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Near Real-Time Tests of a Multivariate Analysis System

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1. INTRODUCTION

Weather radar's ability to measure precipitation continuously in time and space makes it a very attractive tool for hydrologic applications. Most of the existing operational streamflow forecasting systems use mean areal precipitation (MAP) over a basin as the main input driving the system. Traditionally, MAP is computed from rain-gage data via some interpolation techniques (see Sing and Choudhury, 1986, for references). Radar systems, if equipped with the necessary digital signal processing capabilities and applications, can provide similar information. A number of papers describe and discuss hydrologic applications of radar systems (Kessler and Wilk, 1968, Anderl et al., 1976; Crawford, 1979).

To experience the full benefit of radar in an operational hydrologic forecasting system, the system has to be totally automated. Although the radar systems are in general very well suited for automation, the blind use of radar-rainfall data can lead to serious problems. As has been demonstrated in many studies, radar-rainfall data are often subject to high errors, both random and systematic. For the discussion of some of the error sources see for example Austin (1964).

There is a consensus among researchers that in order to improve the reliability and accuracy of radar-rainfall data, rain-gage data should be used. The process has been called "calibration" and can be dealt with on various levels of sophistication. Some of the more sophisticated techniques used are described by Brandes (1975), Crawford (1979), and Ahnert et al. (1986). Krajewski and Hudlow (1983), Krajewski (1986b), and Creutin and Delrieu (1986) describe an approach which should be termed estimation rather than calibration due to the fact that neither radar nor rain gages measure what hydrologists use in their models, i.e., MAP. Thus, MAP values have to be estimated from both radar and rain-gage data. This paper describes the first operational experience and problems with a precipitation data processing system that is based on such an approach. This interim system contains some of the "core" elements of a more comprehensive precipitation processing system to be implemented coincident with the Next Generation Weather Radar (NEXRAD) systems beginning in 1989. For a description of the NEXRAD era precipitation processing system, see Ahnert et al. (1983) and Hudlow et al. (1983).

2. DATA DESCRIPTION

Radar-rainfall data used in this study come from a WSR-57S radar equipped with a Radar Data Processor II (RADAP II) system installed at the Weather Service Forecast Office (WSFO) in Oklahoma City, Oklahoma. The system produces hourly estimates of rainfall on a 2° by 1 nautical mile resolution polar grid. The radar range is approximately 140 miles and covers a large part of the Tulsa River Forecast Center (RFC) which is responsible for issuing streamflow forecasts for that area. Radar data are transmitted to the Central Computer Facility (CCF) of the National Weather Service (NWS) in Suitland, Maryland where the data are transformed to the so-called Hydrologic Rainfall Analysis Project (HRAP) grid which is roughly rectangular with a resolution of approximately 4 km on each side. For a detailed description of the RADAP II and HRAP coordinate systems, see Greene et al. (1983) and Greene and Hudlow (1982), respectively.

Rain-gage data used by the Tulsa RFC come from various networks maintained and operated by organizations such as the National Weather Service (NWS), U.S. Geological Survey (USGS), and Corps of Engineers (USACE). Most of the rain-gage data are daily accumulations with only a few stations reporting 6-hourly data. There are some networks in the area that report hourly data, but they are not currently used in the operation of the Tulsa RFC. Rain-gage data are also transmitted to the CCF of NWS where they are accessed for subsequent analysis.

As was pointed out, both data sets are collected on different time scales. In order to make them compatible with each other, the radar data are accumulated to form 6-hourly and daily (24-hourly) data sets.

3. ESTIMATION ALGORITHM

Krajewski and Hudlow (1983) list requirements that a method which combines multiple sensor rainfall data should meet. It has been determined that a stochastic interpolation technique called cokriging (see Journel and Huijbregts, 1978) can be adopted to meet these requirements. The procedure, which follows, is here also called "merging" or "multivariate objective analysis."

The main idea of the cokriging method is to use spatial covariance analysis in order to obtain the weights of a linear estimator. The estimator has the form:

$$\hat{Y} = X \cdot \beta + \varepsilon \qquad (1)$$

where, $X = \langle X_G, X_R \rangle$ are gage and radar observations,

$\beta = \langle \beta_G, \beta_R \rangle$ are coefficients (weights),

and

ε is estimation error.

The vector of weights (β) can be estimated by minimizing the estimation variance:

$$\min \mathrm{Var}\{Y - \hat{Y}\} \qquad (2)$$

under unbiased conditions:

$$\Sigma \beta_G = 1$$
$$\Sigma \beta_R = 0 \qquad (3)$$

This leads to the system:

$$\begin{vmatrix} \beta_G \\ \beta_R \end{vmatrix} = \begin{vmatrix} \mathrm{Cov}(G,G) & \mathrm{Cov}(G,R) \\ \mathrm{Cov}(R,G) & \mathrm{Cov}(R,R) \end{vmatrix}^{-1} \begin{vmatrix} \mathrm{Cov}(G,Y) \\ \mathrm{Cov}(R,Y) \end{vmatrix} \qquad (4)$$

The terms in Eq. (4) are covariance matrices which can be estimated from the data, except the terms Cov(G,Y) and Cov(R,Y). These two represent the covariance of the measurements (either radar or rain gage) with the true value of rainfall. They are unknown and are estimated from a simple parameterization of terms Cov(G,G) and Cov(R,R):

$$\mathrm{Cov}(G,Y) = \alpha_G \cdot \mathrm{Cov}(G,G)$$

and

$$\mathrm{Cov}(R,Y) = \alpha_R \cdot \mathrm{Cov}(R,R)$$

The sensitivity of the method to this model has been studied within a framework of a fully controlled experiment and described by Krajewski (1986). For the purpose of our test, the parameters α_G and α_R were both set to 0.5.

The actual computational algorithm works as follows:

(a) Estimate the spatial covariance function from the rain-gage data.
(b) Interpolate gage data to obtain a gridded analysis.
(c) Compute the covariance matrices of the radar data, gridded data obtained in (b), and the cross-covariance matrix.
(d) Merge the two fields using cokriging.

That way the cokriging system, Eq. (4), needs to be solved only once and the same weights can be applied to all the grid points. This is due to the constant geometry in the cokriging process once the gage data are interpolated to the grid points.

4. SEMI-OPERATIONAL TEST

One way to evaluate the performance of the described procedure is to check the improvement in streamflow forecasting accuracy which highly depends on the quality of rainfall input. Five basins have been selected for this purpose. The basins are located to the north and northeast of Oklahoma City and range in size from 150 to 2000 square miles. Their distance from the radar site ranges from 15 to 100 miles.

Streamflow forecasting is done using the National Weather Service River Forecasting System (NWSRFS) Version 5 which has a basic time step of 6 hours. This means that the input is composed of 6-hourly time series of MAP. Currently, the MAP time series is computed based on daily rain-gage data and distributed in time into 6-hourly intervals based on a few 6-hourly reporting gages. The model is run once a day producing forecasts up to 72 hours ahead. In the test, the MAP time series is produced after the rain-gage data are merged with radar data. The merging is done on daily data and the product is time distributed based on radar 6-hourly data. This method of estimating rainfall introduces many additional inaccuracies but is dictated by the reality of the operational environment, i.e., the small number of 6-hourly gages. In the future, when the Next Generation Radar (NEXRAD) is in place, and there are more automated rain gages, the merging will be done on a 6-hourly basis, and ultimately on an hourly basis, which is required especially in flash-flood situations.

In our test, the NWSRFS model is run twice, once using the MAP generated by the current operational procedures, and the second time, using the merged input. The evaluation is based on the comparisons of both simulated hydrographs against the observed data.

Although it seems like a very natural way of testing a new rainfall estimation method, one needs to be cautious while interpreting the results. First of all, the hydrologic model used is a conceptual-type model with parameters estimated based on historical data records. Since the quality (in the sense of error structure) of the new input is quite different from the old one (based on rain-gage data only), the model is really not calibrated for the new input and this fact could be responsible for some inconsistencies. Ideally, one should collect a record of at least 3 to 5 years of data, recalibrate the model, and then proceed with the test. Another way to avoid miscalibration problems would be to run the test with an automatic update procedure implemented in the model so that the states of the model would be more "tuned" with the new input and less dependent on the model's parameters. Both approaches are planned for the future testing.

The second problem is the quality of the radar and rain-gage data with more emphasis on the former. Since the intention of the study is to test an operational procedure, some steps should be taken to ensure high quality of the radar data. These steps should be fully automated and take care of anomalous propagation (AP) contamination of the radar data as well as other outliers present both in radar and rain-gage data. The word outliers is used here in a very general sense but refers basically to either unrealistic data values or values with gross errors. Such steps, although designed and partly tested (Fiore et al., 1986; Krajewski, 1986a; and Krajewski, 1986b) were not implemented in the part of the test reported on here.

5. RESULTS

The operational test runs were initiated at the beginning of April 1986. In this paper the results for the period of April 21 through May 28 are presented. Since there was only one major storm in the test area in Oklahoma during that period, and flow data are collected on most of the test basins only during flood situations, the results presented here are for only one basin which had a continuous flow record. The Deep Fork River basin (2018 sq. miles) is the largest of the test basins. Its stream gage is located at Beggs, Oklahoma.

Figure 1 presents two rainfall inputs: one based on rain-gage data only, and the second based on the merged radar and rain-gage data. Figure 2 presents the corresponding hydrographs. The figures support our previous arguments that a much longer record is necessary for any conclusive results. For the case presented here, the input based on gage data only lead to overestimation of the flood peak; however, the timing was better than for the merged data based input. In order to better understand the quality of the merged data based input, we should mention some problems concerning the amount and quality of our radar data. For only a few days, out of the total of 38 days, were more than 20 hours of data received, 4 days received no data at all, and 8 days received less than 10 hours of data. This fact, plus the presence of AP on at least 15 days significantly lowered the potential for benefiting from the use of the radar data. However, both problems can be solved. The first problem, not getting all the hours of data, is strictly operational and will hopefully be resolved in the near future by slight modifications of the communication software. The second problem, lack of automated AP elimination, can be dealt with using, for example, satellite data, at least in clear-air situations. Other methods for cloudy skies are being developed as well.

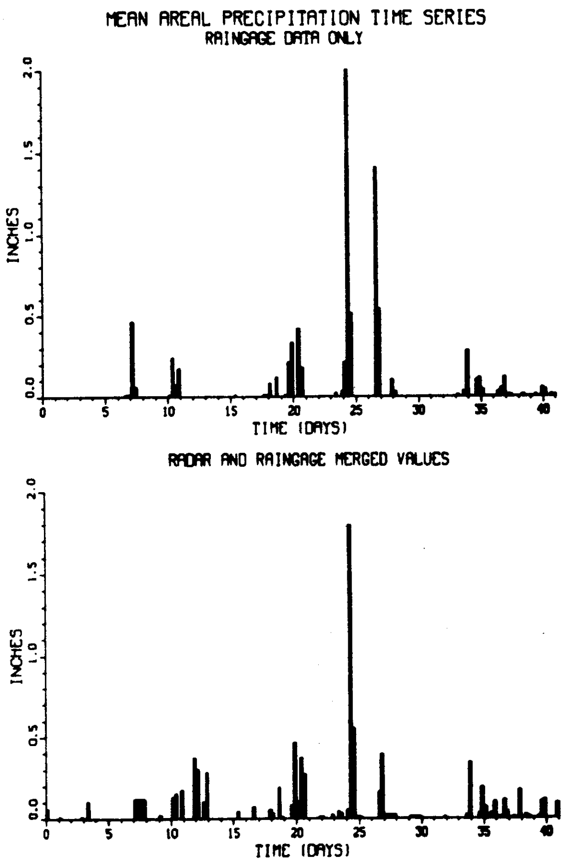

Fig. 1. Rainfall input for Deep Fork basin at Beggs, Oklahoma. Time units correspond to days beginning April 21, 1986.

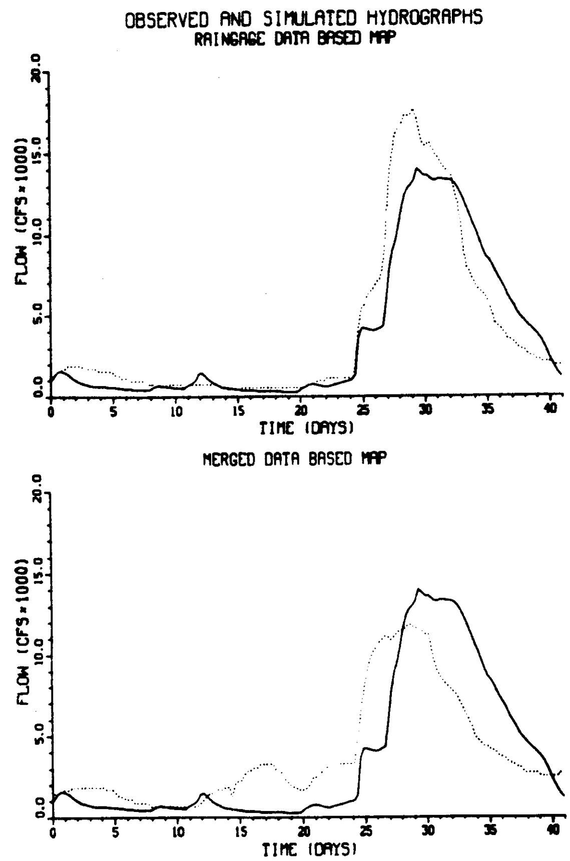

Fig. 2. Observed and simulated hydrographs for Deep Fork basin at Beggs, Oklahoma. Time units correspond to days beginning April 21, 1986.

The way AP affects the estimates of rainfall is twofold: first, the radar-rainfall estimates themselves are in error; and second, the estimates of the covariance matrix of the radar data and the cross-covariance of the radar and rain-gage data are in error, affecting the optimality of the weights in our interpolation procedure. For the case presented here, the presence of AP caused spurious MAP at the beginning of the test period, which in turn lead to superficially wet conditions of the hydrologic model states and, consequently, bad timing of the following flood event.

6. CONCLUSIONS

The very first experience with the hydrologic application of the fully automated precipitation processing system combining multisensor rainfall data is described. The setup of a semi-operational test experiment and the multivariate objective analysis procedure are discussed. Although the limited experience precludes any definite conclusions as far as the quantitative benefits are concerned, it clearly identified three major problems which need to be solved if any similar system is to be successful:

(a) Reliable communication. It is of critical importance that all the radar data are collected and processed. It is especially important for convective type storms where one missed hour may mean a missed storm.

(b) Elimination of AP and other quality control steps. Automated procedures must be developed and implemented to ensure that radar data are of the highest possible quality prior to entering any merging with other (in situ) sensors data (which should be quality controlled as well).

(c) Compatibility of rainfall estimates and the hydrologic models used. It is important that time sampling scale is compatible for rainfall data coming from various sensors and that the estimates produced are compatible with the time scale of the hydrologic model input. The hydrologic models should be calibrated for the new quality input data; otherwise, biased estimates of streamflow may result.

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