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A RADAR RAINFALL FORECASTING METHOD DESIGNED FOR HYDROLOGICAL PURPOSES

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ABSTRACT

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Advanced techniques in sewer management need a reliable rainfall forecasting methodology to satisfy the urban hydrologist. In close cooperation with the users, a community remotely controlling a suburban county of Paris, specific requirements were precisely defined. The proposed forecasting method is based on recent advances of pattern recognition and image processing. Its user-defined hydrological features focus on heavy rainfall and on accuracy at a small time–area scale. The reliability of the actual forecast is calculated and issued in real-time. By comparison with earlier forecasting methods, the proposed method proved to be slightly superior in hydrological terms. However, the appropriate quality criteria always depend on the application. Further research is being undertaken in this direction. The method has been in operational use since May 1988.

INTRODUCTION

In the last five years, a requirement for spatially and temporally detailed rainfall forecasts has emerged from research on real-time control of sewer systems. The reasons for controlling urban combined drainage systems are storm water problems, such as water quantity in the sewer network, and water quality of the receiving waters. The design and operating conditions for such a control scheme can vary widely depending on the local conditions (Schilling, 1985). However, common features are that:

(1) measurements are made in real-time;
(2) control has to be performed within a strictly limited time;
(3) the control objectives are well known, but contradictory;
(4) the system is too complex to be manipulated manually.

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Rainfall is the most important factor for the actual flow volume in the sewer (Schilling and Fuchs, 1986). Schilling and Petersen (1987) and Denoeux (1988) proved that there is a considerable gain of time using short-term rainfall forecasts (30–60 min) of high spatial accuracy. This allows for an improvement of on-line defined control strategies and for additional control actions.

Rainfall forecasts, based on reliable radar rainfall measurements with an error of the order of 30% (Bellon and Austin, 1984), can add valuable information. The hydrological impact of difficulties in measurement, owing to radar calibration and maintenance, will not be discussed here; a more detailed description of these topics and of the radar rainfall measurement technique can be found in Collier (1986a) and Wilson and Brandes (1979).

PROJECT AREA

The Seine-Saint-Denis county, a Paris suburban area (Fig. 1), is a flat, highly

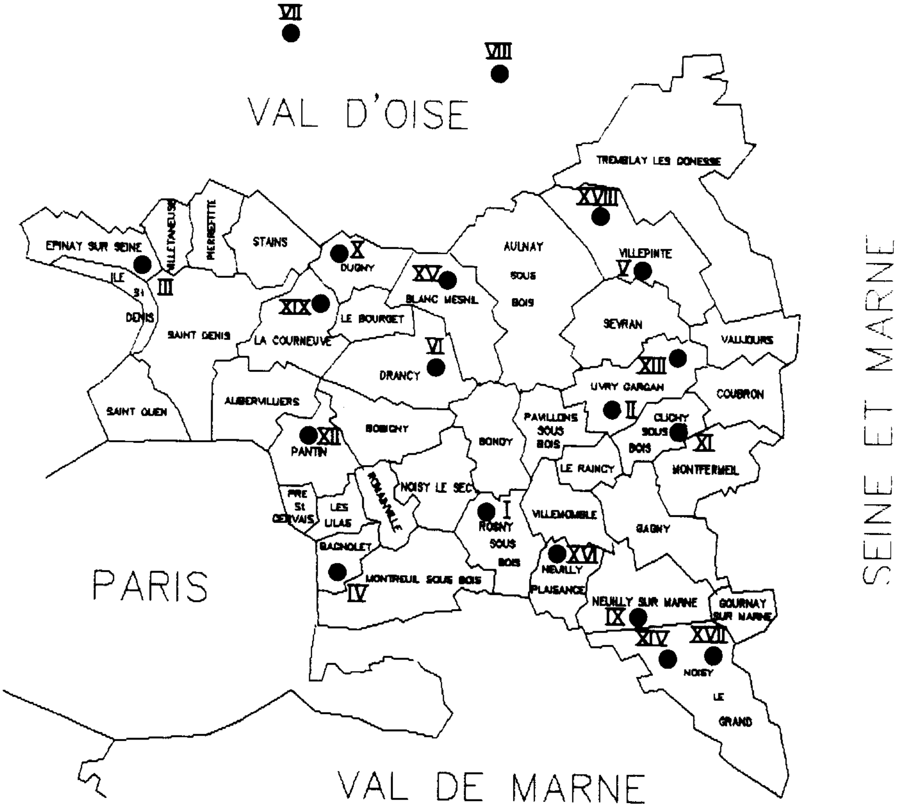

Fig. 1. The Seine-Saint-Denis county (the roman numbers denote the raingauge sites).

impervious area of 250 km^2 and 1.5 million inhabitants (Bachoc et al., 1984). Frequent flooding of the urban area and pollution of the river Seine occur because the rapidly growing new cities have been connected to the old county sewer system.

In 1981, it was decided to start a real-time control scheme, allowing for about 700 000 m^3 of rainwater to be temporarily stored in retention facilities in the event of flooding or pollution hazards. Proper operation of a retention basin necessitates detailed knowledge of the current flows in the sewer system as well as reliable information on future local rainfall and its runoff into the system. Hence, studies directed towards the use of radar rainfall forecasts were added to the project in 1985. They considered three hierarchical control goals, flood prevention, pollution reduction and cost minimization (basin cleaning, etc.), provided that the security of the sewer teams is always guaranteed.

STATE-OF-THE-ART OF RADAR RAINFALL FORECASTING

Few studies concentrate on hydrological applications of radar rainfall forecasts; all of them stress the need for further research and development (Damant et al., 1983; Jacquet, 1983; Schilling, 1984; Bellon and Austin, 1984). Some hydrometeorological projects have led to promising results, but none of them has become fully operational (Saffle and Green, 1978; Brunkow, 1980; Huff and Vogel, 1981; Fouroud et al., 1984).

As for rainfall forecasting methodologies, the approaches developed some 15 years ago have not changed. Owing to limited storage capacities, 'global' forecasting approaches were based on the comparison of whole radar images (e.g. Barclay and Wilk, 1970; Austin and Bellon, 1974; Collier, 1978, 1981; Bellon and Austin, 1978; Browning et al., 1982). The rapid development of computational capacities in the last ten years has led to more sophisticated 'structured' approaches in real-time.

The 'global' approach is based on the statistical comparison of the rain fields in two successive radar images, using, for example, the cross-correlation function. The cross-correlation coefficient is calculated for different displaced

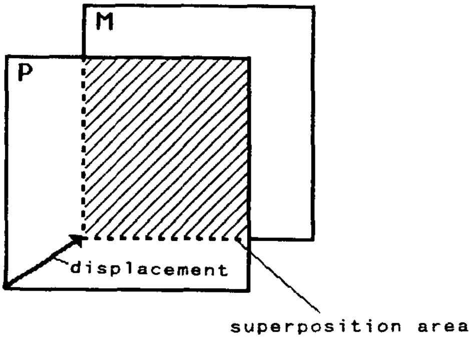

Fig. 2. Superposition of two images P and M for the calculation of the cross-correlation coefficient.

superpositions of the two images (Fig. 2). Its maximum indicates the most probable displacement. The forecast is obtained simply by extrapolating the displacement vector, applied to the whole image.

However, different directions of movement of rainfall areas cannot be recognized or forecast in this way. As a result, images have been divided into several regions which are treated independently by the 'global' approach (Bellon et al., 1980).

Since 1978, early 'structured' approaches, i.e. pattern recognition oriention (Ostlund, 1973; Blackmer et al., 1973) have been improved. Methodological work (Wiggert and Ostlund, 1975; Bjerkaas and Forsyth, 1980; Einfalt and Schilling, 1984), including that on satellite images (Endlich et al., 1970; Wolf et al., 1977), led to the incorporation of more advanced image processing techniques.

The 'structured' (pattern recognition) approach essentially consists of four steps: (1) 'simple' echo definition; (2) echo description by features; (3) echo matching; (4) forecast by vector extrapolation.

In the first instance, the image points (pixels) are grouped to form entities, which are called 'echoes'. As a simple connectivity test is usually performed, these echoes are called 'simple echoes'. For each of these echoes, the most significant features are calculated, be it form features, historical or statistical ones. Thereafter, echoes of two successive images are matched by using only their features. This results in a displacement vector for each individual echo. Finally, the calculated displacement can be extrapolated individually for every single echo. The echoes that have not been matched, are displaced globally.

As the pattern recognition-oriented approach tries to recognize individual 'radar echoes', it is appropriate to meet hydrological concerns regarding the 'most threatening rainfall areas'. This was the rationale for the choice of the scout II.0 method (Einfalt and Schilling, 1984; scout stands for *s*econd moments *clou*d *t*racking) for solving the particular problems at the Seine-Saint-Denis catchment.

THE SCOUT RAINFALL FORECASTING APPROACH

The objective of pattern recognition in rainfall forecasting is the recognition of rainfall structures, either rain cells or more complex structures, having a homogeneous behaviour. This behaviour has to be uniform both in time and space. The three basic hypotheses of this approach are: (1) uniform spatial behaviour of a rainfall structure (no split or merge); (2) uniform temporal behaviour of a rainfall structure (no growth or decay); (3) representation of a rainfall structure on the radar image as one echo.

None of the above hypotheses, however, is realistic. Depending on the meteorological situation, the physical rainfall process is seldom spatially or temporally uniform. Also, a rainfall structure does not generally appear as a connected region on a radar image. However, a more appropriate echo definition leads to a technique that is not based on the first and third

Fig. 3. Echoes, their connectivity and their forms as a function of the working threshold. A threshold level of 5 is marked, compared with the outline (level 1).

hypotheses above. Further improvements may even be powerful enough to eliminate the need for uniform temporal behaviour.

To concentrate on the most important rainfall structures, a 'working threshold' is defined on-line, based on the mean image rainfall intensity. A rainfall structure as defined above may or may not appear spatially connected on a radar image (Fig. 3). As connectivity is the defining feature for 'simple echoes', both cases have to be considered by any reliable forecasting method that is based on rainfall structures. A technique to introduce them into the reasoning is the definition of 'structured echoes', the union of two or more 'simple echoes' that are connected in an artificial manner.

Considering a set of n simple echoes $\{e_l, \ldots, e_n\}$, a first structured echo e^* is defined by

$$e^* = e_i \cup e_j \tag{1}$$

with

$$\text{edist}(e_i, e_j) = \min\{\text{edist}(e_k, e_l), k \neq 1\} \tag{2}$$

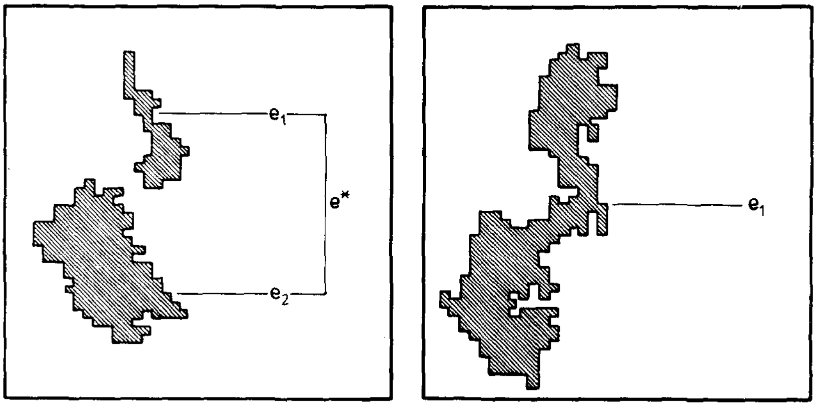

Fig. 4. The construction of the structured echo e^* (left) and its use for recognition of echo e_1 on the following image (right).

and

$$\text{edist}(e_i, e_j) = \frac{m_i + m_j}{m_i \times m_j} //c_i - c_j//^2 \tag{3}$$

where: m_i is the mass (see Table 1) of echo i; c_i is the centroid of echo i; $//.//$ is the euclidian distance.

Using automatic classification theory (Emptoz, 1983), this technique takes into account the physical importance m of the echoes as well as their euclidian distance for calculating a new distance between them, thus focusing on heavy (intense) rainfall areas.

For defining the next structured echo, e^* substitutes e_i and e_j (Fig. 4), and the algorithm is repeated until a terminal condition is reached (e.g. maximal number of structured echoes; min $\{\text{edist}(e_k, e_l), k \neq 1\}$ showing no mutual influence of the echoes).

The echo features (Step 2) have been chosen according to the scout idea,

TABLE 1

Features used to characterise the echoes

$* n$	:	size — number of pixels
$* m$	:	mass — rainfall volume $= 1/n * \sum_{i \in e} R(i)$
		where $R(i)$: measured rainfall intensity at pixel i
$* c$	:	centroid — centre of gravity
$* a$	:	orientation (angle of the principal axis of inertia)
$* E$	:	elongation (quotient of the principal moments of inertia)
$* D$	:	intensity distribution
$* n_0$	:	previous size
$* v$	:	previous movement vector
$* \sigma_v$	:	rms-variation of previous movement vectors
$* n_p$	:	number of previous recognitions of the echo

mainly using the echoes' moments up to second order (Table 1). This also allows rapid calculation of all the features of structured echoes.

For the matching process (Step 3), all elements of the resulting binary chain of simple and structured echoes are used. First, all possible matching partners are pre-selected on the basis of speed and size considerations as well as on the previous movement. Secondly, a heuristic analysis of the form features and of their variation is performed to choose the 'right' partners and to eliminate the unwanted pre-selected pairs. This analysis relies on the echo features size, previous movement, elongation, orientation, and intensity distribution, and a reasonable degree of change in each of the features is admitted. This matching process results in a displacement vector for each individual echo. The forecast is then made by displacing each echo by its vector. This technique allows the history of echoes to be followed even after splitting and merging and is therefore no longer based on Hypotheses 1 and 3.

FORECASTING QUALITY

To judge the absolute quality of a forecast or to compare the performance of different forecasting methods, both a reference and a quality criterion have to be determined.

Despite the methodological problems raised by the comparison between point and areal rainfall measurements (Collier, 1986b), raingauge data have been frequently used by hydrologists and meteorologists to assess the quality of radar measurements and forecasts (Bellon and Austin, 1984). Considering these problems and the sparseness of available raingauge data, we chose to use radar measurements as the reference during the development phase of the method. We are well aware that this choice introduces a bias in the absolute performance values expressing the comparison between forecast and reality, because some radar measurement errors (especially systematical ones) are not taken into account properly. However, the comparison of the forecasting performance of different methods can be expected not to be affected by this bias.

Since the beginning of the operational use in May 1988, real-time raingauge and flow data have started to be available, thus providing the possibility to analyse more completely the quality of the implemented forecasting method.

TABLE 2

The Critical Success Index (CSI) (a, b, c, and d are numbers of pixels)

Measured	Forecast	
	Rain	No rain
Rain	a	b
No rain	c	d

with CSI $= a/(a + b + c)$

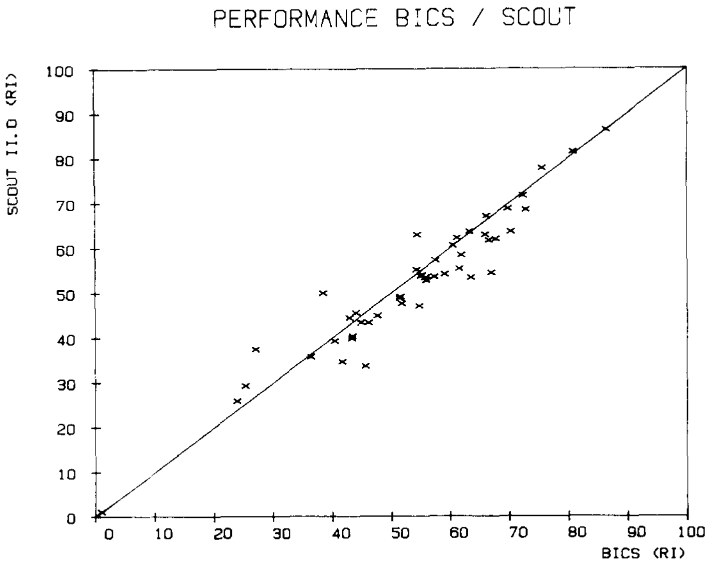

Fig. 5. Rousseau Index scores of Bics vs. scout II.0 (forecasts with 15 min lead time).

The problem of the adequacy of a quality criterion for the requirements of a particular user has not yet generally been solved (Denoeux, 1989). Nevertheless, it remains that this choice has to be guided by the intended application. Following this basic idea, specific quality indicators have been defined, which were jointly used with more traditional ones (critical success index (CSI), Table 2, and cross correlation (CC)), to enable a comparison with other research results. Results of other statistically based criteria, like RMS-error or Rousseau Index, approximated those of CSI and CC, and therefore their results are not explicitly included in this analysis (Fig. 5).

A new quality criterion

The hydrological system in the Seine-Saint-Denis county is known to be much more sensitive to underestimation than to overestimation of rainfall. Bad control strategies result from overestimation over 150% whereas this threshold is 50% for underestimation (Denoeux, 1988). Hence, a proper quality criterion for this application has to distinguish between over- and underestimation, concentrate on hydrologically significant rainfall and compare the rainfall forecast on an areal basis (urban drainage catchment).

To satisfy the last point, the new criterion uses an average value of nine points for calculating a 'local areal rainfall' (Fig. 6). Thus, the measured areal value $M(i)$ and the forecast areal value $F(i)$ of a pixel i are obtained from the measured and the forecast (instantaneous) radar image, respectively. For the calculation of the forecast error $dH(i)$, (eqn. (4)), only the pixels i with a

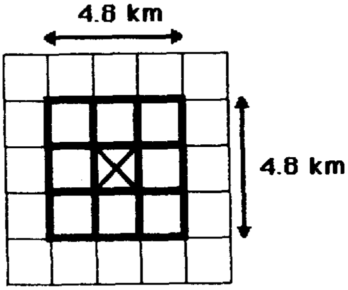

Fig. 6. The 'local areal rainfall'.

measured local areal rainfall value greater than 1 mm h^{-1} and within a distance of 100 km from the radar are considered (second point).

$$dH(i) = F(i) - M(i) \tag{4}$$

Denoting by n^+ and n^- the number of cases where $dH(i)$ is positive or negative, respectively, the overestimations dH^+ and the underestimations dH^- are given by eqns. (5) and (6).

$$dH^+ = (1/n^+) \sum dH(i), \quad dH(i) < 0 \tag{5}$$

$$dH^- = -(1/n^-) \sum dH(i), \quad dH(i) > 0 \tag{6}$$

In this manner, the more important danger of underestimating the real rainfall volume can be taken into account in the interpretation phase of the results.

This set of criteria satisfies the above points, and therefore expresses model

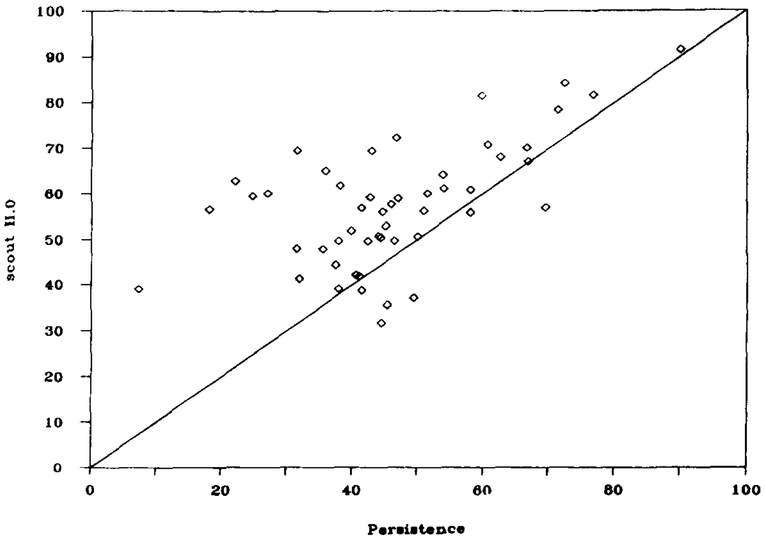

Fig. 7. CC scores of scout II.0 vs. persistence (forecasts with 15 min lead time).

quality in the hydrological terms important for the Seine-Saint-Denis sewer system.

Test results

A test was performed, comparing the 'global' CC method bics (Ciccione and Pircher, 1984) and the scout II.0 method (Einfalt, 1988) with more simple methods, such as persistence or the mean wind value between 3000 and 5000 m altitude, measured once every 12 h. The performance quality of the simple methods proved to be considerably inferior to the more sophisticated methods (Fig. 7), according to all of the considered criteria. Therefore, a more detailed analysis has been restricted to the latter ones.

A set of more than 1000 radar images was used, representing 50 meteorologically different events from the Trappes C-band radar of the French National Meteorological Service. The images were characterized by a temporal resolution usually of 15 min and consisted of 256 × 256 pixels on a 1.6 km^2 grid, digitized to 16 reflectivity levels. All forecasts in this study had a lead time of 15 min (Jacquet et al., 1986; Einfalt and Denoeux, 1987; Denoeux et al., 1987).

As was expected, the bics method performed slightly better on the CC and CSI criteria (Figs. 8 and 9) than the scout II.0 method.

The dH^- criterion indicated that the scout II.0 method underestimated less often than the bics method (Fig. 10), whereas the overestimation of the scout II.0 method was much higher than that of the bics method (Fig. 11). However, the overestimations were for very few cases which, hydrologically, were insig-

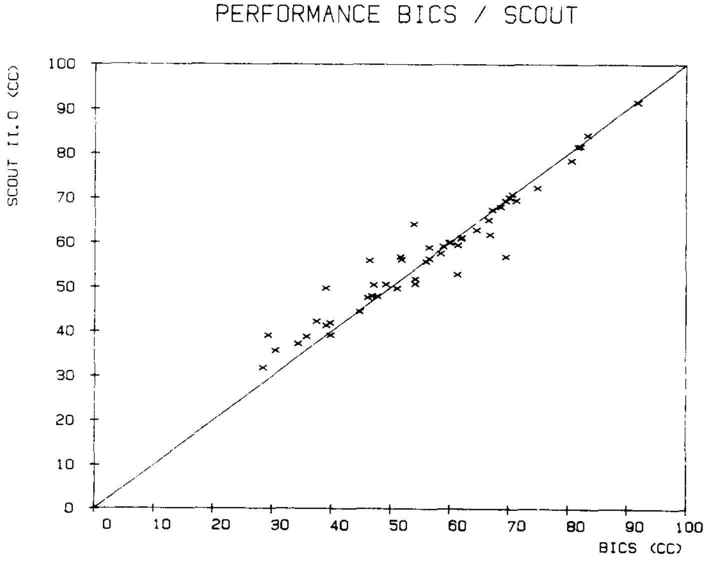

Fig. 8. CC scores of bics vs. scout II.0 (forecasts with 15 min lead time).

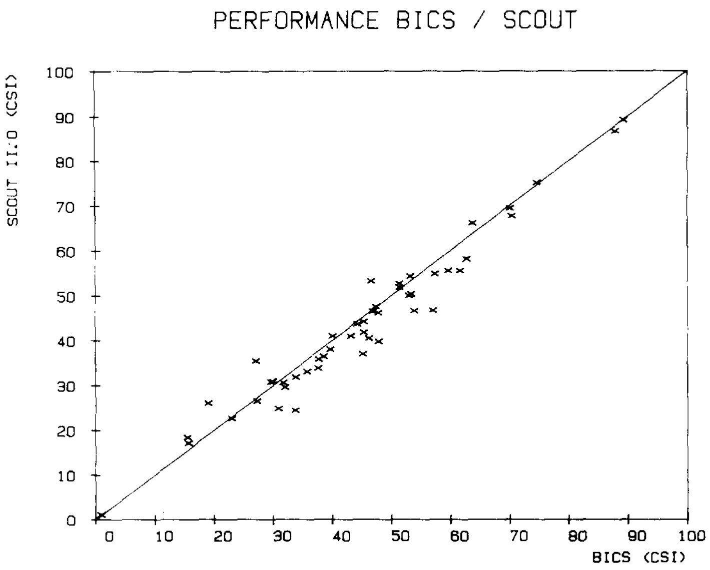

Fig. 9. CSI scores of bics vs. scout II.0 (forecasts with 15 min lead time).

nificant as can be seen by taking the absolute values (eqn. (7)) as a parameter (Fig. 12).

$$|dHS| = 1/n \sum |dH(i)| \quad \text{with} \quad n = n^+ + n^- \qquad (7)$$

For the needs of the Seine-Saint-Denis county, the scout II.0 method has

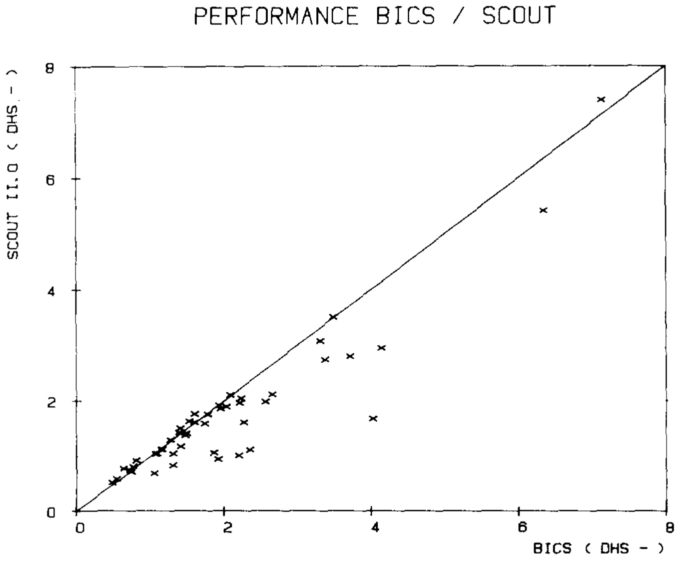

Fig. 10. dH^- errors of bics vs. scout II.0 (forecasts with 15 min lead time).

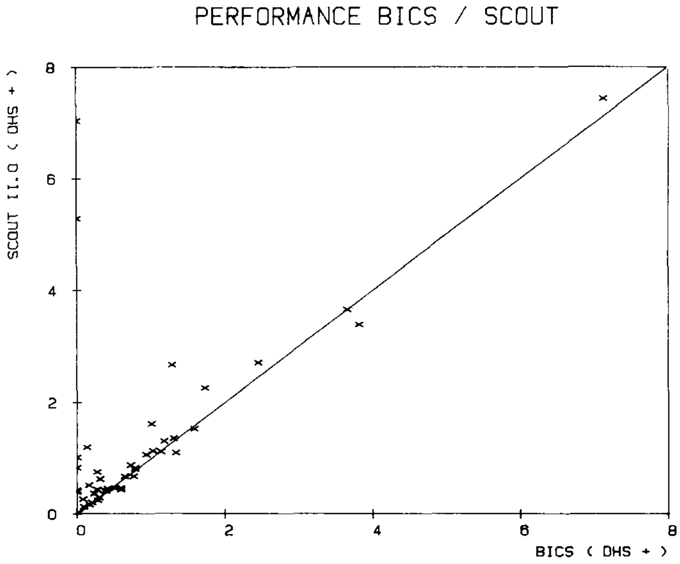

Fig. 11. dH^+ errors of bics vs. scout II.0 (forecasts with 15 min lead time).

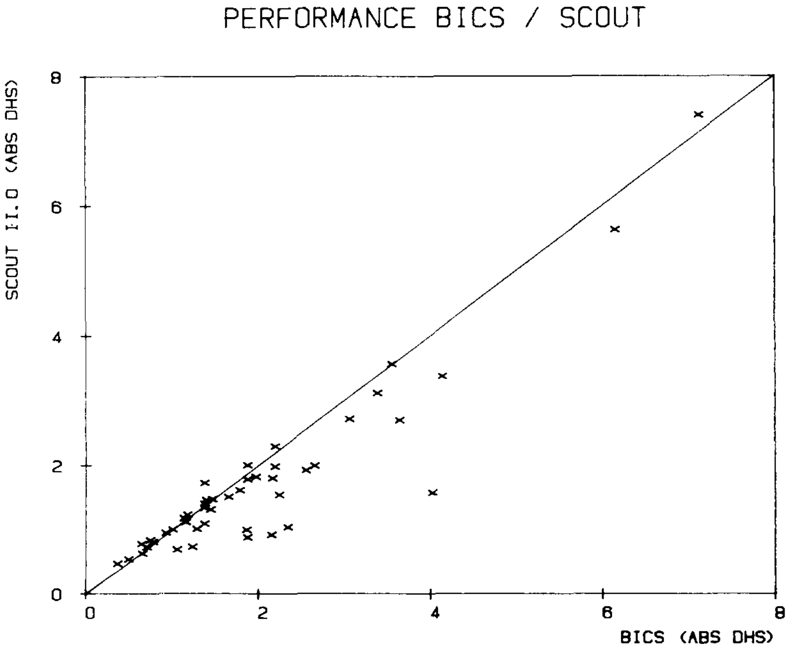

Fig. 12. $|dHS|$ errors of bics vs. scout II.0 (forecasts with 15 min lead time).

proven to be superior to a 'global' method. Whether this result is transferable to other areas has to be examined for each individual application.

An additional feature of the scout II.0 forecasting method is the possibility of a forecasting quality assessment, based only on imagery. Using echo number and echo number variation, the forecasting quality can be estimated even without running the forecasting program. By this means, the user can decide whether a forecast should be calculated or not, depending on whether it is sensible for him to use it or not.

OPERATIONAL USE

The scout II.0 model has been implemented operationally in real-time at the control centre of the Seine-Saint-Denis county. The fields of application and development are:

(1) remote call. At times when the control centre is unmanned (at night or at weekends), an automatic alarm can call the team on duty by telephone in the case of a high rainfall volume forecast;

(2) on-line forecast for real-time control of the sewer system and input for rainfall–runoff models;

(3) training of control teams. The model can be used to show the impact of different control strategies in different rainfall situations on the sensitive points of the sewer system;

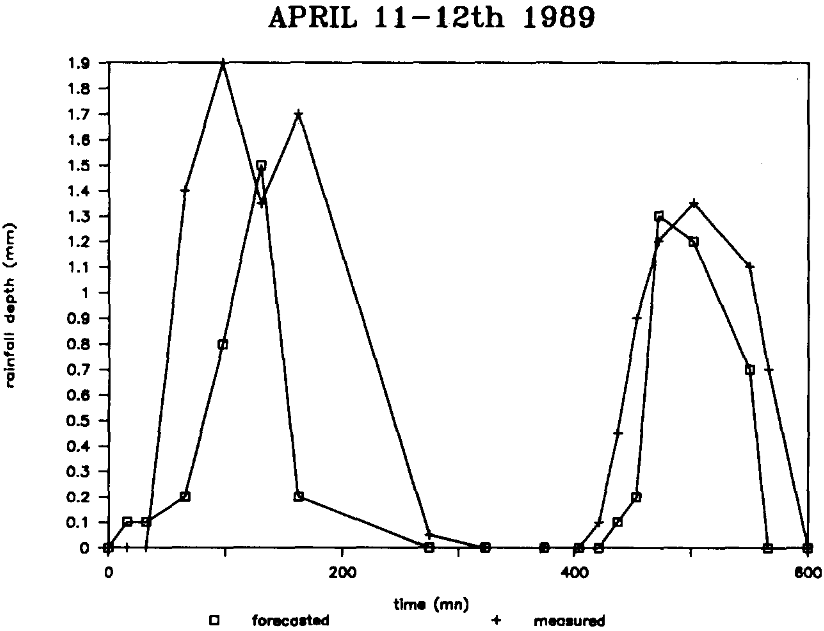

Fig. 13. Rainfall volume for one hour: radar forecast (□) and raingauge measurement (+) for April 11–12, 1989.

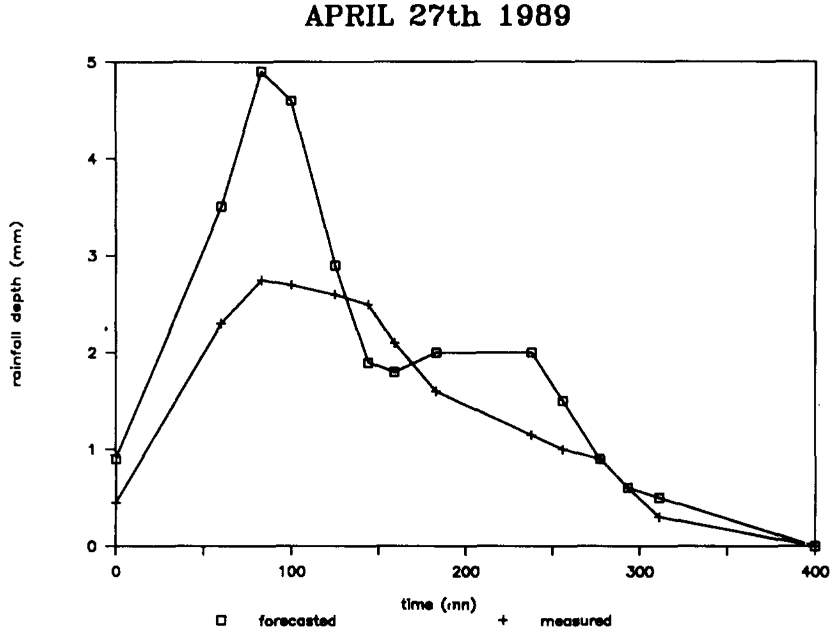

Fig. 14. Rainfall volume for one hour: radar forecast (□) and raingauge measurement (+) for April 27, 1989.

(4) further research, including 'convective' forecast (growth and decay), further refinement of the link to the operating staff, optimization of decision rules and analysis of forecast results.

First operational results

For operational use, the forecasts of scout II.0 are issued in terms of hourly accumulated rainfall volume. Routinely, these values are compared with the measured raingauge values of the raingauges operational at the same time. First results of a rainfall volume assessment for the whole area of the Seine-Saint-Denis county (250 km^2) during two moderate rainfall events of 1989 are illustrated in Figs. 13 and 14. For each time t_0, the forecast and the measured values for the time interval (t_0, t_0 + 1 h) are presented. As the measured value is considered the mean value of all available raingauges (19 and 21 raingauges for Figs. 13 and 14, respectively).

CONCLUSIONS

The close cooperation of the sewer department of the Seine-Saint-Denis county has helped considerably to establish a reliable rainfall forecasting tool, focusing on urban hydrology problems. A model design guided by the subjective needs of the users has not only gone some way to solving one of the typical problems of the 'structured' (pattern recognition) approach (splitting and merging of echoes), but the same technique has allowed a basis to be established for future development of a simple growth and decay forecast. The goal-oriented quality control of the forecast is the second main result of this study. Having previously defined their concerns, the user can directly exploit (and understand) the quality of the information issued. Comparison of the bics and the scout II.0 models yields a slight superiority of scout II.0 in hydrological terms. The forecasting model has been implemented operationally at the control centre of the Seine-Saint-Denis sewer system, where it is used as a tool in the daily routine by the different teams working on the sewer system (maintenance, real-time control, observation, measurement, teaching, etc.).

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