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Flash flood forecasting using weather radar

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Abstract

A hydrometeorological study in a Pinios river subbasin was conducted to demonstrate the use of a WSR-74 S-band weather radar and raingage data for flash flood forecasting. A series of storm events recorded every 20 to 30 minutes were analysed and processed. Two different approaches were employed for the adjustment of the radar rainfall field. A rainfall-runoff model based on the unit hydrograph theory was applied by using as rainfall input raingage and radar rainfall information. It was found that the model performs better using weather radar combined with raingages than raingages alone.

1 Introduction

The traditional approach to flood forecasting is to use rainfall input estimated from a number of raingages driving a lumped parameter hydrologic model. The recent advent of new technologies such as weather radar and satellites, Geographic Information Systems and high-speed computer workstations provides new opportunities for improved hydrologic forecasting. However the new technologies present new challenges and also pose new questions. One central question regards the accuracy of rainfall estimates based on radar and satellite observations. Knowledge of this accuracy is of crucial importance for the assessment of the effects errors in rainfall estimates.

Flood damages in a given basin may be prevented or reduced by using short-term real-time forecasts of river flows. Practically, operational forecasting requires rainfall-runoff models incorporating a procedure for the correction of forecasts according to the discrepancies observed in earlier forecasts (O'Connell and Clarke, 1981). Weather radar provides spatial and

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temporal measurements of precipitation that are immediately available at one location but the accuracy of those measurements may not be adequate.

In this paper the research is focused on the implementation of weather radar for hydrological applications and especially for spatial rainfall measurement and estimation and consequently for flash flood forecasting and warning. Weather radar rainfall data were corrected from errors of multiple nature. Initially a ground clutter map was utilised for the suppression of the ground clutter. After the hourly integration of radar reflectivity data and the conversion to rainfall rate estimates by using the exponential Z-R relationship $Z=aR^b$, the radar rainfall values were corrected from a variety of error sources. Two different approaches namely the Kalman filter method and the Brandes method were employed for the need to merge radar and raingage rainfall information. A rainfall-runoff model the HEC1F model based on unit hydrograph methodology was applied to the Pinios river subbasin.

2 Study region and data used

The study region is located within the 100 km circle under the WSR-74 S-band Larissa radar umbrella. More specifically a Pinios river basin called the Ali Efenti basin, as shown in Fig. 1, with drainage area of 2763 km^2 was selected for the hydrological application (rainfall and runoff estimation and forecasting) of the radar collected data. The basin suffers from frequent and hazardous storm and consequent flash floods.

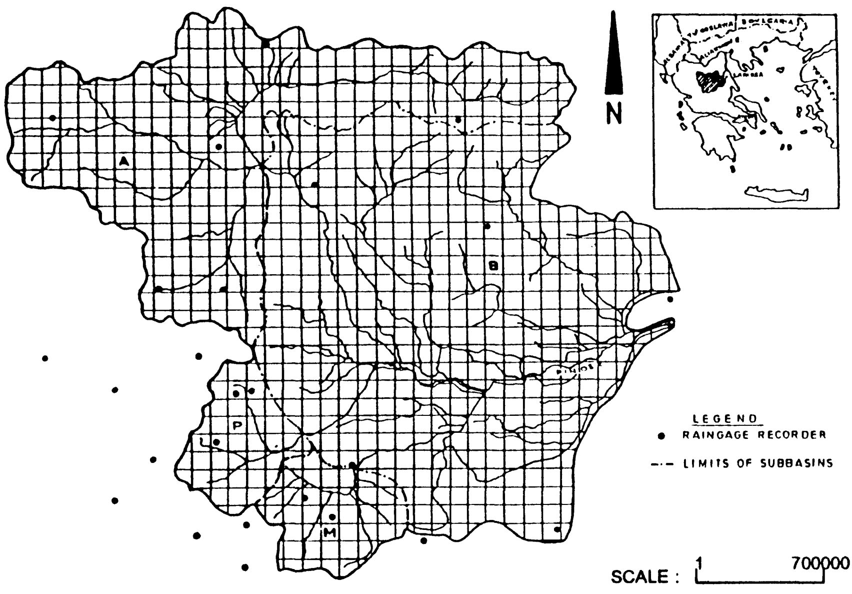

Figure 1: The study basin

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Regarding the ground truth monitoring twenty five raingage stations are operating in the range of 40 to 120 km over and near the basin. The basin is located in Western Thessalian region with vegetation varying from grasslands to dense forest. The climate of the basin is temperate and humid with substantial seasonal variation in temperature. Frequent and rapid changes in weather are caused by frontal air mass activity resulting in frequent flash floods. The topography of the basin varies from narrow gorges to wide flood plains. All the events analysed and processed belong to the same type of precipitation considered as cyclonic with moderate intensity long duration and widespread distribution.

3 Radar rainfall estimation

Rainfall estimation from radar measurements has been a frequent topic in meteorological, hydrological, and remote sensing literature within the last 35 years. Radar rainfall data free of errors is an ideal information source for the forecaster or the hydrologic models, since it has been stated that for catchments smaller than 1000 km^2 small-scale measurement errors may affect hydrograph predictions significantly (Georgakakos, 1987).

Despite the efforts to maintain a high level of quantitative accuracy in estimating precipitation by using radar data, it is certain that errors will be encountered in these estimates. In fact there is a variety of factors that can cause systematic, random, and range dependent errors. Some of these are due to the particle size distribution that is of special interest, since it determines the relationship between the radar reflectivity factor Z and the associated rainfall rate R. Others are due to vertical reflectivity profile because of high variability in growth, evaporation of precipitation, air motion and change phase. Another serious error factor is anomalous propagation which occurs when a cool moist air at the surface produces echoes from ground targets that are normally below radar horizon. Furthermore, ground clutter and shielding where the radar encounters ground targets add up to appear as large rain amounts. Common and serious problem encountered, is the one produced by hardware calibration, including the measurement of transmitted power, antenna gain, beamwidth, antenna pointing error, pulse duration, and receiver sensitivity.

Three dimensional polar co-ordinate maps of equivalent reflectivity factor Z in dbz are recorded every 20 to 30 minutes. The raw radar data measured in polar co-ordinates in dbz are converted to cartesian ones in dbz with grid dimensions 2x2 and 4x4 km^2. A large area under the radar umbrella suffers from ground echoes which is a fact prohibiting radar utilisation for such areas. Since the WSR-74 S-band radar system is not dopplerised a ground clutter map was utilised for the detection and suppression of the ground clutter from radar rainfall fields. The ground clutter map was measured during a cloudless sky in the optimum elevation of 0.8 degrees. The optimum angle elevation was derived after drawing the longitudinal cross-section from topographic maps from the radar site to the Ali Efenti basin. After the integration of radar reflectivity data in whole hours the well known Marshall-Palmer Z-R exponential relationship was applied for the conversion of the radar reflectivity data to rainfall estimates. The reason that the Marshall-Palmer relation was used is that all the events analysed and processed found to have a ranging from 170 to 215 and b from 1.2 to 1.6 relatively close to the Marshall-Palmer coefficients where a=200 and b=1.6.

The next step is the application of the influence function method (Krajewski, 1987), which is applied to solve the problem of outliers detection resulting from errors due to abnormal beam refraction and losses, anomalous propagation, and interference of signal from other than rain targets. This method applied to radar rainfall fields is based on analysis of spatial correlation in the field. The reason that the method was selected is that applied to the same type of precipitation considered as cyclonic, doesn't require any external information or calibration, as well as any knowledge of distribution of the data and can be fully automated and used in an on line mode.

4 Radar raingage combination

In order to cope with biases in radar rainfall estimates the joint use of radar and raingage data has been recommended (Doviak and Zrnic, 1984). Joint use of radar and raingage data aims at the utilisation of the high point accuracy of the latter and the wide areal coverage of the former.

Two different approaches were developed for the need to merge radar and raingage rainfall information and thus to improve radar rainfall estimates in a number of storms, trying to explain quantitatively any discrepancies between the rainfall amounts indicated by the two different measurement techniques. The main characteristics of the first method the Brandes one, (Brandes, 1974) based on G/R ratio, is the comparison between radar and raingage measurements in order to achieve adjustment factors which are used to force radar estimates to agree with raingage observed values. In this method an adjustment factor derived by using the raingages located in a selected range around that point is assigned to each grid point. The adjustment factor F1 at each grid point is a weighted mean of the N raingage observations

$$F1 = \sum_{i=1}^{N} W_{Ti} G_i \, / \, (\sum_{i=1}^{N} W_{Ti}) \tag{3}$$

where W_{Ti} is a weight function depending on the range from the raingage to the grid point r given by

$$W_{Ti} = \exp(-r^2/EP) \tag{4}$$

where EP is a filtering parameter considered constant.

The second method is a more advanced method proposed by Ahnert et al. (1986) to estimate the mean radar rainfall field bias based on a Kalman filter procedure as a technique to achieve a fast adjustment. This technique was selected because it is very efficient for computer processing and therefore for real-time utilisation and has some advantages over the classical G/R methods.

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Furtermore, it avoids instability associated with low R values in G/R ratios, provides an estimate of the error in the computed bias and combines an estimate of the bias and its error variance made one hour before with the actual measurements and the estimated measurement error variance to compute an updated bias estimate taking into account the noise in the measurement and new forecast for the next hour. This technique is based on a mathematical model composed by two equations. The two equations used in the Kalman filter method are the system equation given

$$B(t) = B\,(t\text{-}1) + S \qquad S \sim N\,(O, Q) \tag{5}$$

and the observation equation given

$$G(t) = R(t)\,B(t) + M \qquad M \sim N\,(O, F) \tag{6}$$

where B represents the Bias, G and R are the hourly raingage and radar rainfall amounts respectively, and M and S are the additive noises approached by a normal distribution with mean zero and variance Q supposed known and constant. Figure 2 shows the uncalibrated radar rainfall field and the calibrated one using the G/R ratio for the event of 18/11/1992.

5 Flood flow forecasting

The HEC1F computer program an adaptation of the computer program (HEC-1, 1985) widely used in flood-runoff analysis based on the unit hydrograph theory was applied. HEC1F is intended for short term forecasts of flood runoff since it doesn't provide a continues accounting of soil moisture. The HEC1F model uses a two-parameter unit hydrograph model, a two-parameter loss model and a three-parameter base flow model.

It has already been shown that the model performs better in a semi-destributed manner by dividing the entire basin into a number of subbasins incorporating the extreme spatial variability of the storm events and accurately simulate the evolution of the resulting flash-flood in the study region than in the lumped manner by using the entire basin (Mimikou et al., 1993b). This supports the idea of applying the HEC1F model by using as rainfall input the average radar rainfall over the basin in order to take into account the extremely uneven and non-uniform rainfall distribution in the study region. A series of storm events acquired producing flash floods were analysed and processed. Respresentatively, as depicted in Fig. 3 the model's performance appears to be improved when the model is applied by using weather radar data, encouraging thus the use of weather radar for flood flow forecasting. A multiple step ahead forecasting was carried out using lead-time 2, 4 and 6-hours, as shown representatively in Fig. 4. Forecasts were carried out for each flood event beginning on the rising limb and updating them until the observed peak flow had passed. These results encourage the idea of developing a flood flow forecasting model in a fully distributed manner on a 2x2 km^2 or 4x4 km^2 grid network combined with distributed on-site and remotely sensed rainfall input information taken by the nearby S-band radar.

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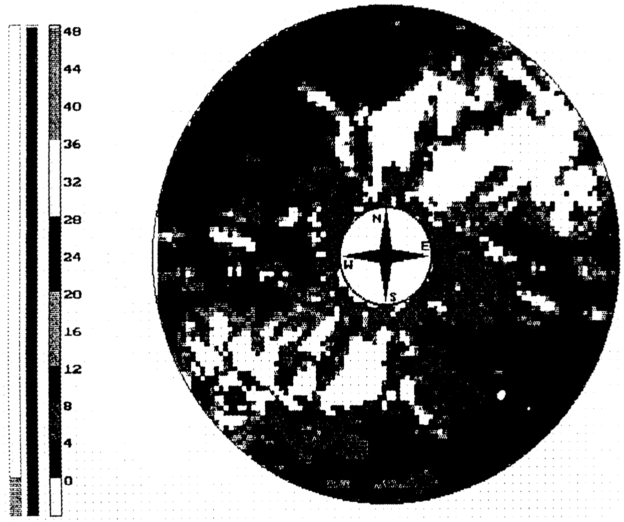

Figure 2: Unacalibrated radar rainfall fied for the event of 18/11/92 (11:00-12:00).

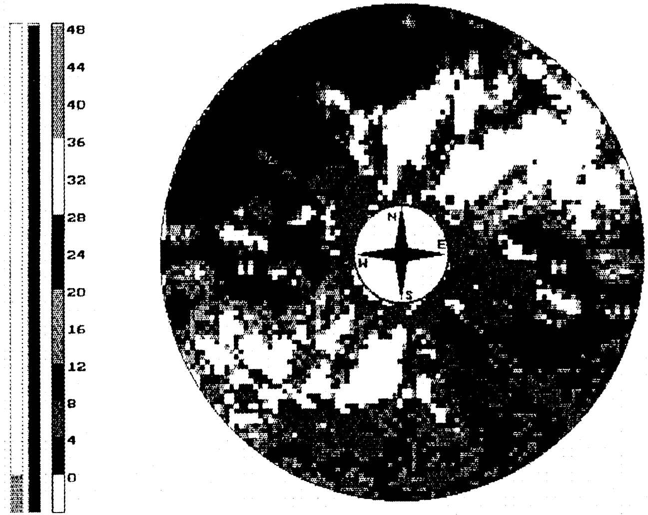

Figure 3: Calibrated radar rainfall field for the event of 18/11/92 (11:00-12:00).

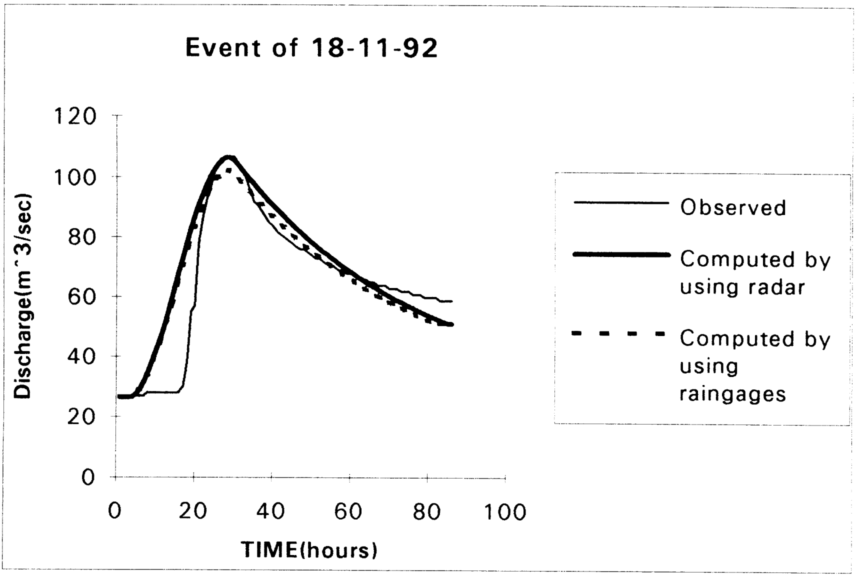

Figure 4: Observed versus flood hydrographs based on raingage and radar data.

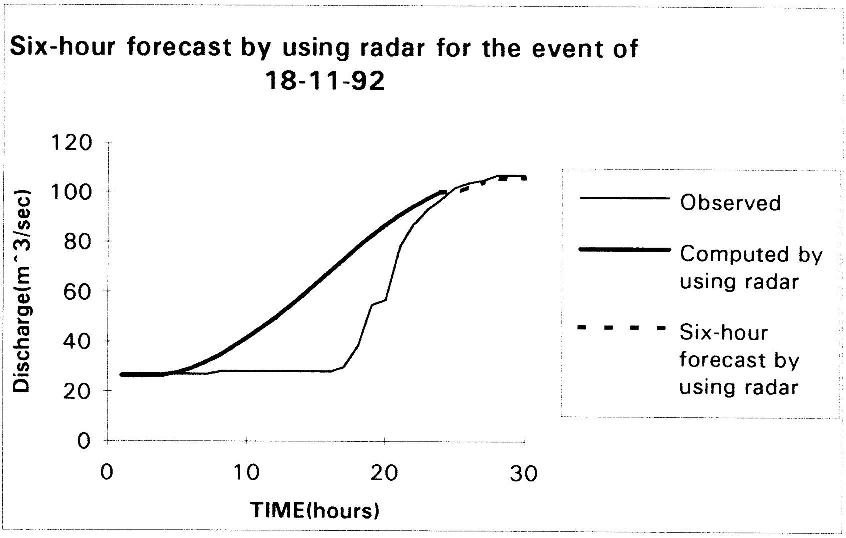

Figure 5: Six-hour forecast by using radar data.

6 Summary and conclusions

A number of storm events under the same objective criterion that is the type of precipitation producing flash floods were analysed to evaluate flood-flow forecasting by using weather radar data for the basin of Ali Efenti located within the 100 km WSR-74 S-band radar umbrella. All rainfall patterns converted from polar co-ordinates to cartesian ones with dimensions 2x2 and 4x4 km^2 were corrected from a variety of error sources coming from ground clutter, abnormal beam refraction and losses, anomalous propagation, and interference of signal from other than rain targets. A Z-R relationship for each event was derived by estimating the coefficient a and b and was found that a and b for all the events are close to the ones of Marshall-Palmer Z-R exponential relationship. For the conversion of the biased weather radar rainfall estimates to the unbiased ones two different approaches namely the Kalman filter method and the Brandes method were employed. It was found that weather radar with adequate precipitation gaging stations for calibration can be effective for flood forecasting. The rising limb and peak discharge of all streamflow hydrographs computed from weather radar data and calibrated with precipitation gaging station data were more accurate than the rising limb and peak discharge of hydrographs computed from gage precipitation data alone.

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