# USING HIGH RESOLUTION RAINGAUGE DATA FOR STORM TRACKING ANALYSIS IN THE URBAN AREA OF PALERMO, ITALY

by

Lo Conti, F. [(1)], Noto L.V.[(1)], Quatrosi A. [(1)] and La Loggia G.[(1)]

[(1)] *Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali, Università di Palermo, Italy* (*loconti@idra.unipa.it*)

**ABSTRACT**

This paper presents a comparative analysis between rain-gauge storm tracking techniques in order to achieve a better knowledge of the rainfall dynamics over an urbanized area. The temporal and spatial distribution and kinematics of short term rainfall are recognized as one of the most important reasons in error production in rainfall-runoff on urban catchments. The uncertainty due to rainfall variability can greatly affect urban drainage modeling performance and reliability thus reducing the confidence of operators in their results. Modeling representations of urban catchments and drainage systems are commonly adopted for surface flooding forecasting and management and an adequate knowledge of rainfall spatial and temporal variability should be considered as a fundamental step for a robust interpretation of the physical processes that take part in urban areas during intense rainfall events. The starting basis of such studies is usually given by a network of high resolution raingauges disseminated inside and around the examined urban area. One of the raingauge techniques used is based on simulating the storm motion by visualizing the sequence of the rainfall patterns obtained using rain-gauge data and on spatial correlation. The storm speed and direction are obtained using the rain-gauge method by tracking the advance of the maximum rainfall intensity in time and space. A second method is based on the identification, for each gauge, of the time of occurrence of some significant features such the time of onset of a storm or the time of peak. A third method is based on the classical idea of space-time autocorrelation function; This function describes the way in which the correspondence between the rainfall patterns at two points in space-time reduces as the distance between two points is increased.

The analysis has been carried out on the basis given by high resolution rainfall data collected over Palermo urban area (Italy). The urban area has a surface of around 30 km$^2$ and it is mainly distributed on North West – South East direction. The monitoring network is made of 10 tipping bucket raingauges. Bucket volume is equivalent to 0.1 mm rainfall.

Raingauges have been uniformly distributed over the urban areas allocating them mainly over public buildings and school in order to allow for easy access. The network has been put in place in January 2006 and it is still working. Data is monthly collected by the operator that also provide for clock synchronization and ordinary maintenance and cleaning.

An accurate analysis of the results of this comparison between the techniques has been carried out and, since the city of Palermo is not covered by any meteorological radar, the analysis of storm dynamics will allow to create a system monitoring hydrometeorological conditions which operates on time basis using the information coming from the raingauge network as forecast triggers.

*Keywords:* rainfall, storm tracking, raingauge data

## 1 INTRODUCTION

The outflow hydrographs within natural or urban catchment can be significantly affected by characteristics of the rainstorms as speed and direction. The missing knowledge of the spatial distribution and the movement parameters of the precipitation input is the most important cause of the presence of errors in runoff simulation (Niemczynowicz, 1987). For these reasons it is important to point out that the rainfall input to the hydrological models should be based on the recognition of rainfall dynamics containing the movement parameters.

The problem of the analysis of rainfall dynamics has been carried out since ’60. The most of methods of storm movement estimation starts with the identification of some recognizable feature of the rainfall pattern called usually reference point (Niemczynowicz, 1987). This feature is followed as it moves in space across the raingauge network. Usual reference points are the peak of the hyetograph, the leading edge of the rain, the maximum of cross-correlation function and/or the maximum of lag-correlation structure and the choice of these reference points differentiates the various storm tracking techniques.

One of the early storm tracking techniques is the “full correlation analysis” developed by Briggs et al. (1950) and Felgate and Read (1975). In this method, the reference point is the maximum of the cross-correlation function between pairs of raingauges from every three-gauge group selected from the raingauge network. The time displacement between the maximum of the cross-correlation function in three raingauges are used in order to estimate the velocity and the direction of analyzed storm.

Johnson and Bras (1979) tested several storm velocity estimators ranging from storm feature tracking to co-variance maximization clearly converged in a regression procedure based on time series of the raingauges. The procedure proposed by the Authors proved to be stable and convergent under many different conditions.

One of the methods analyzed by Johnson and Bras (1979) is the “lag-correlation method” developed by Marshall (1975). This method calculates the spatial correlation pattern based on the calculation coefficients between the time pattern of the rainfall in pairs of gauges with a known applied time lag.

The Marshall method has been used and modified by different researchers like Niemczynowicz (1987) and Upton (2002). Niemczynowicz (1987) presented the results of the comparison of the “lag-correlation method” with other two simpler storm tracking methods on a set of rainfall data coming from a 12-raingauges network in Lund, Sweden concluding that a really objective and reliable tracking method does not exist and that the performances of different methods depend on rainfall field structure. Upton (2002) presented a study focused on the short-term tracking of rainstorms, using data from a network of 20 tipping-bucket raingauges over a region of 600 km$^2$ in northwest England. He proposed an approach based on the “lag-correlation method” improved by adding some tools finalized to identify misleading raingauges.

The main aim of this study is to perform the correlation based method (Upton, 2002) on a set of rainfall data coming from a 10-raingauges network in Palermo (Italy); the results of this method has also been compared with wind data (speed and direction at 10 m) coming from a meteorological network.

## 2 THE CORRELATION BASED METHOD

The first methodology here used to analyze the storm dynamics above the urban area of Palemo has been proposed by Upton (2002). Let $R_i(t)$ be a measurement of precipitation at raingauge $i$ at time $t$ after the start of the storm, and $R_j(t+l)$ being the corresponding measurement at raingauge $j$ at time $(t+1)$ and suppose that there are $G$ useful raingauges in the network. For a given event, let $\overline{R_i}$ and $\overline{R_j}$ be the mean precipitation values at the two raingauges $i$ and $j$. By defining $d_i(t)$ and $d_j(t+l)$ as $R_i(t)-\overline{R_i}$ e $R_j(t+l)-\overline{R_j}$ respectively, it is possible to calculate the correlation $r_{ij}(l)$, for a time shift of $l$ minutes as:

$$r_{ij}(l)=\frac{\sum_i\sum_j d_i(t)d_j(t+l)}{\sqrt{\sum_i d_i^2(t)\sum_j d_j^2(t+l)}} \quad (1)$$

It is important to point out that the values for $R_i(t)$ come from the so-called “integrated hourly rain profile” where the height at time $t$ is proportional to the sum of number of tips recorded in the interval ($t$-30, $t$+30).

The cross-correlation analysis has been used to determine the lag corresponding to the maximum of $r_{ij}(l)$. The classical procedure has been modified in order to take into account that a wide range of lags, for which $r_{ij}(l)$ is very similar, could exist. Let $r_{max}$ be the maximum value of $r_{ij}(l)$ and define $l_1$ and $l_2$ to be the lowest and highest values for $l$ for which

$$r_{ij}(l) > \varepsilon\, r_{\max} \quad (2)$$

where $\varepsilon$ is a coefficient here equal to 0.90÷0.95. The estimated time-lag $l_{ij}$ between raingauge *i* and *j* is calculated by averaging $l_1$ and $l_2$.

The determination of the cross-correlation function $r_{ij}(l)$ is also important since it provides the opportunity to detect and remove data anomalies by calculating a diagnostic statistic $z_c$ (Upton, 2002) whose distribution, in a homogeneous rainstorm, with correctly functioning raingauges, is approximately symmetric with mean zero and variance close to one. If the information provided by raingauge *i* is incorrect then the cross-correlation involving gauge *i* is lower than those typically noted and $z_c$ will be negative and lower than -3.

Suppose that, after screening operation above mentioned, information is retained on *n* of the *G* gauges. Suppose that gauges *i* and *j* are located at the points ($x_i$, $y_i$) and ($x_j$, $y_j$), respectively. Writing $x_{ij}=(x_i-x_j)$ and $y_{ij}=(y_i-y_j)$ and assuming a constant storm velocity, the set of triples {$x_{ij}$, $y_{ij}$, $l_{ij}$) will satisfy the following planar equation:

$$l_{ij} = a\,x_{ij} + b\,y_{ij} + \varepsilon_{ij} \qquad (3)$$

where the $\varepsilon_{ij}$ are random errors and *a* and *b* are constants that must be estimated.

The parameters *a* and *b* can be estimated using ordinary least squares (*OLS*) method assuming that the random errors are independent observations from a common distribution with a constant variance $\sigma^2$.

An estimate of the speed of the storm $\hat{v}$ is given by:

$$\hat{v} = \frac{1}{\sqrt{a^2 + b^2}} \qquad (4)$$

while an estimate of the direction is given by $\theta$, where $\sin(\theta)=a$ and $\cos(\theta)=b$. The results of planar regression allow also to identify and eliminate other misleading raingauges another diagnostic statistics $z_r$ whose distribution is very approximately normal. For details see the original paper of Upton (2002).

## 3 THE CASE OF STUDY

The analysis has been carried out on the basis given by high resolution rainfall data collected over Palermo urban area (Italy). The urban area has a surface of around 30 km$^2$ and it is mainly distributed on North West - South East direction. The monitoring network is made of 10 tipping bucket raingauges. Bucket volume is equivalent to 0.1 mm rainfall and raingauge funnel has a maximum horizontal cross-section equal to 0.1 m$^2$. The tipping bucket is connected to an electrical switch able to measure the time of each bucket floatation. This information is passed to a data-logger able to aggregate data with a temporal resolution equal to 1 minute and store them on a hard memory. Memory is able to collect data for 2 months without human supervision but after that period data are progressively overwritten. Data is monthly collected by the operator that also provide for clock synchronization and ordinary maintenance and cleaning.

Raingauges have been uniformly distributed over the urban areas allocating them mainly over public buildings and school in order to allow for easy access (*Figure 1*). The network has been put in place in January 2006 and it is still working. Raingauge DL10 (indicated by a square in *Figure 1*) has been damaged in July 2006 and it was not replaced.

Data has been collected in a geographical database developed on ArcGIS platform. The geographical database collects all the information about instrumentation, raingauge location and installation photos according to *World Meteorological Organization* (*WMO*) standards. Rainfall data is also automatically aggregated over time intervals ranging between 5 minutes and 24 hours (*Figure 2*).


*Figure 1* – Monitoring network distribution over Palermo urban area

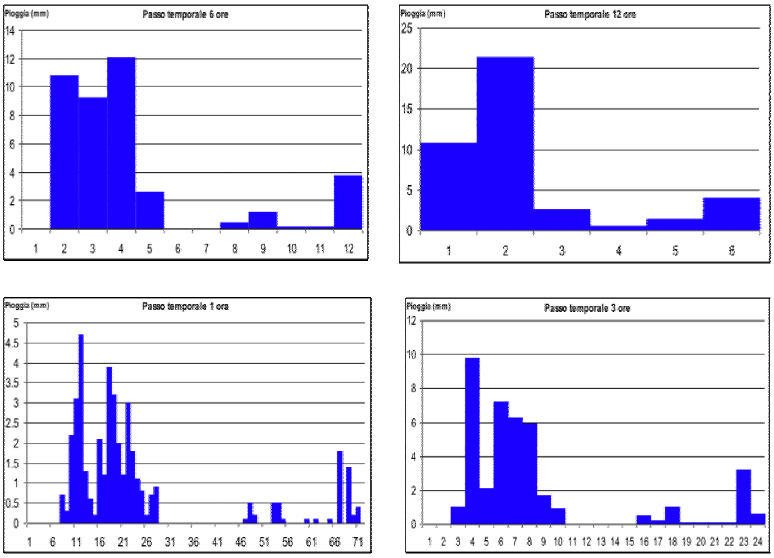



*Figure 2* – Data temporal aggregation example

## 4 RESULTS

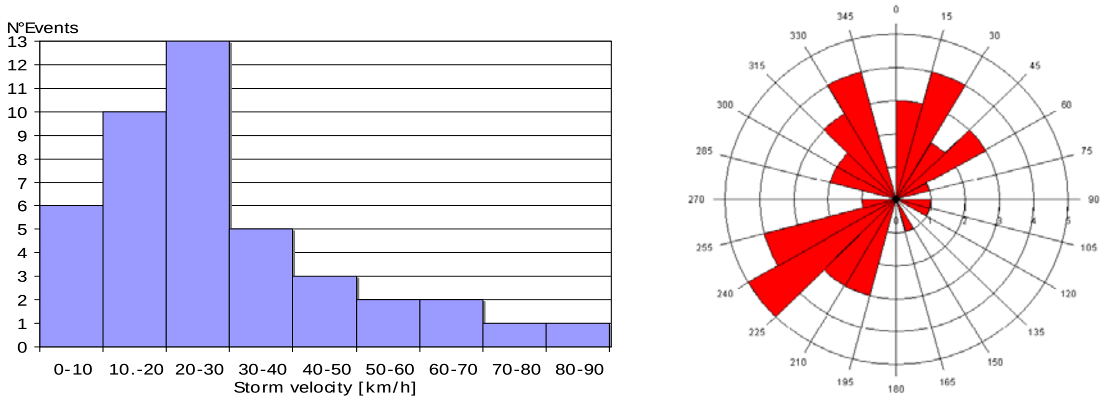
The storm tracking technique has been here implemented in a framework comprising a database (*Microsoft Access*) and a numerical computing environment and programming language (*Matlab*) that has been linked to the database in order to get raw rainfall data to process.

In a first phase, the correlation analysis (Upton, 2002) has been run over the whole rainfall database. Secondly, a comparison has been performed on 5 selected events for which validation wind data where available from SIAS regional monitoring network. The database consists of 107 events measured between 20th January 2006 and 31st January 2007. Among them, 43 events have been selected neglecting local events (not involving the whole monitored area), too short events and events characterized by small rainfall volumes (during the workshop the results related measures between 31st January 2007 and 28th February 2009 are going to show). Maximum rainfall volume has been registered during the event of 23rd - 24th February 2006 and the related event duration was 23 hours. The correlation analysis allowed for better understanding rainfall dynamics over the analyzed urban area. Figure 3 summarizes the results of correlation study:

the relative frequency of storm velocity (figure 3a) shows that the more than 60% of monitored events has a velocity lower than 30 km/h and around the 30% of events has velocities ranging between 20 km/h and 30 km/h;

40% of the monitored storms comes from the South-West quadrant and the remaining are equally distributed among North-West and North-East quadrants and this result has a qualitative confirmation in local fishermen traditions suggesting to look at South-West for forecasting weather over Palermo urban area.

In order to better discuss the effectiveness of correlation method, event registered on 24th December 2006 has been used as an example. Table 1 shows cross-correlation between raingauge. Raingauge DL10 has not been considered because it was damaged before that event. The cross-correlation matrix is skew-symmetric by definition and with the main diagonal elements equal to zero. For the selected event, cross-correlation coefficients are ranging between -29 and 31 showing a good agreement between the rainfall patterns monitored by the different raingauges.




a) b)

*Figure 3* – . Relative frequency of storm velocity (a) and storm direction (b) for the Palermo urban area (based on 107 events)

*Table I* - Cross-correlation coefficients between different raingauges during the rainfall event occurred between 23rd and 24th December 2006

| Gauge | DL1 | DL2 | DL3 | DL4 | DL5 | DL6 | DL7 | DL8 | DL9 |
|---|---|---|---|---|---|---|---|---|---|
| DL1 | 0 | 31.5 | 29.5 | 5.5 | 6 | 29.5 | 31 | 5.5 | 37.5 |
| DL2 | -31.5 | 0 | 4 | -19.5 | -23.5 | -3 | -1 | -22.5 | 10.5 |
| DL3 | -29.5 | -4 | 0 | -18.5 | -20.5 | -5 | -3 | -19.5 | 4.5 |
| DL4 | -5.5 | 19.5 | 18.5 | 0 | 0.5 | 18.5 | 21 | 0 | 26 |
| DL5 | -6 | 23.5 | 20.5 | -0.5 | 0 | 22 | 24.5 | 0.5 | 26 |
| DL6 | -29.5 | 3 | 5 | -18.5 | -22 | 0 | 2.5 | -21 | 13.5 |
| DL7 | -31 | 1 | 3 | -21 | -24.5 | -2.5 | 0 | -23 | 11.5 |
| DL8 | -5.5 | 22.5 | 19.5 | 0 | -0.5 | 21 | 23 | 0 | 29 |
| DL9 | -37.5 | -10.5 | -4.5 | -26 | -26 | -13.5 | -11.5 | -29 | 0 |

Cross-correlation approach requires a preliminary data validation analysis obtained evaluating statistic $z_c$. If $z_c$ is lower than -3 for any of the raingauges adopted in the study, such raingauge can be dropped from the study because the registered rainfall pattern is sensibly uncorrelated with the others. The preliminary validation of rainfall data has confirmed that all raingauges can be used for the correlation study of the selected event. For all the analyzed events, the pre-validation phase has always confirmed the correlation among the adopted raingauges.

After the cross-correlation analysis, the method proposes a post-validation phase based on the evaluation of $z_r$ statistic as described in the previous paragraphs. Accordingly to the method, $z_r$ values lower than -3 for a specific raingauge show that the results of storm-tracking study are suspiciously far from the rainfall pattern registered at the raingauge and it should be dropped from the analysis.

The post-validation test performed for the selected event reported that all the raingauges should be maintained and the cross-correlation study is satisfactory. For all the analyzed events, the post-validation test seldom allowed for dropping one or more raingauges from the analysis.

# 5 CONCLUSIONS

The present study performed a storm tracking analysis in urban areas using a cross-correlation method. This has been validated by the mean of wind data collected in the analyzed area. The study has been carried out using data collected by a raingauge network located in Palermo (Italy). Ten tipping bucket raingauges have been distributed over a 30 $km^2$ urban area. Data have been collected with a time resolution equal to 1 minute and a volume resolution equal to 0.1 mm. Field campaign started in January 2006 and more the one hundred rainfall events have been registered during the monitoring phase. Results of study allowed for the following considerations:

The study demonstrated that cross-correlation analysis can be efficiently applied determining the main features of storm propagation over Palermo urban area; the method demonstrated a good agreement with wind data and meteorological propagation information over the area.

Preliminary and subsequent validation processes increase method reliability and robustness increasing operator confidence in the derived results.

Future research development should be focused on monitoring network empowerment by the introduction of new raingauges or by enlarging the monitored area in order to better catch rain cells movements over the area. This approach would increase the reliability and the forecasting ability of the cross-correlation method.

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