Hydrology of the Mediterranean and Semiarid Regions (Proceedings of an international symposium held at Montpellier, April 2003). IAHS Publ. no. 278, 2003.

Assessing the effects on flood risk of land-use changes in the last five decades: an Italian case study

ARMANDO BRATH, ALBERTO MONTANARI & GRETA MORETTI
Faculty of Engineering, University of Bologna, Viale del Risorgimento 2, I-40136 Bologna, Italy
alberto.montanari@mail.ing.unibo.it

Abstract The present work aims to assess the effects that recent land use changes might have induced on the flood risk. The analysis has been carried out by applying hydrological simulation techniques to the Samoggia River basin in the Apennines Mountains (Italy). The man-induced extensive land use modifications, which have affected the drainage basin during the last 50 years, have been assessed by historical land use maps, relative to the years 1955, 1980 and 1992. The variations of the peak flow regime, due to increasing urbanization, have been investigated by simulating the Samoggia River flows for the different historical land use scenarios. The results indicate that the higher the return period of the flood is, the less significant the effects of the human activities are.

Key words distributed models; flood risk; peak flow; simulation; stochastic processes

INTRODUCTION

In the last few decades several inundations have occurred in Europe causing loss of life and financial deficits. After these disasters questions have often been raised about the possibility that they could be the result, at least partially, of an increased magnitude of flood flows due to the enlargement of the impervious areas caused by recent urbanization. There is therefore a great deal of concern in the scientific community about the effects that human activities can induce on the river flow regime.

Many studies were performed in the last three decades in order to analyse the effects that land use changes can induce on the river runoff (Hollis, 1975; Bannister, 1979; Bosch & Hewlett, 1982; Peck & Williamson, 1987; Brath & Montanari, 2000; Beighley & Moglen, 2002). Briefly, these studies came to the conclusion that the effects on the river flows of land use change depend on: (a) the extension of the area affected by urbanization, (b) the climate, and (c) the return period of the event. In particular, it appears that such effects are less intensive the more the return period of the event is high (Hollis, 1975). Such a conclusion arises from the fact that extraordinary events are caused by rainfall which nearly saturated the soil. The reduction of the infiltration therefore affects the surface flow to a lesser extent.

The modifications induced by human activities on the flood regime have often been less considerable than expected because the land use changes have affected a restricted portion of the whole basin for most of the case-studies. Even though this goes beyond the scope of the present analysis, it is worth pointing out that the same conclusion cannot be extended to effects on flood hydrometric levels, and hence on the flood risk, of man-induced land use changes, even if restricted, that are made inside the river beds.

The present work aims to propose a methodological procedure to assess the effects on the flood flows of land use changes by developing a specific case-study which refers to the Samoggia River basin, located in the Emilia-Romagna region. This watershed has been selected in view of the good availability of historical rainfall, hydrometric and land use data, which have enabled a reliable calibration of hydrological simulation models that can refer to different historical land use configurations.

THE SAMOGGIA RIVER BASIN

The Samoggia River basin flows in the Apennine Mountains in northern Italy (Fig. 1). The total area of the basin, closed at the river cross section of Calcara, is 178 km^2. The drainage basin is mainly constituted of mountain areas; the altitude ranges from 850 and 50 m a.s.l., while the main stream length is 60 km. The maximum peak discharge observed at Calcara in the period 1938–1997 is 452 m^3 s^{-1} (year 1940). The topography of the Samoggia River basin is described by a Digital Elevation Model (DEM), whose resolution is 250 × 250 m. The hillslopes are significantly steep, since the slope of 44% of the contributing area is between 10 and 20%.

Historical available data is constituted by hourly rainfall depths that have been observed for the three-year period 1994–1996 in three different rain gauges located at Monte San Pietro (317 m a.s.l), Montepastore (596 m a.s.l.) and Monteombraro (727 m a.s.l.). A total of 59 observations of annual maximum rainfall depth for storm duration of 1, 3, 6, 12 and 24 h are also available for the Monteombraro rain gauge and have been collected during the period 1938–1997 (except 1943). Historical data of hourly river discharges recorded at Calcara are also available for the year 1996. Hourly temperature data recorded at Monteombraro in 1994, 1995 and 1998 are also available.

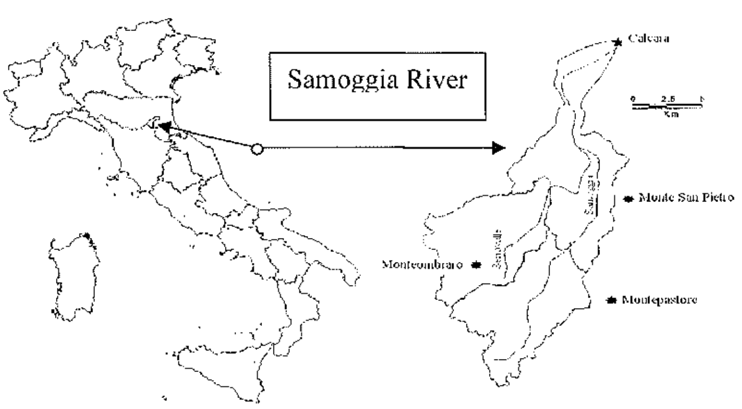

Fig. 1 Location of the Samoggia River basin and the rainfall and river flow gauging stations.

The soil use of the Samoggia River basin has been derived, at each DEM-cell scale, from a series of surveys which refer to the years 1955, 1980 and 1992. The first two surveys have been carried out by field investigations, while the third map has been produced within the CORINE Land Cover EC-funded project (1992), by photo-interpretation of pictures from remote sensor. A detailed description of the land use changes that have been observed in the period covered by the three described surveys can be found in Brath *et al.* (2002). At last, an extensive data base of soil texture, relative permeability and organic substance content has been derived from the soil map, at a scale of 1:250 000 in digital format provided by the public administration of Italy.

THE SIMULATION PROCEDURE

The simulation procedure is based on the use of a distributed continuous simulation rainfall–runoff model, which computes the river discharges from rainfall and temperature records and from geomorphologic and soil use information relative to the drainage basin. The model discretizes the basin in square cells coinciding with the pixel of the Digital Elevation Model (DEM). The river network is automatically extracted from the DEM itself by applying the D-8 method (Band, 1986). The interaction between soil, vegetation and atmosphere is modelled by means of a distributed conceptual scheme. The model firstly computes the local rainfall $P_l[t,(i,j)]$, for each DEM cell of coordinates (i,j), by interpolating the rainfall observed in each rain gauge through an inverse distance method. Then, for each cell, the model separates between surface and sub-surface flows and computes the infiltration by applying a modified CN approach (Soil Conservation Service, 1972), which runs continuously in time. Evapotranspiration is accounted for by the radiation method and computed as a function of the hourly temperature data. For further details see Brath *et al.* (2001). Surface and subsurface flows are propagated downstream by applying the variable parameters Muskingum-Cunge model. Extensive details can be found in Cunge (1969) and Orlandini *et al.* (1999), for the surface and subsurface propagation, respectively. Most of the model parameters have a well defined physical meaning and were estimated on the basis of *in situ* surveys. However, it was necessary to optimise 6 of them by means of a trial and error procedure, through a manual calibration which has been performed by comparing observed and simulated hourly river flows of the flood event that occurred on 8 October 1996. In the calibration phase reference was made to the 1992 soil use scenario, which is temporally closer to the calibration event. The model has been subsequently validated by simulating the hourly discharges of the whole year of 1996. A dispersion diagram of the observed versus simulated 1996 hourly flows is reported in Fig. 2. The coefficient of efficiency for the simulation of the 1996 hourly discharges (validation phase) is 0.82.

As a first step of the simulation procedure, the three-year historical hourly rainfall and temperature series have been given in input to the model, which was run referring to the land use scenarios observed in 1955, 1980 and 1992 (simulation with historical data). This procedure allowed the derivation of indications on the effects of the urbanization on peak discharges. Nevertheless, the limited extension of the historical series has not enabled the assessment of the effects on the extreme floods. Therefore,

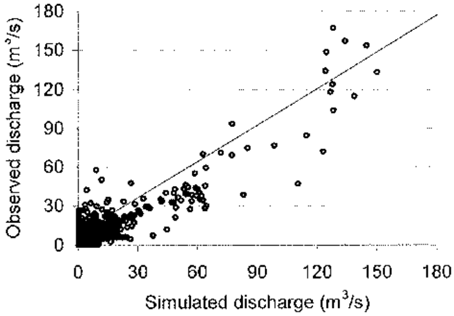

Fig. 2 Dispersion diagram of observed versus simulated hourly discharges; year 1996.

1000 years of synthetic hourly temperature and rainfall data have been generated using stochastic models, namely, a fractionally differenced ARIMA model (Montanari, 2002; Montanari *et al.*, 1997) and the multivariate Neyman-Scott rectangular pulse model (Cowpertwait, 1996) for temperature and rainfall, respectively. These models were calibrated using the historical data. Then, by applying the rainfall–runoff model, 1000 years of river flows have been simulated (simulation with synthetic data), referring to the three soil use scenarios, and a more complete indication of the effects of land use change on the river flows regime has been derived.

RESULTS OF THE ANALYSIS

The effects of the land use change on the flood flows have been assessed for the 1955, 1980 and 1992 land use scenarios, respectively, the analysis spanning over a period of almost 40 years. The model has been firstly parameterized on the basis of the 1955 land use scenario and then on the basis of the 1980 and 1992 scenarios. As previously mentioned, the observed hourly rainfall and temperature data for the period 1994–1996 have been given primarily in input to the rainfall-runoff model. Figure 3 shows a dispersion diagram of the river flows simulated in the 1955 scenario, in ordinate, versus the ones simulated in the 1992 scenario in abscissa. As can be seen, the discharges in the 1992 scenario are systematically greater than the ones in 1955. As far as real applications are concerned, this implies that the parameterization of the rainfall–runoff model, considering the 1955 land use scenario, would introduce an underestimation of the actual hydrological response of the Samoggia River basin.

The module of the relative deviation $\varepsilon(t)$, which is defined as:

$$\varepsilon(t) = \frac{|Q_{1992}(t) - Q_{1955}(t)|}{Q_{1992}(t)} \tag{1}$$

is shown in Fig. 4; the difference between the discharges in the two scenarios is on average 20%. Moreover $\varepsilon(t)$ tends to decrease with the increase of the discharge and of the return period of the event. Nevertheless, even for the highest observed discharges during the three-year period 1994–1996, the value of $\varepsilon(t)$ is comprised in between 0.1 and 0.2. But one has to consider that the flows of the years 1994–1996 have never been of exceptional nature, about 170 m^3 s^{-1} being the highest discharge value registered in

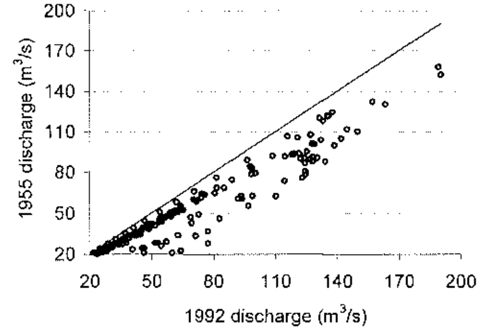

Fig. 3 Simulation with historical data. Dispersion diagram of the simulated discharges (>20 $m^3 s^{-1}$) for the 1992 *vs* the 1955 land use scenario.

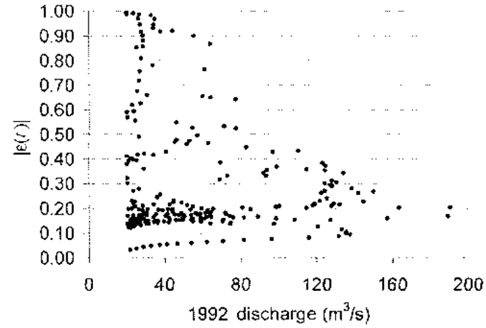

Fig. 4 Simulation with historical data. Module of the relative deviation ε(*t*) as a function of the 1992 land use scenario discharges (>20 $m^3 s^{-1}$).

that period, which corresponds to a return period of about two years. For that reason, the analysis of the effects of land use changes on flood flows is limited to non extreme events. To overcome this limit, the simulation with synthetic data has been carried out, to give more complete indications on the effects of land use changes on the flood regime. The 1000-year synthetic rainfall record is the input variable of the rainfall-

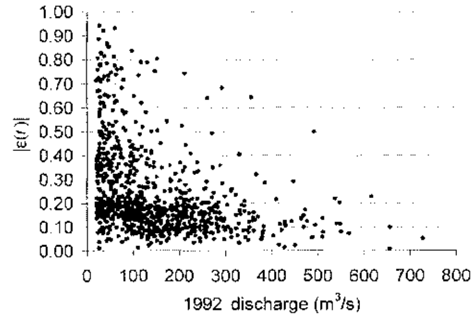

Fig. 5 Simulation with synthetic data. Module of the deviation ε(*t*) as a function of the 1992 scenario flows (Q_{1992}>20 $m^3 s^{-1}$).

runoff model, together with the 1000-year hourly temperature series, generated by the FARIMA model. Figure 5 confirms the results achieved in the simulation with historical data, by showing that the incidence of the land use changes tends to decrease con-sidering higher return periods, as even suggested by intuitive considerations. In part-icular, for river flows greater than 400 $m^3 s^{-1}$, $\varepsilon(t)$ seems to assume values around 0.1.

CONCLUSIONS

In the present work the effects of land use changes on the flood frequency, which have taken place in the last decades, have been investigated for an Italian river. The estimation of the hydrological effects of the land use changes is not an easy task to solve, even in light of the variability of such effects with the variations of the climate and of the geomorphologic characteristics of the territory.

By exploiting detailed information on the land use changes, which have taken place in the Bologna Administrative District since 1955 and for the following four decades, and by using hydrological simulation techniques in cascade, the present study has tried to assess the modifications that the human activities may have induced on the flood flows of the Samoggia River basin, located in the Apennine Mountains.

The results of the analysis have highlighted the remarkable sensitivity of the flood flow regime in response to the occurred land use changes, which implies an increase in the peak discharges of a given frequency. In percentage terms, this increment reveals itself with greater incidence for the lower return period discharges, whereas it seems to be scarcely significant for very infrequent discharges. Considering return periods ranging between 10 and 200 years, which are more relevant for real applications, the increase of the peak flow, even if noteworthy, does not appear to be so important as to justify the conviction of profound alteration in the flood frequency regime. This outcome is consistent with previous ones presented in the scientific literature. Nevertheless, one may observe that the results of the study strictly depend on the adopted infiltration model. In particular the assumption has been made that the separation between surface and sub-surface flows takes place accordingly to a CN-type scheme. This hypothesis seems to be reasonable, in view of the good performances of the CN model in describing the infiltration process in a wide number of case studies, but one has to consider that it is an empirical method. The analysis of other case-studies, which refer to different rivers affected by different anthropogenic pressure and which are based on a different representation of the rainfall–runoff transformation, could confirm the generalization of the results proposed here.

Acknowledgements The work presented here has been supported by the Italian Government through its national grants to the programmes on “Climate and anthropogenic effects on hydrological processes” and “Hydrological safety of basins regulated by dams”, and by the National Research Council of Italy, through the National Group for the Prevention of the Hydrogeological Disasters.

REFERENCES

Band, L. E. (1986) Topographic partition of watersheds with digital elevation models. *Water Resour. Res.* **22**, 15–24.

Bannister, E. N. (1979) Impact of road networks on southeastern Michigan lakeshore drainage. *Water Resour. Res.* **15**, 1515–1520.

Beighley, R.E. & Moglen, G.E. (2002) Trend assessment in rainfall–runoff behavior in urbanising watersheds. *J. Hydrol. Engng. ASCE* 7(1), 27–34.

Bosch, J. M. & Hewlett, J. D. (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrol.* **55**, 3–23.

Brath, A. & Montanari, A. (2000) Effects of the spatial variability of soil infiltration capacity in distributed rainfall runoff modeling. *Hydrol. Processes* **14**(15), 2779–2794.

Brath, A., Montanari, A. & Moretti, G. (2001) Analisi degli effetti sul regime di frequenza delle piene delle variazioni recenti di uso del suolo (Analysis of the effects of recent land use changes on flood frequency regime). In: *La progettazione della difesa idraulica: interventi di laminazione controllata delle piene fluviali (The design of flood protection works: measures for the reduction of peak river flows).* (ed. by U. Maione, A. Brath & P. Mignosa), 53–92. Editoriale Bios, Cosenza, Italy.

Brath, A., Castellarin, A. & Montanari, A. (2002) Assessing the effects of land use changes on annual average gross erosion. *Hydrol. Earth System Sci.*, 6(2), 255–265.

Cowpertwait, P. S. P. (1996) A generalized spatial-temporal model of rainfall based on a clustered point process. *Proc. Roy. Soc.* **A450**, 163–175.

Cunge, J. A. (1969) On the subject of a flood propagation computation method (Muskingum Method). *J. Hydraul. Res.* **7**, 205–230.

Hollis, G. E. (1975) The effect of urbanization on flood of different recurrence interval. *Water Resour. Res.* **11**(3), 431–435.

Montanari, A., Rosso, R. & Taqqu, M. S. (1997) Fractionally differenced ARIMA models applied to hydrologic time series: identification, estimation and simulation. *Water Resour. Res.* **33**, 1035–1044.

Montanari, A. (2002) Long range dependence in hydrology. In: *Long Range Dependence: Theory and Application* (ed. by P. Doukhan, G. Oppenheim & M.S. Taqqu), 461–472. Birkhauser, Boston, USA (in press).

Orlandini, S., Perotti, A., Sfondrini, G. & Bianchi, A. (1999) On the storm flow response of upland Alpine catchments. *Hydrol. Processes* **13**, 549–562.

Peck, A. J. & Williamson, D. R. (1987) Effects of forest clearing on groundwater. *J. Hydrol.* **94**, 47–65.

Soil Conservation Service (1972) *National Engineering Handbook*, Section 4, Hydrology. US Department of Agriculture, Washington DC, USA.