8th ICUSD, 30 August 1999, Sydney/Australia, proceeding Vol. 1, pp. 441-449

LIMITS OF RADAR RAINFALL FORECASTING FOR SEWAGE SYSTEM MANAGEMENT : RESULTS AND APPLICATION IN NANCY.

FAURE D.*, SCHMITT J.P.*, AUCHET P.**

* *NAN.C.I.E (International Water Centre), 149, rue Gabriel Péri - B.P. 290, 54515 Vandoeuvre Les Nancy cedex, FRANCE*
** Metropolitan Authority of Nancy : *Communauté Urbaine du Grand Nancy, 22-24 Viaduc Kennedi, C.O. 36, 54035 Nancy cedex, FRANCE*

ABSTRACT

Guided by the European Legislation regarding the Protection of Environment, and facing difficulties linked to rainy weather, managers must adapt the management of the urban sewage system to every rain event. In these circumstances, weather radar seems a precious tool in evaluating the spatial structure of the rain areas and in anticipating the very short-term evolution of precipitation over the urban centre. But the rainfall variability in space and time restricts the forecasting period, this period varying from a few minutes to a few hours. The word "nowcasting" is used but the forecasting range limit is uncertain.
This paper concerns the forecasting range limits for catchment areas in accordance with urban requirements (1 to 180 km²) and for two different types of rain. Specific validation criteria have been defined in accordance with the requirements of the operational department in charge of sewage system management in Nancy. The results show that the limits of forecasting in Nancy vary greatly according to the conditions. These limitations have led to consider an adapted sewage system management strategy using radar data. This strategy is based on predefined management scenarios and real time identification of the type of rain event.

KEYWORDS

radar, sewage system management, rainfall forecasting, short-range forecasting, nowcasting, urban hydrology

INTRODUCTION

The sewage systems of the majority of the larger European urban centres are of the combined sewer network type, designed to convey a mixture of wastewater and storm water, which are connected to limited capacity sewage treatment plants. In the past, the major problem was to protect urban areas against flooding. Since 1991, European Legislation relative to the Urban Treatment of Waste Water has required local authorities to take into consideration the treatment of the polluted water transported by the sewage network both during dry and wet weather (periods of exceptional rainfall excepted).

Facing difficulties linked to rainy weather, managers must adapt the management of the sewage system to every rain event. Given this situation, weather radar seems a precious tool in evaluating the spatial structure of the rainfall and in anticipating the very short-term evolution of precipitation over the urban centre. Many projects plan to use radar rainfall forecasting, and commercial tools are now available. Two major difficulties however still exist :

1. The estimation of rainfall from radar data : the understanding of the principles of the major errors in quantitative rainfall estimation and recent progress in research have allowed theoretical treatments to be designed that are specifically adapted to these errors. Despite this, operational utilisation needs rain gauge data to verify the radar estimation, radar data being an indirect measurement of rainfall at ground.

2. The rainfall variability in space and time restricts the forecasting period. Radar data allows short-range forecasting for a period varying from a few minutes to a few hours (the word "nowcasting" is used), but the limit is uncertain.

This paper concerns the temporal limits of rainfall forecasting over catchment areas in accordance with urban requirements. Brémaud and Pointin (1993) demonstrated that the accuracy of rainfall forecasting, and the best method of making forecasts (cell detection and tracking, cross correlation, ...), depend on the type of precipitating meteorological structure and on the desired forecast period : to obtain the best rainfall forecast "*both the rainfall forecasting method and the radar data must be adapted to their use*". Bellon and Zawadski (1994) indicate that to optimise the forecast of radar rainfall rate maps T minutes apart, the forecast values must be averaged over an area $A=L^2$ (km²) such that $L=kT^{\lambda}$ ($1\leq k \leq 1.3$, $0.7\leq \lambda \leq 0.8$). Such a result highlights the uncertainty on small-scale variations in rainfall, and suggests a limited capacity of quantitative rainfall forecasting for small urban areas.

Recently, a study was conducted for the Nancy Urban Community in order to estimate the limits of operational use of radar rainfall forecasting. Specific validation criteria were defined in accordance with the requirements of the operational department in charge of sewage system management. The limits were determined for every forecast variable in function of different sizes of catchment area (1 to 180 km²) and for two types of rain events. The results show the limitations of use of radar rainfall forecasting in Nancy, which is in a favourable situation as regards climatology and radar location. These limits combined with feedback of the use of radar data since 1995, have led to develop a management strategy for the sewage system of Nancy using radar data to anticipate the rainfall evolution over the urban centre. Real-time processing of radar data has been developed, and an operational project supported by the European Life program should be ready by the end of 1999 (Schmitt and all, 1999). This paper explains the constraints linked to this project, which is a good example of operational needs, and presents the results of the study and the strategy developed.

AN EXAMPLE OF OPERATIONAL REQUIREMENTS

The operational Life project currently underway in Nancy concerns an in-line storm water tank named Gentilly (12 000 m^3) built in 1970 to protect one urban area against flooding. The aim of the project is to optimise the management of the tank in order to reduce pollution overflows into the River Meurthe for all moderate rain events, while retaining the initial function of the tank for storm events. Achieving this objective requires anticipation of the rainfall evolution over the urban centre.

Human constraints :

A major constraint is the obligation to retain the initial function of the tank to protect people and properties against flooding. The sewer network downstream from the tank is close to the centre of Nancy, and the flow into the sewer network must not exceed 3 m^3/s. If it is too high, an automatic device progressively closes the outlet valve of the in-line tank to control the flow, and the Gentilly tank fills.

Spatial constraints :

A difficulty is the small size of the urban catchment areas compared to the spatial and temporal variability of the rainfall. Figure 1 shows the area concerned by the sewer network of the Boudonville basin. The area drained by the Gentilly tank is the upper area of this basin. Rain gauge network cannot allow anticipation of the major rain events. Radar images are available but the pixel size is 1 km², roughly the same size as the Gentilly catchment area. The frequency of radar images is 1 image per 5 minutes, and the motion of the rain cells often exceeds 60 km/h, corresponding to 5 pixels per 5 minutes or 5 times the size of the Gentilly catchment area from one image to the next.

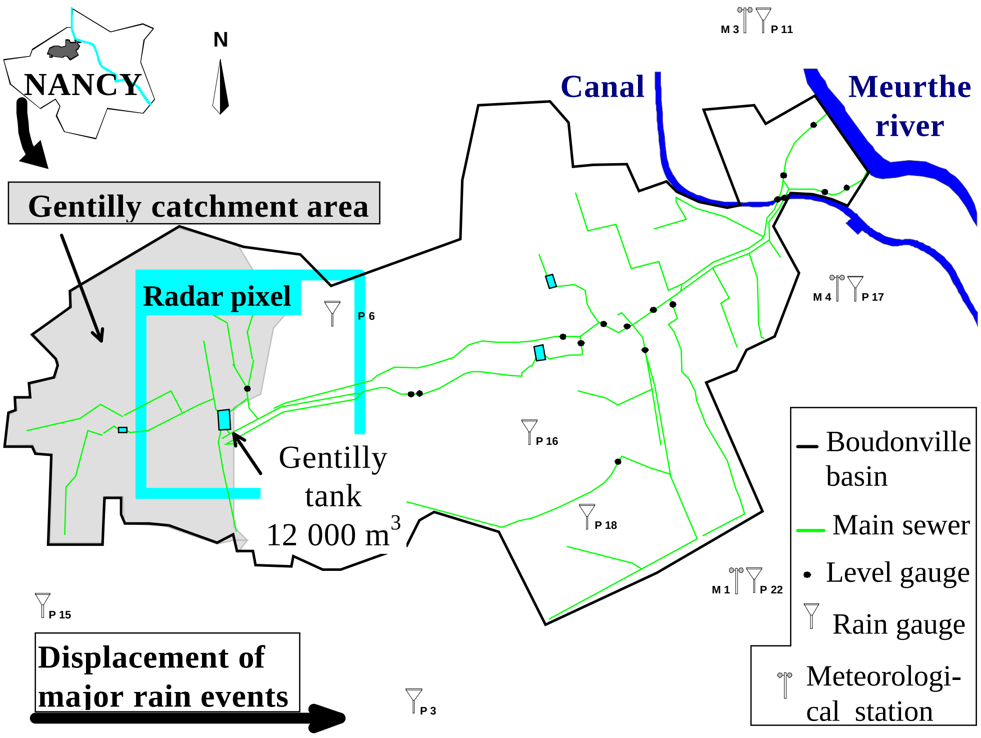


Figure 1. Boudonville (6.6 km²) and Gentilly catchment areas. A radar pixel is located.

Temporal constraints :

Another difficulty is the short time available for action, which requires a relatively long anticipation time. Figure 2 shows the Gentilly tank filling up during the 22/07/95 rain event (return period of ten years). The tank started filling up only 10 minutes after the beginning of rainfall, and was full 45 minutes later. 2h30 at maximum flow rate was required to drain the tank completely to return it to a large storage capacity. The figure also shows a time lag of only 10 minutes between the flow at the Gentilly tank and the storm overflow into the Meurthe river, at the outlet of the Boudonville basin.

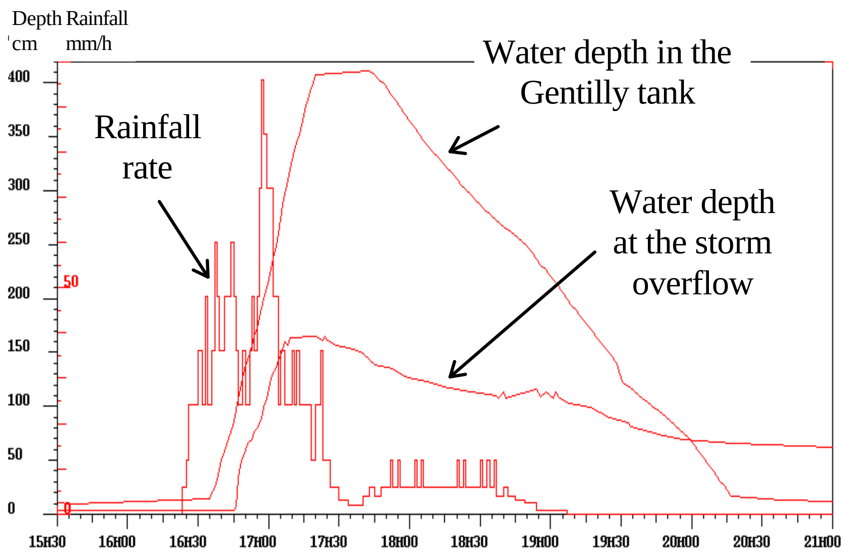


Figure 2. The 22/07/95 rain event with a return period of ten years.

ASSESSMENT OF RADAR FORECASTING : METHOD

This study was conducted to estimate the limits of radar rainfall forecasting for the management of the sewage system of Nancy, in particular the Gentilly storm water tank. The study did not use rain gauge data, only radar data. The method compares rainfalls estimated from radar data averaged over areas, for different sizes of areas and for different types of rain events. Spatial Averaged Rainfall (SAR) values estimated from forecast radar images are compared to SAR values estimated from the actual recorded radar images, for very short-range forecasting (0 to 55 minutes). This procedure permits to evade the difficulties linked to the estimation of rainfall at ground, but does not remove all the effects of the classical radar measurement errors, in particular errors dependent on distance from the radar.

The selected areas :

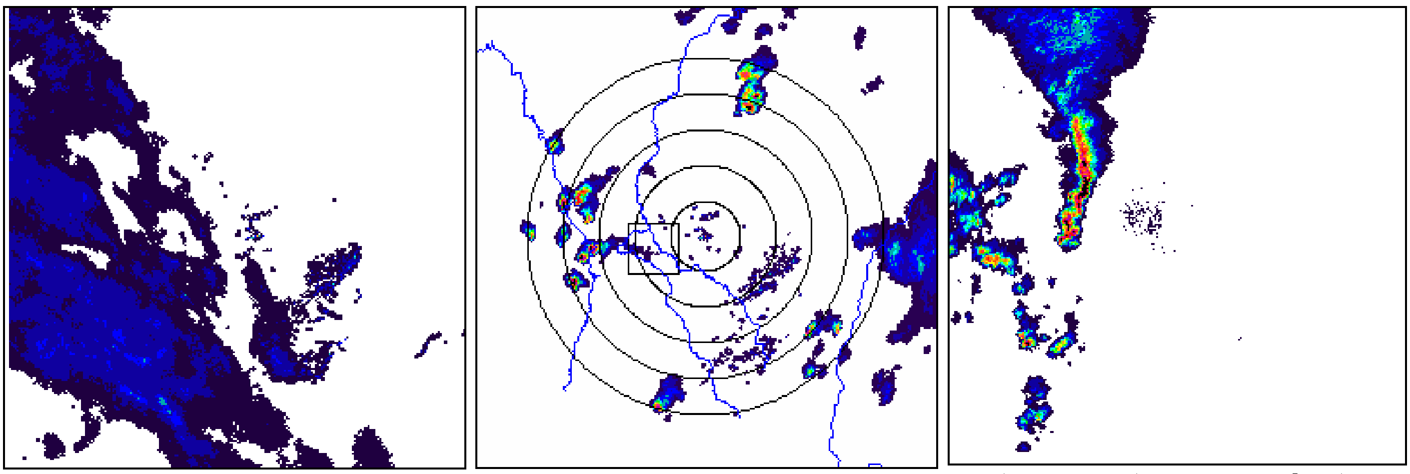
The Areas selected are real urban catchment areas of the Urban Community of Nancy, and geometrical surfaces located within the perimeter of the district. The size of these areas varies from 1 and 6.6 km² (Gentilly and Boudonville catchment areas) to 180 km² (i.e 1, 6.6, 12, 34, 64, 128 and 180 km²)

The radar data :

The radar data stems from the Météo-France radar located 30 km to the East of Nancy (wavelength = 5cm). The radar data are recorded every 5 minutes by PPI procedure, and integrated into images of 256*256 square pixels. The radar image pixels have a size of 1 km², and are digitized in 16 levels of reflectivity. The area corresponding to the Urban Community of Nancy is not affected by ground echoes or shadows.

Selection and classification of the rain events :

The rain events selected were classified into categories defined by an operational software used in real time to assist the management of the sewer system of Nancy (Faure and Auchet, 1997). This software determines the type of rain event from radar images by analysing the frequency distribution and the spatial distribution of the pixel values. Two types are presented in this paper. The first type (called type 1) corresponds to homogeneous and low intensities of rainfall rates (figure 3a), and is representative of the majority of the radar images recorded in Nancy over the winter periods from 1995 to 1998. The second type (called type 2) corresponds to radar images showing very heavy rainfall rates (typically convective cells and storm events), representing more than 40% of the radar images recorded in Nancy during summer periods and only 2% during winter periods. For type 2, 6 events correspond to isolated heavy rain cells (figure 3b), and 6 events represent spatially structured rainfall rates (figure 3c).



a) Type 1 (01/08/97 03h00)

b) Type 2 (17/05/97 16h45) : isolated heavy rain cells

c) Type 2 (22/07/95 09h15) : spatially structured rainfall rates

Figure 3. Example of type 1 and type 2 radar images. Distance between circles = 20 km. Square = Nancy.

The set of 1348 radar images used in this study represents 25 rain events (table 1). The selection of the radar image sequences was guided by several conditions :

- radar images constituting each sequence was admitted as typical of the type of rain event;
- significant rainfall was observed on the selected areas for each sequence;
- the sequences are continuous (no missing image), a radar image being recorded every 5 minutes;
- the sequences include a set of 2 hours of radar images before the rainfall begins over the selected areas;
- For type 2, the sequences include a set of radar images after the end of rainfall over the selected areas, longer than 1 hour period if possible. This condition could not be respected for type 1.

Table 1. Radar images selected

	number Ne of sequences (or rain events)	number of images (total)
Type 1	13	778
Type 2	12	570

The software used :

The software used to forecast SAR values is that developed for the managers of the sewage system of Nancy. This software is included into real time operational weather radar data processing (Faure and Auchet, 1997). The procedure defined in this software determines rainfall displacement between two radar images for several rectangular areas covering the entire surface area of the radar images. Then, rainfall rate maps are forecast assuming that the displacements are constant for short-range forecasting (0 to 55 minutes). These forecast maps are used to estimate the SAR values over each selected area.

Rainfall displacements are determined by cross-correlation between two parts of successive radar images. A limited increase or decrease in rainfall intensities is taken into consideration for the map forecasting. The rainfall motion is used in the spatial averaging procedure to compute an intermediate map once per minute.

The validation criteria :

To estimate the limits of radar rainfall forecasting, validation criteria were defined in accordance with the requirements of the operational department in charge of sewage system management in Nancy. Several rainfall characteristics were calculated from series of observed SAR values and predicted SAR values, for each forecasting range, each area and for both types of rain events.

Two criteria allow estimation of the possibility of forecasting two important temporal characteristics of a rain event : the beginning and the peak of the rain event. Two other criteria concern the possibility of forecasting the maximum 5 minutes averaged SAR value during a rain event, a few minutes below it occurs. The next criteria tests the accuracy of the response to the question : what depth of rainfall accumulation is expected to occur during the next m minutes, m varying from 0 to 55 minutes. The last criteria estimates the difference between observed series of SAR values averaged over 5 minutes and predicted series of 5 minutes averaged SAR values, for a forecasting range varying from 0 to 55 minutes.

ASSESSMENT OF RADAR FORECASTING : RESULTS

MOY and COR are the mathematical function of *arithmetic mean* and *correlation coefficient*. For a selected area and for a sequence of radar images (a rain event), the index ^{0} indicates a value estimated from a recorded radar image (observed value); index ^{*i} indicates a value estimated from a map forecast, for a forecasting range equal to i minutes (predicted value). The index ' is used for "minutes" (5' = 5 minutes).

SAR_t^0 and SAR_t^{*i} are the observed and forecast values of SAR integrated from *t* to *t+5'*.
t1(e) and t2(e) are the date of the first image (t1) and the date of the last image (t2) for sequence *e*.

Prediction error of the rainfall beginning

The date of the rainfall beginning $t_{beg}(e)$ is defined as the date of the first SAR_t value above zero for a rain event e and a selected area. The mean absolute time lag LBEG between the predicted and observed dates of the rainfall beginning is calculated for both types of rain event and for each selected area :

$$LBEG(i) = MOY(| t_{beg}^{0}(e) - t_{beg}^{*i}(e) |) \quad ; \qquad e = 1,Ne \tag{1}$$

This error increases with the forecasting range i. For both types 1 and 2 rain events and for every size of area, LBEG(i) exceeds 15' for a forecasting range i exceeding 35'. However LBEG(i) does not exceed 20' for i equal to 55'.

Prediction error of the date of peak rainfall

The peak rainfall date $t_{max}(e)$ is defined as the date of the maximum SAR_t value for a rain event e and a selected area. The mean absolute time lag LMAX between predicted and observed peak rainfall dates was calculated for the two types of rain event and for each selected area :

$$LMAX(i) = MOY(| t_{max}^{0}(e) - t_{max}^{*i}(e) |) \; ; \qquad e = 1,Ne \tag{2}$$

This error also increases with the forecasting range i. For type 1 and the smallest areas (1, 6.6, 12, 34 km²), LMAX(i) does not exceed 15' for a forecasting range i of 55'. For the biggest areas (> 60 km²), LMAX(i) can exceed 20' for predictions made 45 minutes before the actual peak rainfall over the area. For type 2 rain events, for all the sizes of areas LMAX(i) does not exceed 20' for a 55' forecast.

Prediction error of the peak rainfall value

The peak value $SAR_{max}(e)$ is defined as the maximum SAR_t value for a rain event e and a selected area. The mean RAPMAX ratio and the mean absolute difference DMAX between predicted and observed values of $SAR_{max}(e)$ were calculated using the following equations :

$$RAPMAX(i) = \sum_{e=1}^{Ne} SAR_{max}^{*i}(e) \Big/ \sum_{e=1}^{Ne} SAR_{max}^{0}(e) \tag{3}$$

$$DMAX(i) = \sum_{e=1}^{Ne} \left| SAR_{max}^{*i}(e) - SAR_{max}^{0}(e) \right| \Big/ \sum_{e=1}^{Ne} SAR_{max}^{0}(e) \tag{4}$$

For the 13 type 1 rain events, the observed $SAR_{max}(e)$ values do not exceed 5 mm/h. The forecast errors of $SAR_{max}(e)$ values do not exceed a few mm/h. The mean RAPMAX(i) ratios indicate a tendency to slightly overestimate the $SAR_{max}(e)$ values, for every size of area selected and for all the forecasting ranges i. The mean absolute differences increase sharply in function of the forecasting range, and DMAX(i) > 100% for all the areas when i ≥ 20 minutes.

For the 12 type 2 rain events, the $SAR_{max}(e)$ values vary greatly from 0.4 to 89. mm/h for the Gentilly catchment area, or from 2.7 to 28.7 mm/h for the largest area (180 km²). The forecast errors of $SAR_{max}(e)$ can be very large. For every size of area, the mean RAPMAX(i) ratios indicate a marked tendency to underestimate the $SAR_{max}(e)$ values for a forecasting range exceeding 30 minutes (-30% to -50% for i=55'). DMAX(i) increases very sharply in function of the forecasting range : DMAX(i) > 100% when i ≥ 20' for the largest areas (>30 km²), DMAX(i) > 100% for i ≥ 15' for the Gentilly and Boudonville areas.

Prediction error of the SAR values integrated over 5 minutes

The mean RAPMOY ratio and the correlation coefficient ROMOY between every observed series and predicted series of SAR_t values were calculated for each prediction period, each selected area and for both types 1 and 2 rain events. ROMOY were calculated only for the observed values above zero :

$$RAPMOY(i) = \sum_{e=1}^{Ne} \sum_{t=t1(e)}^{t=t2(e)} SAR_t^{*i} \Big/ \sum_{e=1}^{Ne} \sum_{t=t1(e)}^{t=t2(e)} SAR_t^0 \qquad (5)$$

$$ROMOY(i) = COR(SAR_t^0 \,,\, SAR_t^{*i}) \quad t=t1(e),t2(e) \,;\, e=1,Ne \quad \text{if } SAR_t^0 > 0 \qquad (6)$$

For type 1, the mean ratios are close to the value 1 for all forecasting ranges varying from 0' to 55' and for all areas. Nevertheless, RAPMOY(i) indicate a slightly tendency to over-estimate the SAR_t values. The correlation coefficients decrease steadily as the forecasting range i increases. ROMOY also decreases with the size of the area selected (figure 4). Despite the low spatial and temporal variability of the rainfall rates, the contribution of the forecasting procedure is highlighted by the comparison with the forecasting results obtained using a persistence hypothesis : the measured rainfall rate is assumed to remain unchanged over the same pixel during the following 55' (figure 5).

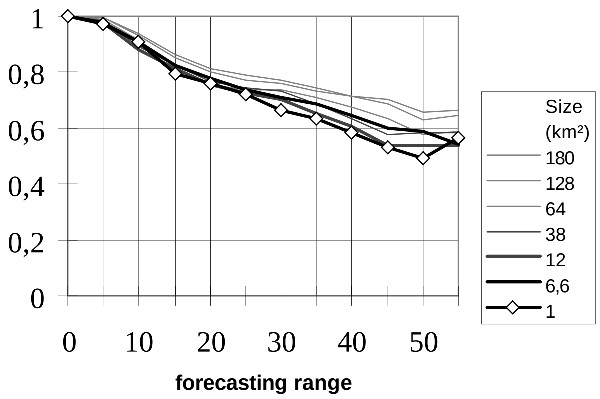


Figure 4. Type 1 rain events : ROMOY in function of forecasting range and size of area.

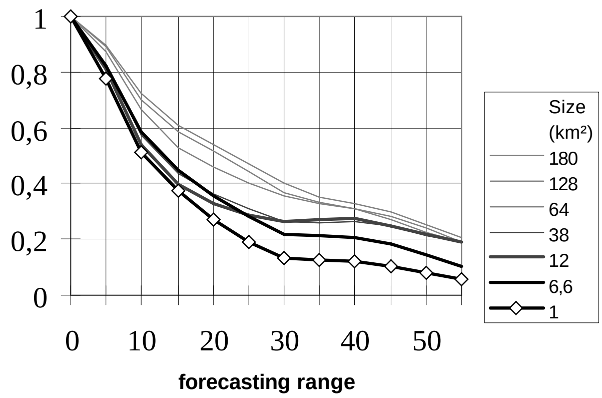


Figure 5. Type 1 rain events : same as figure 4 for persistence forecasting.

For type 2, the mean RAPMOY(i) ratios decrease significantly with the forecasting range for all the areas (not shown). This result traduces a marked tendency to underestimate the SAR_t values when the forecasting range increases (for i=55', -50% for the Gentilly area, -35% for areas from 64 to 180 km²). This phenomenon can be explained, with reservations, as the combination of several effects :

- incoming rain cells are more often in increasing phase than in decreasing phase in the selected sequences;
- the selection of sequences corresponding to significant rainfall over the selected areas tends to favour forecast underestimation;
- the effects of radar measurement errors dependent on distance favours forecast underestimation;

For type 2, the correlation coefficients ROMOY(i) go down steadily as forecasting range i increases, and are equal to zero for a wide forecasting range. This decrease is more appreciable as the size of the area gets smaller (figure 6). For forecasting using a persistence hypothesis this decrease is more dramatic : for all the selected areas, ROMOY(i) = 0 for i=20' (not shown).

Consequently, the SAR values integrated over 5 minutes appear to be unusable for type 2 rain events when the forecasting range exceeds a few minutes. The mean limit seems to be a 10' forecast for the areas interested in operational use : the Boudonville and Gentilly catchment areas. Figure 7 shows a sequence with several peak rainfall and illustrates forecast errors linked to the increasing or decreasing of the rain cells.

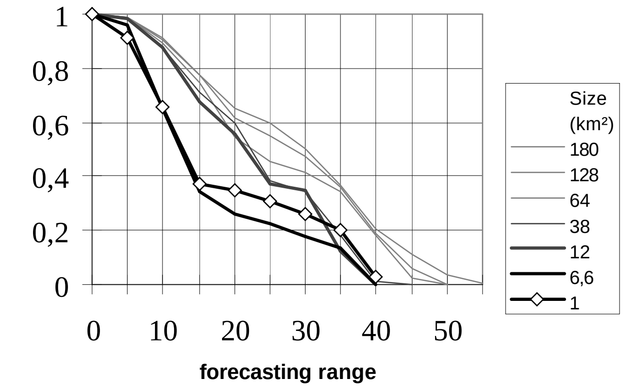


Figure 6. Type 2 rain events : ROMOY in function of forecasting range and size of area.

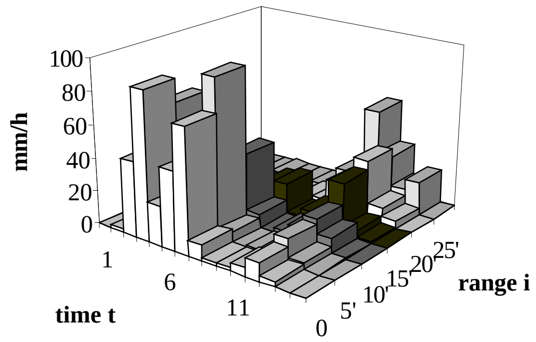


Figure 7. Example of type 2 : 29/07/96 18h. Series of SAR_t^0 and SAR_t^{*i} for the Gentilly area

Prediction error of the accumulation of rainfall over the next m minutes

The mean ratio and the correlation coefficient between the predicted and observed values of the depth of spatial rainfall cumulated for the next *m* minutes (*m* varying from 5' to 55') was calculated for both types of rain events and for every selected area. The correlation coefficient was calculated only for the observed values of accumulation above zero.

For type 1, the mean ratios are close to the value 1 for all forecasting ranges varying from 0' to 55' and for all the areas. The correlation coefficients (figure 8) decrease very slightly as the forecasting range *m* increases. This trend is not as significant as the decrease shown in figure 4. Therefore, the use of integrated values over a longer time interval provides greater forecast accuracy. Moreover, these cumulated values, the depth of rainfall accumulation expected to occur over the next m minutes, are important variables for sewage system management.

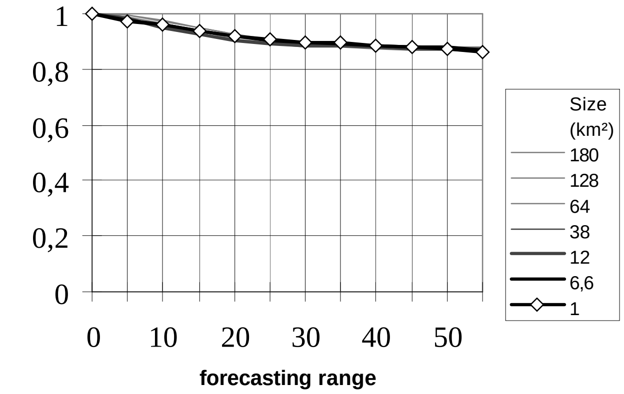


Figure 8. Type 1 : same as figure 4 for the accumulation of rainfall over the next minutes.

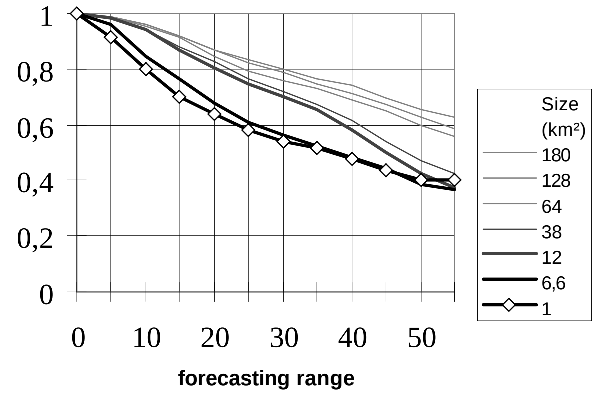


Figure 9. Type 2 : same as figure 6 for the accumulation of rainfall over the next minutes.

For type 2, the marked tendency to underestimate the SAR values when the forecasting range increases induces a steadily decrease of the mean ratios with the forecasting range for all the areas. (for i=55', -35% for the Gentilly area, -15% for the 180 km² area). The correlation coefficients (figure 9) decrease steadily as the forecasting range increases, but this diminution is not as great as in figure 6. The use of integrated values over a long time interval provides a more accurate forecast. However for this type of rain event, the accuracy of these accumulated forecast values limits its use in the case of the smallest areas, which are the areas of interest in operational application.

CONCLUSION FOR SEWAGE SYSTEM MANAGEMENT

Although radar data monitoring improves the assessment of weather situation and allows the anticipation of rainfall evolution in operational situation, the preceding results show that the accuracy of quantitative forecasts is limited for both temporal characteristics of rain event and rainfall rates.

For rain events corresponding to homogeneous and low intensities of rainfall rates (type 1), it is possible to forecast the accumulation of rainfall over the next m minutes for values of m exceeding one hour. Nevertheless, these rainfall accumulations do not generate major difficulties for the manager in charge of the sewage system. For type 2 rain events, the forecast of quantitative values for the small areas concerned in operational urban hydrology seems possible only for extremely short-range forecasting ("nowcasting" is a very appropriate word). This limitation seems to may be attributed principally to the very important variability in space and time of rainfall rates and to the short life cycle of the heavy rainfall cells. For the smallest areas, another factor of forecasting errors is the accuracy of displacement identification combined with the small size of the areas. For these catchment areas, in case of wrong initial option of management, the possible forecasting range seems shorter than the time necessary to make the sewage system safe.

This results and the feedback of the Nancy experience have led to develop a new sewage system management strategy. In practice in Nancy, the choice of the manager is limited to a few options of management. In real time, the most important information is not the quantitative rainfall rate forecast, but more the ability to identify quickly a situation corresponding to a potential known risk. According to this risk, the manager determines the priority objective of the management and the corresponding action. Taking the example of Gentilly, when a type 2 rain event is detected, rainfall rate forecasting is not very accurate for ranges exceeding few minutes. But the assumption that the future rainfall rates over the catchment area will correspond to a storm event is probable, and the manager selects the automatic pilot warranting the greatest protection against flooding. This strategy based on predefined management scenarios and real time identification of type of rain event, chosen to limit the risks in the Life project, is akin to that used by other managers of sewer networks in France (Browne et al, 1998).

LIMITS OF THE STUDY AND CONTINUATION

These results do not take into consideration rainfall rates at ground, or flow rates measurements. The values of the validation criteria depend on the software used, on the type of precipitating meteorological structure represented in radar data, and on the climatology of the region. Other studies are in progress to perform the relation between types of rain events and potential risks, and to test forecast software based on different methods. Finally, the Life project will provide fundamental feedback from operational experience.

ACKNOWLEDGEMENTS

This study forms part of a major programme carried out in partnership with the International Water Centre, the Metropolitan Authority of Nancy, the Laboratoire Central des Ponts et Chaussées, Anjou-Recherche, and the Rhine-Meuse Water Agency. The operational project is supported by the European Life programme.

REFERENCES

Bellon A., Zawadski I. (1994). Forecasting of hourly accumulations of precipitation by optimal extrapolation of radar maps, Journal of Hydrology, 157 (1994), 211-233.

Brémaud P.J., Pointin Y.B. (1993). Forecasting heavy rainfall from rain cell motion using radar data, Journal of Hydrology, 142 (1993), 373-389.

Browne O., Auriaux G., Idier F., Delattre J.M. (1998). A decision aid system for real-time operation of Seine Saint-Denis sewer network, proceedings of Novatech 1998, vol. 2, 147-154.

Faure D., Auchet P. (1997). Real time process of weather radar data for urban hydrology in Nancy, XXII General Assembly of the EGS, 21 - 25 April, 1997, Vienna/Austria.

Schmitt J.P., Faure D., Badot R. (1999). Sewage system management strategy to reduce rain water pollution overflows : the case of an underground storm basin in Nancy, 8th ICUSD, Sydney, Australia.