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STRUCTURE OF A SYSTEM FOR ON-LINE FLOOD FORECASTING

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SYNOPSIS

A complete system for real-time flood forecasting in large river basins is presented. It was tested on a large Italian basin with a drainage area of 4147 km^2. The experimental network, based on the use of radio waves, involved an ultrasonic sensor for river level measurements and classical instruments for measurements of rainfall and other meteorological quantities. The predictions of flow were carried out by two semi-distributed adaptive models, requiring low computational efforts, for lead-times up to six hours. The system appears to be suitable for operative purposes.

INTRODUCTION

Short-term real-time forecasts of river flows may be used in reducing flood damages or improving management of water resources in a given basin. In the absence of reliable quantitative forecasts of rainfall, flow forecasts for a lead-time of practical interest (a few hours) may be usually formulated only for large basins by taking advantage of their response time. In order to reach this objective it needs: (a) implementing an experimental network for on-line acquisition of hydrological data, (b) building up a model which incorporates the processes of rainfall-runoff and/or hydrograph routing, (c) disseminating the flow forecasts. Basically, an experimental network may involve river level sensors and meteorological radars supplemented, for calibration purposes, by a small number of raingauges [2]. However, if the basin is characterized, for example, by a complex orography and by a 0 °C level localized in the lower layers of the troposphere then a variety of disturbances may substantially reduce the accuracy of rainfall measurements by radar and therefore a simple raingauge network could be preferred. As to the modeling, operational forecasting requires distributed or semi-distributed models with a procedure for the correction of forecasts according to the discrepancies observed in earlier forecasts [8], [9]. Many of these models of adaptive type have been proposed in the literature and range from simple [1] to very sophisticated [6], [7]. Finally, flow forecasts should be on-line transmitted to the local authority concerned which in turn can take a certain number of decisions.

In this paper the structure and performance of a system for real-time flood forecasting, set up for research purposes, are analysed. It was operating in the Upper Tiber River basin (area 4147 km^2), which is located in Central

Italy, and was based on rainfall measurements carried out by a classical raingauge network and on semi-distributed adaptive models describing the rainfall-runoff process. The dissemination of information was limited to the on-line transmission of experimental data because of the absence of an operative centre in the context of the local authority concerned.

EXPERIMENTAL NETWORK

A telemetering network based on the use of radio waves was operating in the period 1981-1987. Its structure is illustrated in Fig. 1. The network incorporated 15 peripheral stations, one relay station and one central station connected to a local computer.

The central station, built up around a microprocessor, carried out the control of the total network. Its available memory size was 56 kbytes of which 24 kbytes of Read Only Memory (ROM), used for the system program, and 32 kbytes of Random Access Memory (RAM). The peripheral stations used a microprocessor involving a RAM of 128 bytes, of which 32 bytes as back-up memory, and an Erasable Programmable Read Only Memory of 4 kbytes. Normally, the central station carried out interrogations of each peripheral station at time intervals of one hour. Further interrogations were performed in alarm conditions which were fixed in advance according to critical values of river level, river level rate and rainfall rate. At the central station the telemetered data were presented on a display unit and on-line transferred to a Hewlett Packard HP1000 computer, where a semi-distributed flood forecasting model was running, to the National Hydrological Service, to the District of Umbria and to a hydroelectric plant. The system program enabled the operator to modify some working characteristics by keyboard and to call the peripheral stations in order to obtain information about their running state by utilizing a self-test routine of which they were provided. Each peripheral station could handle up to eight sensors. All the stations except two had tipping-bucket raingauges. The river level measurements were performed through an ultrasonic sensor. Other involved instruments concerned the measurements of meteorological quantities as direction and speed of wind, air relative humidity, atmospheric pressure and air temperature.

FLOOD FORECASTING MODELS

Two simple models were extensively used for applications. One was proposed by Corradini et al. [5] and is designated henceforth as the RS model, the other, formulated by Corradini and Melone [3] and then adjusted by Corradini et al. [4], is indicated as the CM model. Both the models describe a given basin as an ensemble of n spatially uniform zones defined by isochrones of travel time from the outlet. Flow forecasts are performed, after the first rise in the observed hydrograph, assuming that no effective rainfall occurs beyond the time origin of forecast and adding direct runoff and base flow, B. The latter is assumed equal to the value of flow observed earlier than the first rise in the hydrograph.

The RS model carries out on-line forecasts of flow, Y_t^b, at a discrete

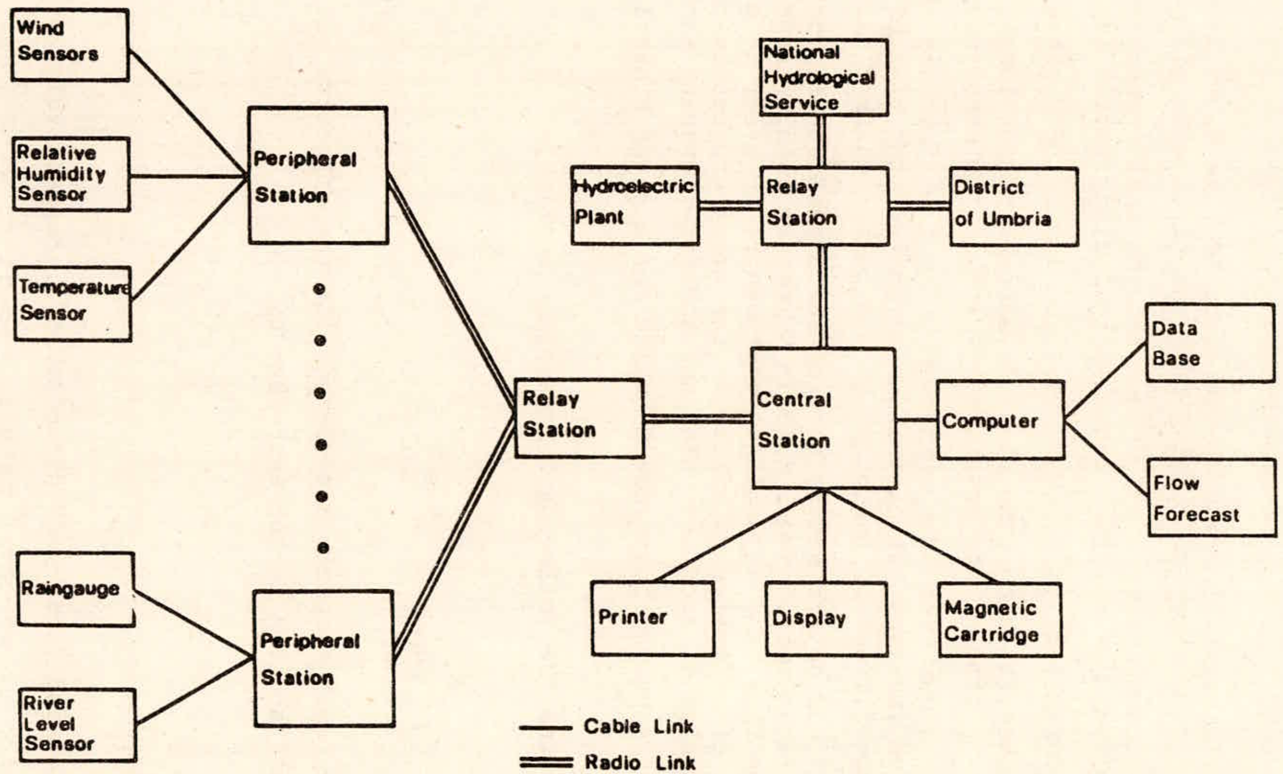

Fig. 1 Structure of the experimental network set up on the Upper Tiber River basin.

time b and for lead-times t-b as:

$$Y_t^b = \sum_{1}^{b}{}_k \left(\overline{R^k} - I^b\right) U_{t-k+1}^k + B \qquad t > b \qquad (1)$$

where $\overline{R^k}$ is the mean areal rainfall depth at the discrete time k, I^b is the mean areal depth of losses in the period ranging from the first rainfall producing direct runoff to the current time b and U^k denotes the basin response to unit depth of mean areal effective rainfall whose spatial distribution is fixed by the distribution of rainfall, R_i^k (i = 1,2,...,n), and losses. For these latter, the distribution in space, at each time step, is assumed proportional to rainfall and the evolution in time of the mean areal value is represented by the Ø-index approach. The U^k functions are represented by the Clark translation-routing procedure which involves estimations in advance of the time of concentration and storage coefficient of basin, which are performed from calibration events. The quantity I^b is determined by setting the direct runoff computed at time b equal to the "observed" direct runoff, obtained as difference of the observed flow and base flow, and adjusting the procedure in order to eliminate unreal negative values of effective rainfall. As the event progresses the estimation of losses is repeated at each time step and the flow forecast accordingly updated. This approach involves functions U^k which for a given k are invariant with increases in b.

The CM model uses the following forecasting equation:

$$Y_t^b = \sum_{1}^{b}{}_k \left(\frac{1}{C^b}\right) X_{t-k+1}^k \qquad t > b \qquad (2)$$

where X^k indicates the basin response associated with the effective rainfall at time k and C^b is a runoff scaling factor expressed by:

$$C^b = Q_C^b / Q_E^b \qquad (3)$$

with Q_C^b and Q_E^b computed and "observed" direct runoff, respectively, at current time b. X^k is a function of observed rainfall together with sorptivity, S, saturated hydraulic conductivity, K_s, depression storage capacity, V_D, and basin lag, K_B. The quantities S, K_s and V_D are involved in the procedure for the computation of effective rainfall from rainfall, infiltration and depression storage. Infiltration is derived by an extended formulation of a point approach utilizing a two-branched scheme for time to ponding and soil infiltration capacity. For rainfall rates less than soil infiltration capacity, a temporal redistribution of rainfall through a sequence of phases composed of unsatured and satured periods for soil surface is incorporated. Basin lag is involved in the transformation process from effective rainfall to direct runoff. Three of the above parameters are determined in advance from calibration events, and therefore in real time X^k is only dependent on S. An optimizing procedure for basin responses in terms of S is used. In particular, for the first time origin of forecast, the optimal value of S, S^b, is computed by a trial-and-error procedure using the objective function:

$$F(S) = \sum_{0}^{1}{}_{m} \left(Q_E^{b-m} - Q_C^{b-m}\right)^2 = $$

$$= \sum_{0}^{1}{}_{m} \left(Q_E^{b-m} - \sum_{1}^{b-m}{}_{k} X^k_{b-m-k+1}\right)^2 \longrightarrow \text{minimum} \qquad (4)$$

subject to the constraint:

$$\frac{Q_E^b - Q_E^{b-1}}{Q_C^b - Q_C^{b-1}} > 0 \qquad (5)$$

However, if a solution of equations (4) and (5) does not exist, or exists but C^b differs considerably from unity, then the solution satisfying only equation (4) is employed. At the second time origin of forecast, considering the contribution to discharge of the new rainfall available on-line, it is chosen S^b equal to the value obtained at the preceding time step and a new C^b is derived. If we have $0.7 \leq C^b \leq 1.3$ then the flow forecast is directly carried out, otherwise the optimization of S is repeated before updating the forecast. The same procedure is used for the successive time origins of forecast. We point out that for a given k the response X^k changes with increases in b if variation in S^b are also involved.

SYSTEM PERFORMANCE

The system was tested during the autumn-winter months in which the main flood events, caused by widespread rainfall, generally occur. The performance of the experimental system was found to be adequate as indicated by a very low number of failures observed. The measurement with the greatest number of failures was that of wind direction, for which one failure per year for a given sensor was commonly caused by a break in the potentiometric unit associated to the wind vane. Furthermore, some failures of the transmitting-receiving sets were also observed.

The RS and CM models were applied to 13 rainfall-runoff events in order to obtain flow forecasts at the outlet of the basin whose time-area diagram is shown in Fig. 2. A maximum lead-time comparable with the delay

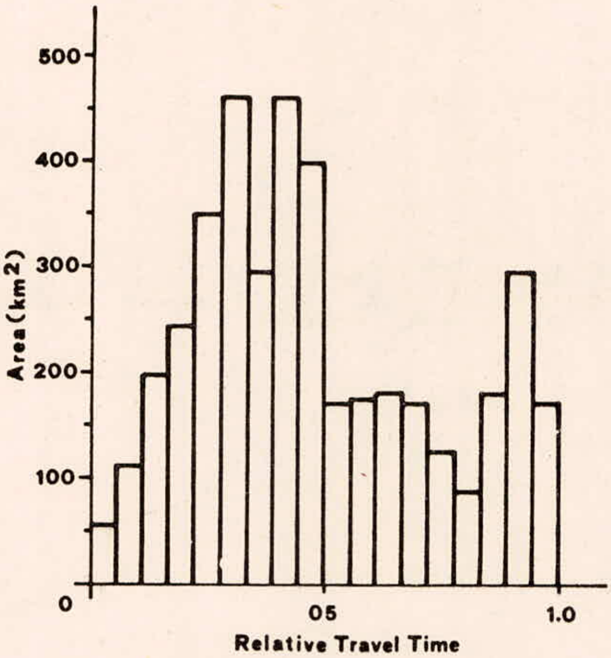

Fig. 2 Time-area diagram of the Upper Tiber River basin.

existing between the occurrence of instantaneous effective rainfall uniform in space and the production of its main effects at the basin outlet was used. Because this value was about 5 h, the predictions of flow were carried out for lead-times up to six hours. They were found to agree reasonably well with the observations in each event, as it is shown in the sample event of Fig. 3 where the errors on peak runoff are very small while the shape characteristics of the hydrograph forecasted by the CM model are more appropriate than those by the RS model. An overall analysis of flow forecasts revealed that the performance of the RS and CM models, estimated by the error on peak runoff and coefficient of persistence [3], was very similar. However, the CM model is closer to physical reality and in principle should be preferred. Using as an example the event of Fig. 3 with 41 time origins of forecast, the computational time and the required memory size for the RS model were less than one minute and 15 kbytes, respectively, while for the CM model were of 15 minutes and 35 kbytes, respectively. In addition, if in the latter model the estimation of sorptivity was carried out at each time origin of forecast, then the computational time amounted to almost two hours.

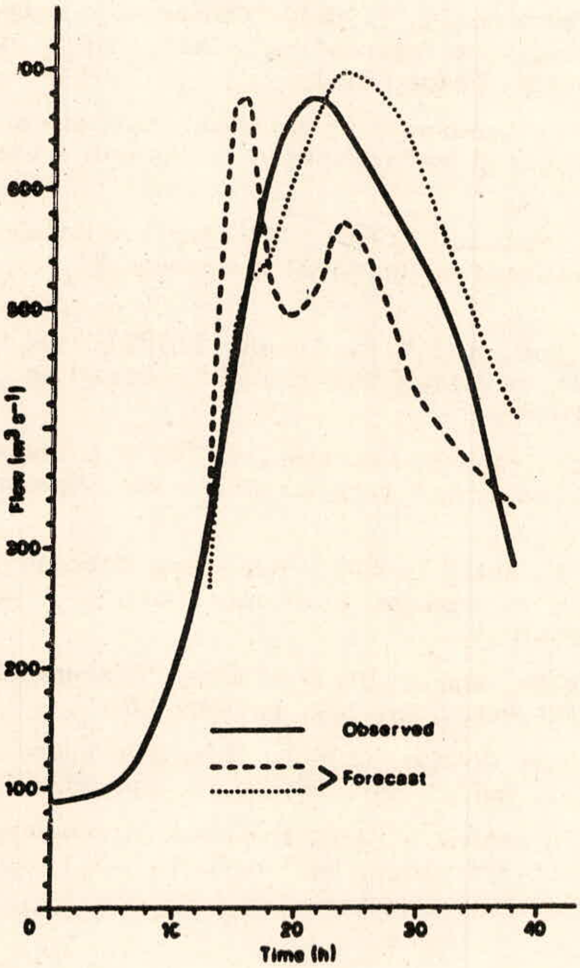

Fig. 3 Comparison of observed and forecast hydrographs for the event of December 29, 1981 on the Upper Tiber River basin. Forecasts carried out for a 6-h lead by the RS (- - -) and CM (······) models are shown.

CONCLUSIONS

The investigated system seems to be appropriate for on-line flood forecasting in large river basins provided the use of a meteorological radar is disadvantageous and the operative forecast is of interest at basin outlet.

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