Radar-based alert system to operate a sewerage network: relevance and operational effectiveness after several years of use

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Abstract
Since January 2000, the sewerage network of a very urbanised catchment area in the Greater Nancy Urban Community has been operated according to the alarms generated in real time by a storm alert system using weather radar data. This alert system is based on an automatic identification of intense rain cells in the radar images. This paper presents the characteristics of this alert system and synthesises the main results of two complementary studies realised in 2002 in order to estimate the relevance and the operational effectiveness of the alert system.

The first study consisted in an off-line analysis of almost 50 000 intense rain cells detected in four years of historical radar data. The second study was an analysis of the experience feedback after two years of operational use of this alert system. The results of these studies are discussed in function of the initial operational objectives.

Keywords
alert system, risk management, sewerage network, storm, weather radar

INTRODUCTION

The Urban Community of Greater Nancy (CUGN) which comprises 20 towns with a total population of 265,000 is located in the northeast of France. The CUGN Water and Sewerage Department has used weather radar data since March 1995 in order to anticipate the evolution of rain in the daily management of its sewerage network. Radar data (table 1) is used to assist the real time decision-making and to improve the security of the technical interventions into the network.

Since the beginning of year 2000, radar data have also been used to select in real time the best operation mode of an underground storage/settling basin integrated in this sewerage network. Security depends on a real time storm alert system based on an automatic identification and monitoring of intense rain cells in the radar images (Faure & al, 2002). This paper presents briefly the characteristics of this alert system, and synthesises the main results of two complementary studies carried out in 2002 in order to estimate the relevance and the efficiency of this alert system:

- a detailed analysis of the intense rain cells identified in the region by the operational algorithm applied to four years of archived radar data ;
- an analysis of the experience feedback after two years of operational use of the alert system.

Results of these two studies are discussed within the specific framework of the utilisation of this alert system by the CUGN.

Table 1. Characteristics of the radar data used (data provider: Météo-France).

wavelength: 5 cm	image resolution: 1 km²
image frequency: 5 minutes	image size: 256 x 256 km²
radar - Urban Community range: 30 km	used values: 16 levels of reflectivity
one elevation angle of measurement: 0.7°	pre-treatment: ground echoes filtered

CHARACTERISTICS OF THE ALERT SYSTEM

Context of use

This alert system was defined during the European project *Life96Env-F-420* (Faure & al 1998) which addressed the implementation of a new operation mode of the « Gentilly » storage/settling basin, in order to guarantee two objectives:

- during intense rainfall, to ensure the protection against flooding of the urban catchment area called « Boudonville », by reducing peak flood flows in the combined sewerage network through temporary storage (role of storm basin) ;
- for common rain events, to limit combined sewage discharges into the natural environment, by storage and settling the maximum volume of combined effluent in this basin of 12,000 m^3 (treatment role).

Each objective requires a specific operation mode of the basin facilities: 7 valves are controlled by algorithms running locally but remotely selected by a human operator. The choice of the operation mode depends on the priority objective according to the rainy situation: for common rain event, the combined effluents are stored from the beginning of the rain ; for heavy rain, the combined sewage stored in the basin are emptied, and the maximum storage volume is preserved until the peak flows occur.

The operational constraints are rather severe: the Boudonville catchment area (660 ha) is densely urbanised (37,000 inhabitants), and to avoid floods in the lower part of the town, the combined sewage and stormwater level should not exceed 70 cm in a strategic point of the sewerage network located 1 km downstream of the Gentilly basin. The concentration time (between the beginning of the rain and the increase in the flows) is 10 minutes at this strategic point, and the total concentration time to the outlet of the catchment area is 20 minutes. On the other hand, before a storm the preventive drainage of the Gentilly basin can require several hours, according to the initial volume of stored sewage and to the concomitant flows downstream. These constraints require great anticipation of the flow in the sewers and of the rainfall over the upstream catchment area.

In 1999, a study concerning the limits of radar rainfall forecasting for sewage system management showed that the possibilities of quantitative precipitation forecasting (QPF) by radar on small urban catchment strongly depend on the type of rain, and can be extremely reduced in case of storm event (Faure & al, 1999): for the Gentilly basin catchment area (1 km²), the recommended forecast lead time varies from 1,5 hour for low and homogeneous rainfall, to 15 minutes for storm event. This gap between the QPF possibilities and the forecast needs for the Gentilly basin operation in case of heavy rain, conduced to define an alert system based on an automatic identification of the potentially dangerous events.

Alert system definition

These dangerous events was defined by the analysis of the Boudonville sewerage network behaviour, based on the simulation of 17 historical rain events with a detailed hydraulic model of the network (Payrastre 1999). This work allowed to precisely define the rainy situations inducing risks of flooding (table 2). This hydraulically-based classification was then used to determine criteria in order to identify these situations by a real time analysis of the radar images. The objective was to define an alert system with a **maximum safety factor** so that all the situations with risks would be announced, while limiting the rate of false alarm.

The alert system was finally based on an automatic identification and analysis of intense rain cells in the radar images. Two types of alarms are generated according to the localisation and displacements of these cells in a large area around the agglomeration (Faure & al, 2002): an alarm of "potential risk" intended to alert the sewerage network supervisor, and an alarm of "confirmed risk" imposing to select the Gentilly operation mode ensuring protection against flooding, and requiring to drain the Gentilly basin as soon as possible if it is not empty.

Before operational use, simulations of this alert system functioning were carried out with several years of archived radar data. This work allowed to estimate *a priori* the following performances: an alarm of confirmed risk before all the rain events of R1 and R2 types, and the storage in the Gentilly basin of 80% of the annual combined sewage effluent flowing from its catchment area.

Table 2. Classification of the rainy situations in function of the risk for the Boudonville basin, and number of rain events simulated in detail to define these risk levels.

Types of risk	Simulated events	Description
NR1	6	Rain events without any risk. Low flows in the sewerage network.
NR2	5	Rain events without risk. More significant flows but which can be drained by the network without storage in the Gentilly basin.
R1	4	Events representing a risk in the event of a bad operation of the Gentillly basin. Necessity to store 3000 to 4000 m^3 in the Gentilly basin to reduce peaks of flows downstream in the network.
R2	2	Exceptional rain events (decennial frequency) requiring the Gentilly basin to be entirely empty at the beginning of the rain.

INTENSE RAIN CELLS ANALYSIS ON FOUR YEARS OF RADAR DATA

Methodology

This study was realised by ALICIME in 2002 in order to confirm the relevance of the alert system and to study potential improvements of this system. The algorithm identifying intense rain cells in the operational alert system was used for off-line processing of a great number of radar images recorded by the CUGN from March 1995 to November 1998 (nearly four years of data). These archives represent rainy days with significant rainfall observed in Nancy or in the close region. At the time, radar data was systematically criticised with visualisation of the sequences of images, and recording of observations about problems or particular phenomena. This information have led to eliminate 91 rainy days with data potentially affected by problems of radar measurement.

On the remaining data, the algorithm identified 49,689 « intense cells » in 12,106 radar images divided in 167 rainy days. These « intense cells » correspond to structures clearly identifiable in the radar images, but which must be carefully interpreted in term of hydrometeorological phenomenon. Large structures could represent a group of very small rain cells which are not easily discriminated by the spatial resolution and the 16 reflectivity levels of the radar data used. Long lifespan structures which can be identified as one single « intense cell » and which can be followed during several hours, often consist of various small rain cells with very short lifespan (15 to 45 minutes): the apparent variations in size, shape and trajectory of the global structure are due to the life cycle of the small cells constituting the global structure. In this paper, the words « intense cell » name all the objects identified by the algorithm and used to generate alarms.

Temporal distribution of the intense cells identified

Figure 1 presents the mean annual evolution of the relative risk to detect intense cells in the Nancy region. More than 95% of the cells are detected from May to October, with 70% in June, July and August. Nevertheless, a more detailed analysis shows that the month corresponding to the maximum of detection changes every year.

Over one day, the intense cells are observed mainly from 12 to 20 UT (70% of all the detections, including 40% from 14 to 17 UT). But 30% of the cells are identified out of this time period, and the variability is important between two successive rain events

Weather parameters associated to the intense cells

CUGN has a network of 6 weather stations located in the agglomeration area, and the 1995-98 data have been validated in previous studies. The analysis of these data indicates that the risk of intense cells detection in the region strictly depends on the conditions of temperature and relative humidity measured in Nancy. Unfortunately, the necessary conditions are very frequent during one year, particularly in summer. Thus, it is not possible to define a set of criteria based on these conditions in order to forecast the formation of intense rain cells near the agglomeration, but only to identify conditions more or less favourable with the observation of intense cells in all the region. This information can also be used to verify the relevance of the generated alarms in real time.

Spatial distribution of the intense cells identified

The intense cells detection depends on the distance from the radar: compared to the number of intense cells detected 20 km away from the radar, 50% are detected 80 km from the radar, 25% 110 km away. This effect can be directly connected to an important phenomenon in the radar measurement of precipitation: the under-detection increasing with the distance to the radar. On the other hand, the mean size of the cells identified by the algorithm (15 km²) doesn't vary with the distance from the radar. It is also noted that very significant cells corresponding to intense rain events seem identified even a long distance from the radar. In the case of Nancy located 30 km from the radar, the under-detection of the less important cells a long distance away does not pose a crucial problem.

This effect induced by the radar measurement being excluded, the frequency of intense cell detection in the region largely varies from one year to another, and is strongly influenced by the few most intense rain events that happen every year. On average over the four analysed years, this frequency seems more significant only in one zone: the area located just at the north of the junction of the rivers Meurthe and Moselle.

Trajectories of the intense cells

The cells identified on two successive images and supposed to be the same rainy structure have been matched using a simplified but rather restrictive procedure (this procedure was defined to reduce the risk of erroneous matching, to the detriment of the total number of matching carried out). 70% of the cells were matched to constitute pairs of cells defining nearly 34 000 displacement vectors between two radar images. The analysis indicates a good confidence in the representativeness of these displacement vectors, allowing to estimate the speeds of the detected structures: more than 85% of the cells would have speeds from 6 to 66 km/h, 60% from 20 to 55 km/h. Only 5% of the cells would have null speed (events inducing the maximum cumulated rainfall at ground level).

The analysis also indicates that the intense cells detected in the Nancy region mainly have displacements oriented toward the 60° North direction (figure 2). This result is really constant from one year to another and corresponds to the general direction of displacement of rains over this region. The displacement vectors allow to define « trajectories » which can be drawn during periods of 5 minutes to several hours. These trajectories have the same general orientation, most of them being approximately rectilinear. No influence due to local geography or to the principal agglomerations could be identified (it is important to note that the region is relatively flat, except the Vosges mountains in the south-east).

These results are interesting because they permit in real time to directly extrapolate the displacements of the existing cells in order to forecast position of most of the cells in the following radar image.

Figure 1. Mean annual evolution of the relative risk to detect intense cells near Nancy.

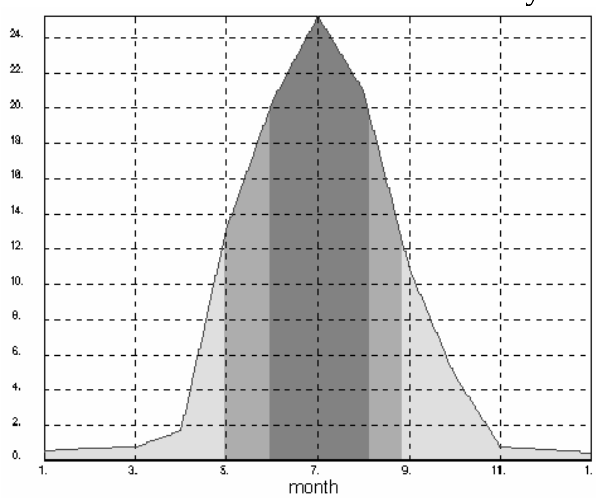
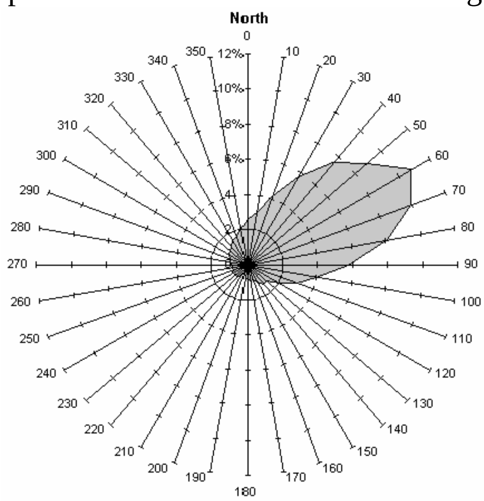


Figure 2. Mean orientation of the cells displacement vectors between two images.



Interdistances between intense cells

These inter-distances were studied between cells identified within the same radar image, or between cells detected in two successive images. The results being very similar, we will not distinguish these situations in this paper.

For each detected cell, we estimated the distance between its centre of gravity and the nearest edge of the other cells. From these values, 3 types of inter-distances were studied: the distance between each cell and its nearest neighbouring cell (MinCCI) ; the distance between each cell and its farthest neighbouring cell (MaxCCI) ; the distance between the most isolated cell and its nearest neighbour (ICCMax). Even if the identified cells tend to be grouped, it is observed that:

- 20 % of the centre of gravity of intense cells are located more than 37 km away from the nearest cell, and 10% more than 65 km away (MinCCi criterion) ;
- 50 % of the centre of gravity of intense cells are located more than 125 km from the farthest cell, and 20% more than 175 km away (MaxCCi criterion) ;
- 50 % of the images including more than one intense cell, present at least one isolated cell more than 50 km from the nearest cell; 20% of images present at least one isolated cell more than 95 km away, and 10% over 125 km from its nearest neighbour (ICCmax criterion).

These results must be considered in relation to the size of the radar images used in this study: 256 X 256 km. The consequence is that it is not possible from the observation of a series of radar images, to define with certainty areas where intense cells will be detected in the following images. The future position of most existing cells can be estimated in the next few minutes with a good precision, by extrapolating the identified displacements. Some cells will disappear or will seem divided in several child cells. A significant number of new cells will appear, some of these far away from the pre-existent cells.

Implication on the relevance of the storm alert system
The obtained results are only validated for the Nancy region. In this region, it is possible to define a period of the year presenting a maximum risk of intense cells detection: from May to October, which is in agreement with the historical observations of damages caused by storm events in Nancy. But 2,450 intense cells were identified out of this period in four years.

No risk criterion relevant for very short range forecasting could be proposed in function of hours, meteorological parameters, and location of pre-existent cells (therefore in function of quantitative rainfall forecasting). If such criteria were used in Nancy, the risk forecasts would be regularly false. This fully justifies the principle of the alert system used by the CUGN, which is based on the identification and analysis of all the intense cells in a large area around Nancy, and on progressive alarms (this procedure allowing a sufficient anticipation for the operational needs).

For example, on June 14, 2003, an exceptional rain event caused significant damage in all the CUGN territory because of unusual rainfall intensities. The rain cell concerned appeared in the radar images only 5 minutes before the rain, a few kilometres from the agglomeration: we can note that a "confirmed risk" alarm was going on, due to several intense cells detected in the region. July 23 2001, with a stationary storm development directly over the basin to protect, represents another situation where alert systems based on QPF can not be relevant.

OPERATIONAL EFFICIENCY OF THE ALERT SYSTEM

Data collected from January 2000 to October 2001 was used to carry out an *a posteriori* evaluation of the actual effectiveness of the operational alert system with respect to the two *a priori* objectives (Payrastre 2002):

- to ensure the safety of the Boudonville catchment area against flooding;
- to limit as much as possible the polluted discharges into the natural environment, by storage and settling the maximum volume of combined sewage in the Gentilly basin.

This evaluation was realised by comparing the hydraulic risk level estimated for all the rain events during this period, with the alarms generated in real time by the system. Only the « confirmed risk » alarms were analysed in this study.

It is important to note that the radar data used were not validated, and could include problems or omissions: in particular, a failure of the radar computer resulted in a systematic over-estimate of the radar measurement during April 2001, which generated 28 "confirmed risk" alarms during this not very rainy month (34 mm of cumulated rainfall). Météo-France having rapidly informed the CUGN, these data were not used for the operational management of the Gentilly basin: consequently, these wrong data were not used in this evaluation of the alert system functioning.

Characterisation of the risk level associated to the rain events
For the alert system evaluation, each rain event observed from January 2000 to October 2001 was situated on the scale of risk defined in table 1. The flow measurements in the sewers depending on the sewerage operation, this rainy events qualification was realised with the CUGN rain gauge data.

The measurements of the two most representative rain gauges for the Boudonville catchment area allowed to estimate the total cumulated rainfall for this period: 1621 mm (April 2001 excepted). This total value includes 192 mm from very weak and diffuse precipitation, and 501 rain events corresponding to continuous rainy periods (without dry period exceeding 15 minutes), each event representing more than 0.5 mm of cumulated rainfall. The risk level of each event was then estimated by comparing estimations of maximal rainfall during various time periods with those obtained for the 17 events of reference (i.e. max. cumulated rainfall during 15 and 30 minutes and total cumulated rainfall). This method was considered as being sufficiently relevant, and permitted to identify 4 rain events corresponding to the R1 and R2 risk levels, the reality of the risk being validated by the water level measurements realised by the CUGN at the strategic point of the sewerage network. All the other events were classified in risk levels NR2 (21 events) or NR1.

Analysis of the « confirmed risk » alarms generated in real time
65 "confirmed risk" alarms occurred from January 2000 to October 2001 (April 2001 excepted). Each of these events was analysed with estimation of the cumulated rainfall at ground level, and visualisation of the radar images for 61 events (table 3).

Table 3. Effectiveness of the Nancy alert system : analysis of the 65 "confirmed risk" alarms generated by the alert system from January 2000 to October 2001 (April 2001 excepted)

	Number of alarms	Cumulated rainfall	Annual rate (%)
Events with confirmed hydraulic risk (4 events)	4	127 mm	7.8%
Events with potential risk (intense rain cells confirmed)	42	43 mm	2.6%
Events without radar data archived	4	0 mm	0%
Events without risk (no cells) having generated an alarm	15	9 mm	0.6%
Events without any alarm	0	1442 mm	89%

Effectiveness for protection against intense rainfall. The four events presenting a risk for the sewerage network (R1 and R2 types) were preceded by an alarm of “confirmed risk”, more than two hours before the beginning of the rain for the two more intense rain events. These "confirmed risk" alarms were also preceded by a "potential risk" alarm alerting the sewerage network supervisor to the intense cells identified on the radar images. Note that for these four events, the alarms were not always activated by the rain cell which produced heavy rainfall on the Boudonville catchment area. This was particularly interesting on July 23 2001, the most intense event for which a stationary storm developed directly over the Boudonville basin. In consequence, the alert system perfectly ensured its role for the hydraulic safety of the network.

On the other hand, 61 other "confirmed risk" alarms were generated without being followed by important rainfall on the Boudonville catchment area. Nevertheless, we observed that in 42 cases these alarms were induced by detection of well marked intense cells in the region, these cells finally not having reached the small catchment area. From a safety point of view, we can thus consider that these cases corresponded to a potential risk which was not materialised.

The residual alarms correspond to the 4 unverified events because of the lack of radar images, and to 15 events for which the alarm generation was considered to be irrelevant. These 15 cases can be considered as false alarms.

Efficiency with respect to the limitation of sewage discharges. Table 3 shows that the rain events for which no alarm was generated account for 89% of the total cumulated rainfall on the catchment area. During these events, the Gentilly basin was completely available for storing and settling combined sewage in order to limit discharges into the natural environment. With the assumption that this rain rate corresponds to an equivalent rate of flow conveyed by the sewerage network, it is possible to estimate that this result exceeds the objective defined *a priori*.

Among the other 11% of cumulated rainfall, nearly 8% correspond to the 4 events which represented a real risk of flood. For these events, the Gentilly basin was used as storm basin (through temporary storage) in order to reduce the peak flows downstream in the sewerage network.

The residual 3% correspond to alarms not followed by actual risk, and thus represent the maximum room for progress to improve this alert system on the Boudonville catchment area. We can note that the reduction of the false alarms rate by focusing the alerts on the nearest cells moving directly toward the basin would significantly reduce the time available to make the system safe.

CONCLUSION

An alert system generally represents a compromise defined according to the risks incurred in case of non-detection of a dangerous event, the consequences in case of false alarm, and the time required for action. It must be evaluated according to these constraints. In the case of the Gentilly basin, the required time is considered longer than one hour, the risk of non-detection of dangerous events is considered to be non-acceptable, and the consequences of false alarms are reduced to the non-availability of the basin to store and treat effluents according to the objectives of depollution (generally, the basin doesn't store a great quantity of sewage before the beginning of the rain, and a preventive drainage is rare).

In this context, this alert system presents two important advantages: it provides an early recognition of a potentially risky situation, and it allows the use of radar data (see table 1) which is not of the best quality (low number of reflectivity levels, succinct treatments of the radar measurement errors, no utilisation of quantitative rainfall estimations or forecasts).

The results of the first study have shown the relevance of this alert system considering the risks represented by the intense rain cells. No other criterion of alarm could be proposed with a sufficient reliability compared to the operational risks.

The second study allows to estimate that in operational use the alert system has a very good effectiveness for the protection against flooding, and has a sufficient efficiency (difficult to improve) to guarantee the respect of the *a priori* objectives concerning the reduction of combined sewage discharges. Moreover, the alarms of "confirmed risk" not followed by dangerous rainfall corresponded in majority to potential risks which were not concretised: thus these alarms did not reduce the confidence of the users in the system.

Following these two studies, the system was slightly modified and extended to all the catchment basins of the CUGN: in addition to the alarms of potential and confirmed risk, an "alarm of impact" is emitted when the passage of an intense rain cell is forecasted over a basin in the next 30 minutes. A user-friendly tool also facilitates the tracking and the analysis of each detected cell. The supervisor of the sewerage system can thus use a range of short-term information sources for its decision-making: weather alerts (24 hours), potential then confirmed risk alarms (few hours), alarms of impact and QPF (30 to 15 minutes).

After these two studies and four years of operational use (at the end of 2004), we estimate that this alert system is an appropriate response to the needs of the CUGN Water and Sewerage Department, needs for which it was designed. It would be very interesting to test this alert system in other operational conditions, and in other regional contexts.

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