s the saturated soil moisture content, θ_0 the residual soil moisture and C the default runoff coefficient, which depends upon slope, land use and soil type (Yongbo [10]). In eqn (1), which represents a simplified expression of the Horton law, runoff is proportional to the soil water content until the cell reaches the saturation state, at that point there is no more infiltration into the soil and all the effective precipitation becomes runoff.

The soil moisture storage is the quantity of water held, at any time step, in the active soil layer whose depth is dependent on the vegetation root. For each grid cell, the soil moisture storage varies in time depending on rainfall, evapotranspiration, interflow and groundwater recharge according to the following water balance equation (Figure 1):

$$S_{t+\Delta t} = S_t + I_t - E_t - R_{out,t}^{(ss)} + R_{in,t}^{(ss)} - RG_t \quad (2)$$

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], I_t ($I_t = P_t - R_t$) the infiltration amount during the time-step Δt [L], E_t the actual evapotranspiration in Δt [L], $R_{out,t}^{(ss)}$ the lateral subsurface out-flow of the cell in Δt [L], $R_{in,t}^{(ss)}$ the lateral subsurface in-flow of the cell in Δt [L], and RG_t the groundwater recharge in Δt [L].

The soil-water content redistribution is accounted for evaluating the subsurface inflow as a function of the wetness index (W_i) introduced by Beven & Kirkby in the 1979 [1]. The interflow is redistributed cell by cell by the equation proposed by Manfreda et al. [7]:

$$R_{in,t}^{(ss)} = \left(\frac{W_i}{\sum^N W_i} \sum^N c(S_i - S_c) \right) - c(S_i - S_c) \quad (3)$$

While the subsurface outflow is evaluated by the following equation:

$$R_{out,t}^{(ss)} = \max\{0, c(S_i - S_c)\} \quad (4)$$

where N is the total number of cells of the basin, $W_i = \ln(a/\tan\beta)$ (where a is the upslope total contributing area per unit contour and β is the local slope angle), S_i is the water content [L^3], S_c is the water content at the field capacity state [L^3], and c is the shallow subsurface runoff coefficient.

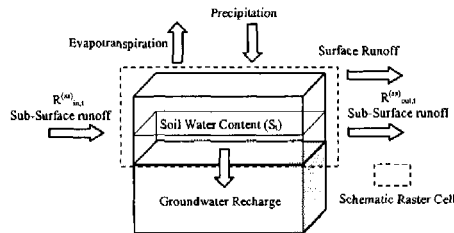


Figure 1: Schematisation of in-coming and out-coming fluxes in a single cell.

When handling the hourly scale module, the generated runoff is routed through the basin in order to compute the discharge at the outlet. The overland and channel flow are simulated under the hypothesis of constant local velocity. Runoff is routed through the basin along flow paths determined by the topography of the catchment described by the digital elevation terrain model with resolution 80 m. The cell parameters used are slope and dissipation characteristics along the flow path. The flow velocity in each cell is determined by using the Manning equation, where the hydraulic radius and the roughness coefficient are assumed a static terrain characteristics that do not change during the flood event.

The basin response function is obtained in a GIS environment, through the extraction of topographic, topologic and hydrologic information from digital spatial data of the hydrologic system.

3 The Agri river basin

The Agri river basin is located in Basilicata, region of Southern Italy (Figure 2a). The hydrographic basin, of area 1763 Km², is characterised by marked morphological, vegetation, climatic and environmental variability. Our attention is focused on the discharge series recorded at Tarangelo, downstream a subcatchment with a total area of 507 km² (Figure 2b). The elevation of this subcatchment ranges from 1800 m a.s.l. to 507 m a.s.l.

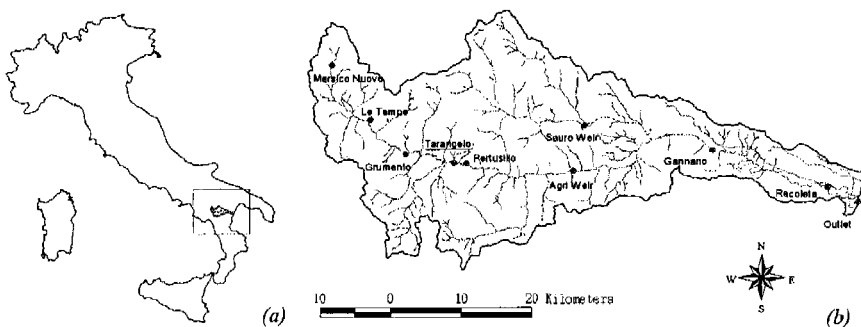


Figure 2: (a) Location of the Agri river basin (Basilicata, Southern Italy). (b) River network and water level gauges in the Agri basin.

The Agri river upstream Tarangelo drains a typical humid basin of Eastern Basilicata with mean annual rainfall depth $h=1100$ mm and a Thornthwaite's climatic index $I_c=(h-E_p)/E_p=0,69$, where E_p is the mean annual potential evapotranspiration. The basin is mostly covered (68% of the total basin surface) by forest and semi-natural areas, while the remaining part consists of agricultural areas for the 31,2% and in a minimum part of water body and artificial surfaces (0.8%); this information is provided by the CORINE-Land Cover Project cartography (1st level), as shown in the Figure 3.

The geomorphology of the basin reflects its geologic and lithological nature. Calcareous mountains and plains made up of gravel, sand, clay and flysch characterize the basin that comprises twelve lithological units listed in Table 1. In Figure 2b the soil map of the basin is reported, while the soil parameters are described in Table 2.

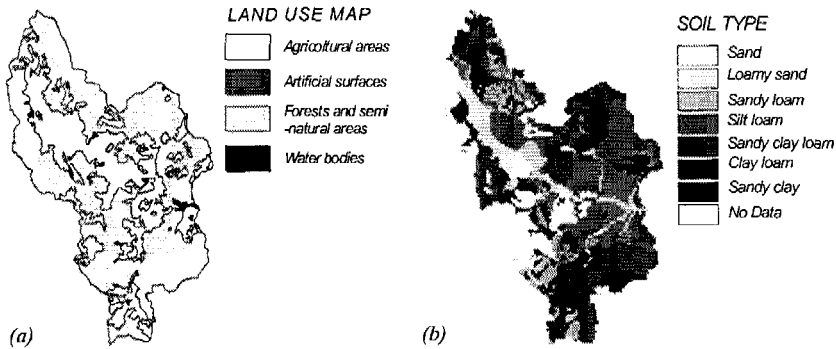


Figure 3: (a) Land use map (1st level of CORINE-Land Cover). (b) Soil type map of the Agri river basin at Tarangelo.

Table 1: Lithological formations within the Agri basin.

Cod.	Lithological formation	Area (Km ²)	Area (%)	Permeability K _v (mm/s)
1	Alluvial deposit	45.99	8.6	5.0E-04
2	Flinty limestone	42.26	7.9	5.0E-04
3	Complex "Varicolori" clay	14.3	2.7	1.0E-08
4	Complex "Liguride"	57.57	10.8	1.0E-05
5	Carbonate Platform	81.98	15.4	1.0E-03
6	Detritic complex	120.67	22.6	1.0E-04
7	Numidic Flysch	0.09	0	1.0E-04
8	Formation of "Galestrino"	40.34	7.6	1.0E-06
9	Formation of "Gorgoglione"	41.3	7.7	1.0E-05
10	Formation of "Facito Mountain"	36.61	6.9	1.0E-05
11	Formation of "Serio Mountain"	17.23	3.2	1.0E-05
12	Formation of Schist Siliceus	34.96	6.6	1.0E-04

Table 2: Soil types within the Agri basin and related properties.

Soil Type	Area (%)	Saturation capacity	Field capacity	Residual soil moisture	Pore size distribution index
Sand	16.1	0.33	0.05	0.04	3.5
Loamy Sand	8.7	0.36	0.1	0.04	4
Sandy Loam	8.3	0.39	0.13	0.04	4.5
Silt Loam	27.8	0.42	0.18	0.04	5
Sandy Clay Loam	29	0.51	0.23	0.04	6.8
Clay Loam	7.3	0.57	0.31	0.04	8.4
Sandy Clay	2.8	0.6	0.32	0.04	9.2

4 Hydrological simulation

In this work a numerical methodology for the estimation of the flood frequency distribution based on continuous simulation is applied to the Agri basin. With this aim the IRP model (Veneziano & Iacobellis [9]) is used in order to disaggregate a 40 years daily record into hourly rainfall series then used as input for the hydrological model simulating the stream discharges. During the 40 years

of simulation 400 extreme events are detected and simulated, providing the discharge series of basin outflow, the flow peak distribution and several maps of distributed hydrologic data. These results are compared with recorded series of annual maximum peak flows available at the Tarangelo gauge station (Figure 4b). Results compare well and provide a realistic interpretation of the basin behaviour. The probability distribution of the source area is well represented by a gamma distribution with mean source area 26% of the total area ($\alpha=33 \text{ km}^2$) and $\beta=4$ (Manfreda et al. [7]).

By means of the daily module we obtain daily soil moisture maps and base flow discharge at the outlet. These informations are used as initial conditions for the hourly-module for each simulated event.

In Figure 4, some results are reported: (a) comparison of probability distributions of synthetic and recorded flow peaks, (b) synthetic hietograph and hydrograph, and (c) runoff contributes to the peak flow.

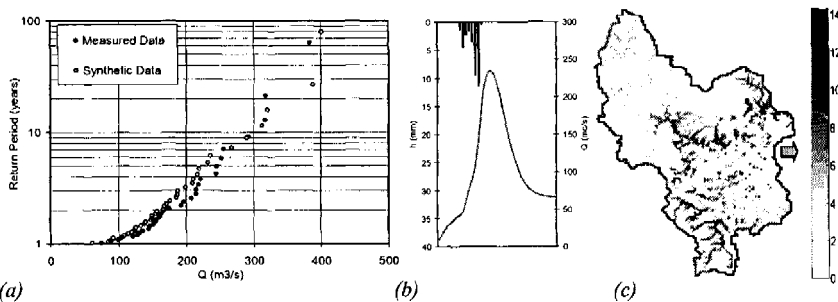


Figure 4: (a) Comparison of probability distributions of synthetic and recorded flow peaks. (b) Example of synthetic event. (c) Contributing area to the peak flow (the colorbar refers to runoff production in mm/hour).

By using the rainfall-runoff model it is possible to simulate extreme events, evaluating the contribute to the peak flow of each cell, and interpreting the cells behaviour by the light of their physical properties. These analyses are developed in the following section.

5 Analysis of the soil hydrological response

In the hydrological simulation performed, the runoff generation process may be interpreted as Hortonian (Horton [5]) or Dunnian (Dunne [3]). The Hortonian runoff (“infiltration excess”) is generated when the rainfall intensity exceeds the infiltration rate that principally depends on soil characteristics, such as permeability; the Dunnian runoff (“saturation excess”) is generated when the active part of soil reaches the saturation from below, therefore it depends on soil thickness, water storage capacity, and morphology.

In order to distinguish between the two mechanisms we tried to investigate the effect of: (i) land use that influences soil thickness and porosity by the plants

root and the agricultural working; (ii) pedology classified in Table 2; (iii) basin morphology described by means of slope and wetness index.

The wide range of simulated flood events, validated by observed data, allows the analysis of the hydrological response for different soil characteristics (land use and soil type) and for specific topographic parameters (slope and wetness index). The mean value of the runoff source areas is evaluated over the 400 simulated floods events; we consider as source area the ensemble of pixels that constitutes the 90% of the flow peak, the remaining 10% is given by a larger area with small unit contribute.

At first we consider the effect of land use: Figure 5a shows the source areas classified for category of land use and the mean value of the source areas subdivided in Hortonian and Dunnian areas. This distinction is based on soil condition status: the saturated areas, contiguous to the river-network, are considered Dunnian vice versa Hortonian the unsaturated zones.

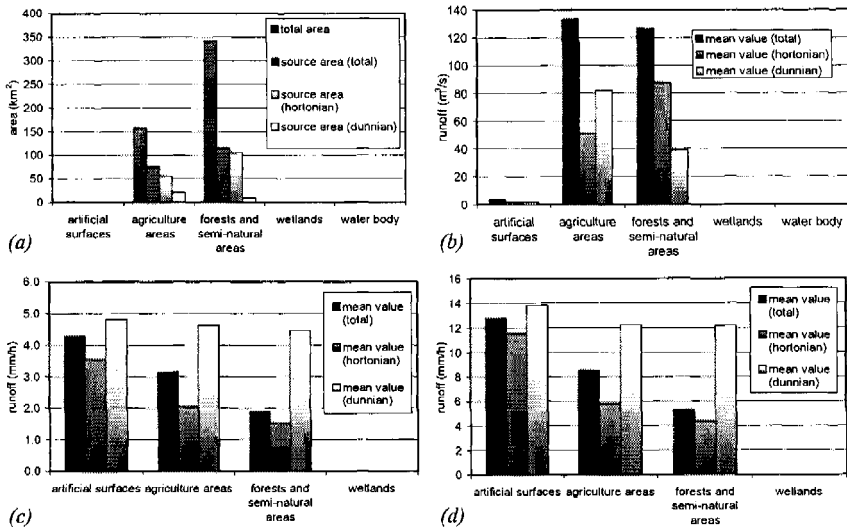


Figure 5: Description of the mean values of hydrological characteristics classified according to the 1st level of Corine land cover legend: total and mean value of the source areas (a), mean runoff value expressed in m³/s (b), mean runoff value per unit area expressed in mm/h for all the simulated events (c) and only for the 40 higher events (d).

Focusing on the agricultural and forested areas, the other land use categories have an insignificant extension, one may immediately observe that the surface interested from Hortonian mechanism is larger (Figure 5a) while the total runoff generated is divided, in different proportions, between Hortonian and Dunnian type with a higher component of the second type in the agricultural area (Figure 5b). The Figure 5 (c and d) emphasize the highest dunnian component per unit

area, the yielded runoff is equal for different land uses and depends only on rainfall intensity. Two sample of different sizes were analysed: the first includes all the considered flood events (Figure 5c), the second one includes only the 40 higher events (Figure 5d). The comparison highlights a similar behavior.

A second interesting analysis focuses on the runoff mechanisms as a function of the pedological classification: terrains with sand contribute to runoff only in a minimum part, essentially for the high infiltration rate and the low field capacity. The main contribute is given by soils rich in clay or silt (Figure 6 a and b).

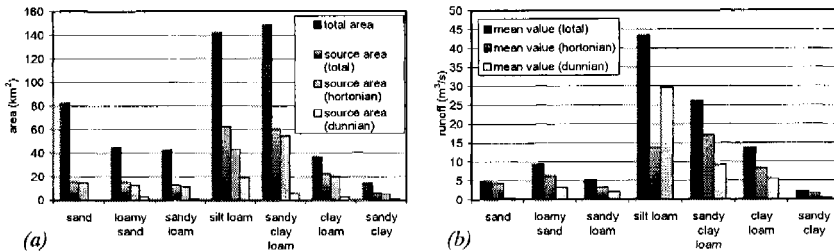


Figure 6: Total area and mean value of the source areas (a); and mean runoff value for different source areas (b) classified according to the basin pedology.

Basin morphology influences the soil moisture status through the subsurface flow and its direction, which is function of the local slope and contributing area (Figure 7 a and b). In particular, in the Figure 7d one may note that high values of mean contribute to the runoff correspond to high values of the wetness index, in other words zones with greater upslope draining area and lower slope reach the saturation level more frequently.

By the light of the obtained results there are different possible interpretations of the processes that control the runoff generation and source area:

- In the basin considered, classified as humid, the saturation process is controlled by water that, during and right after storm periods, infiltrates and migrates downslope; as a consequence the areas at the toe of the slope quickly reach the saturation condition, the saturated area tends to expand upslope (Troendle [8]). In facts, as in Figure 7b a decreasing trend of saturated areas is observed against increasing slope. In the particular case of this basin, the area at the toe of the slopes are prevalently agricultural and rich in silt, so they saturate in a very short time and the runoff contribute varies in function of the quantity of fallen precipitation (Figure 5b and Figure 6b);
- the hydrological and pedological properties of the soil as thickness, root depth, porosity, etc. have a great influence in the runoff processes and also in this case their prevalent mechanism of runoff generation is related to their spatial location.

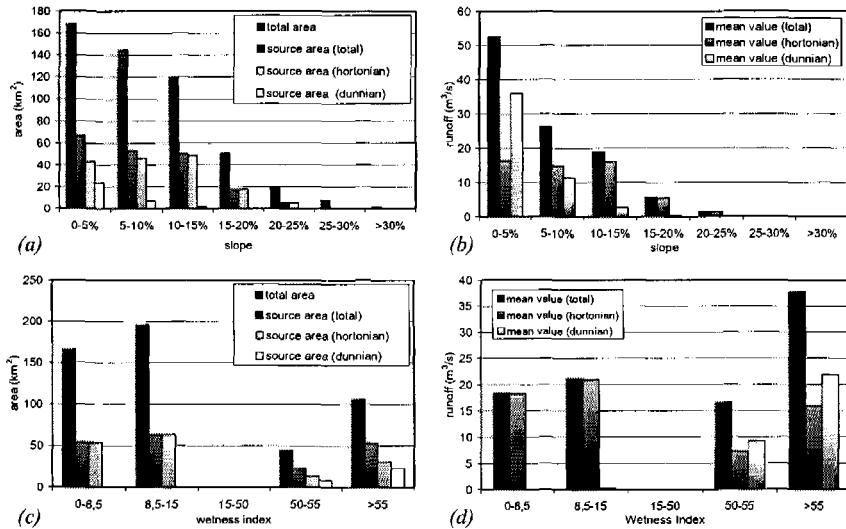


Figure 7: Total area and the mean value of the source areas (a and c), and mean runoff for the different source areas (b and d) classified according to slope and wetness index.

6 Conclusion

The model presented allows to interpret the hydrological processes and represents an useful instrument to control the variation of the soil condition, which influences the hydrological response 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.

Comparing groups of synthetic events chosen by different thresholds, we do not observe significant changes in the prevalent runoff generation mechanisms, fact that also justifies the small values of skewness of the flood frequency distribution obtained by recorded peak flow series (Figure 4a).

The analyses also highlight that the hydrological behaviour of the basin during extreme events may take advantage of information related to land use and/or pedology. In fact results confirm that in a humid basin with forested coverage, as one may expect, Dunnian runoff process is dominant and concerns down slope areas and soils rich in clay or silt while the Hortonian process is generated over upslope areas and for any kind of soil.

The basin morphology seems to behave as the stronger indicator of the hydrological prevalent control mechanisms also in consideration of the high



spatial heterogeneity of soil types and the impact that human activity may have in land coverage.

Acknowledgments

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