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Use of Radar Precipitation Estimates in Urban Areas: A Case Study of Mexico City

Ernesto Caetano[1], Baldemar Méndez-Antonio[2] and Víctor Magaña[1]
[1]*Instituto de Geografía, National Autonomous University of Mexico,*
[2]*Energy Department, Metropolitan Autonomous University,*
Mexico

1. Introduction

Storm events have long been a menace to Mexico City. The main reason is related to the fact that in summer, many showers can reach intensities of more than 20 mm/hour, which makes difficult the management of the drainage system in various areas of the city. As instance discharges of large magnitudes in the western part of the city are an element of danger, as they lead to flash flood that inundate populated areas downstream in a matter of minutes. Recent flooding events in Mexico City have revealed its vulnerability to severe weather conditions. Although regularization programs and new urban land policies are been implemented by the council government, there are still many families living in high risk areas. These areas over hillsides, and irregular human settlements still proliferate. Usually, severe storms can cause hazard landslides because unstable landfills and deforested hill slopes. On the other hand in the flat parts of the city, faulty drainage systems usually cause sewage flooding after continuous rain events. The urban sprawl undergone in the last half century, has not kept pace with urban services such as drainage. In the rainy season, puddles arise, sometimes caused by the presence of silt and debris in the ducts and the drainage system capacity is exceeded, and in other cases there are no absorption wells in areas with problems in the drainage network. Additionally, the lack of maintenance of dams and channels can also result in severe flooding problems. In most cases, the intense rainfall events produce merely an emergency response of fire departments.

In the last three decades there have been major advances in remote sensing techniques for estimation of rain, mainly in the use of meteorological radar and weather satellites, increasing the availability of rainfall data for operational meteorological and hydrological applications. Precipitation estimates derived from meteorological radar are useful in runoff simulation in urban drainage. Spatial distribution of radar rainfall used as input to a distributed hydrological model permit to characterize the performance of drainage infrastructure at local and regional scale. Radar data used in this analysis are obtained from C-band radar deployed at western Mexico Valley basin and derived rainfall estimates provides the input to a distributed hydrologic model applied to the Mixcoac microwatershed located at western Mexico basin. Radar and distributed hydrologic model are capable to provide accurate rainfall and runoff data supporting specific-site flood information and, also provides a baseline for comparison and guides design of radar network as one component of an early warning system for the region.

The international practice aims at a comprehensive approach to flood management in response not only to the consequences of a specific event, but measures that starting from the prediction of extreme events and monitoring for early warning purposes to establishment of civil protection measures for those affected by the occurrence of such events and the hazard remediation, including infrastructure development and non-structural measures to reduce the vulnerability.

The structure of this work is as follows. Section 2 presents the summer precipitation regime over Mexico Valley. Section 3 a brief description the meteorological radar deployed in Cerro Catedral at western of Mexico Valley. In Section 4 a case study for the microwatershed of the Mixcoac River is discussed. In Section 5 new design of a weather information system is proposed. Concluding remarks are found in Section 6.

2. Mexico valley precipitation climatology

The México Valley is located at 2240 m altitude and at a latitude of approximately 19°N and is characterized by well-defined rainy season from late May to early October which can be classified as a monsoon climate type.

The orography of region plays an important role on the precipitation patterns (intensity, timing, spatial distribution and, extreme events occurrence). On northeastern area, region nearly flat, the average precipitation is around 500 mm/year and at southwestern mountainous region part of the México Valley, the average reaches almost 1200 mm/year (Fig. 1). The occurrence of extreme events follows the same patterns as shown by Magaña et al. (2003) by establishing a criterion to determine when intense precipitation should be considered an extreme event based on a Gamma distribution of the observed amount of daily rainfall, for each station of the rain gauge network (Fig. 2). The similarity of spatial variability of severe weather and average precipitation becomes apparent. An extreme precipitation event to occur in the western or southern part of the basin, rainfall in 24 hours should exceed 25 or 30 mm, while in the eastern part of the city, more than 15 mm in 24 hours already constitute an extreme event. To a large extent the interaction of the mountains with the summer easterly winds determines, the characteristics of precipitation (Barros 1994).

The summer precipitation diurnal cycle indicates the intense precipitation begins in the afternoon (Fig. 3), around 16:00 h local time, generally in the eastern part of the valley, and propagate to the western part during the evening, reaching the other extreme of the valley by late evening and midnight (Mendez et al., 2006).

3. The Cerro Catedral radar

The radar network operated by Mexico's National Water Commission is focalized mainly in monitoring of the tropical cyclone activity and consists of thirteen C-band radars (manufactured by Ericsson Inc., Enterprise Electronics Corporation and Vaisala). There is also a weather radar deployed at Cerro Catedral which cover almost all Mexico Basin (located 40 km and altitude 3785 m, approximately 1500 meter above México City), to monitor severe weather over this region (Fig. 4). This radar measures reflectivity and has a Doppler and dual polarization and, is configured as follows (Table 1):

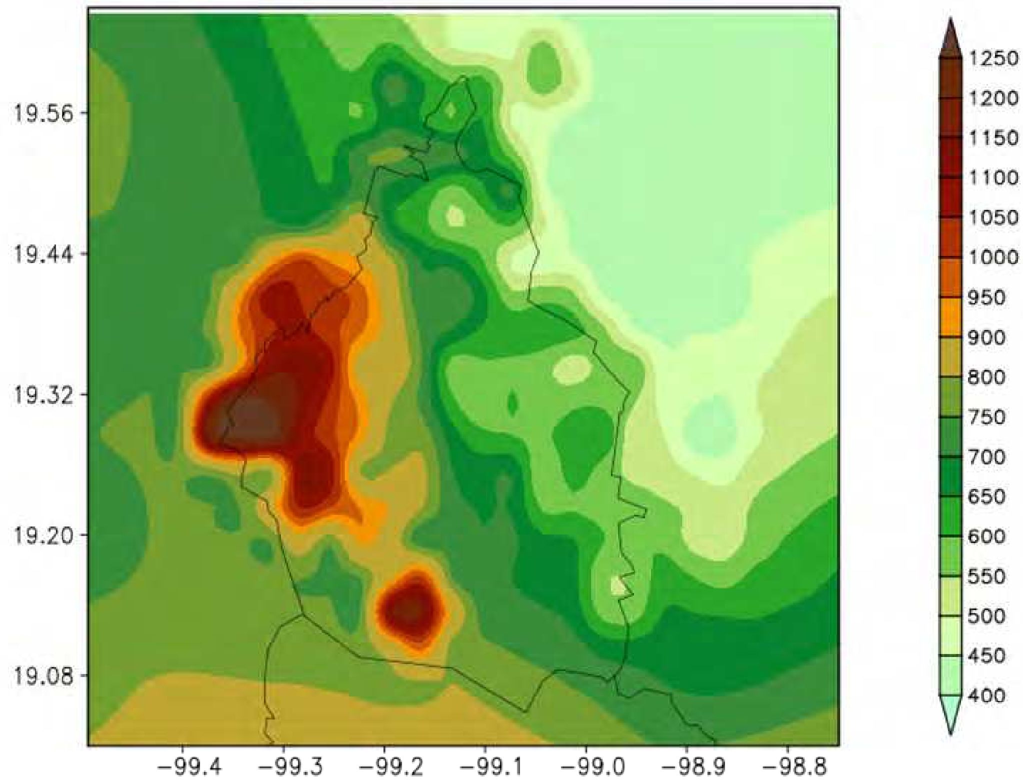


Fig. 1. Summer (May-October) climatology (2003-2008) accumulated (mm) precipitation distribution over Mexico Valley.

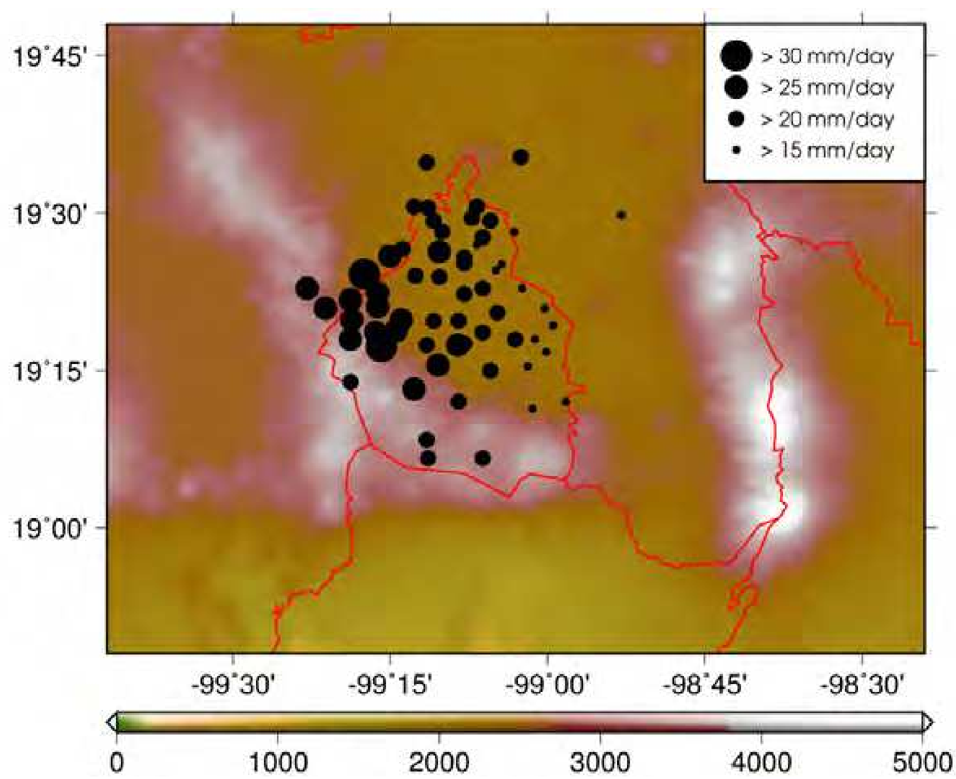
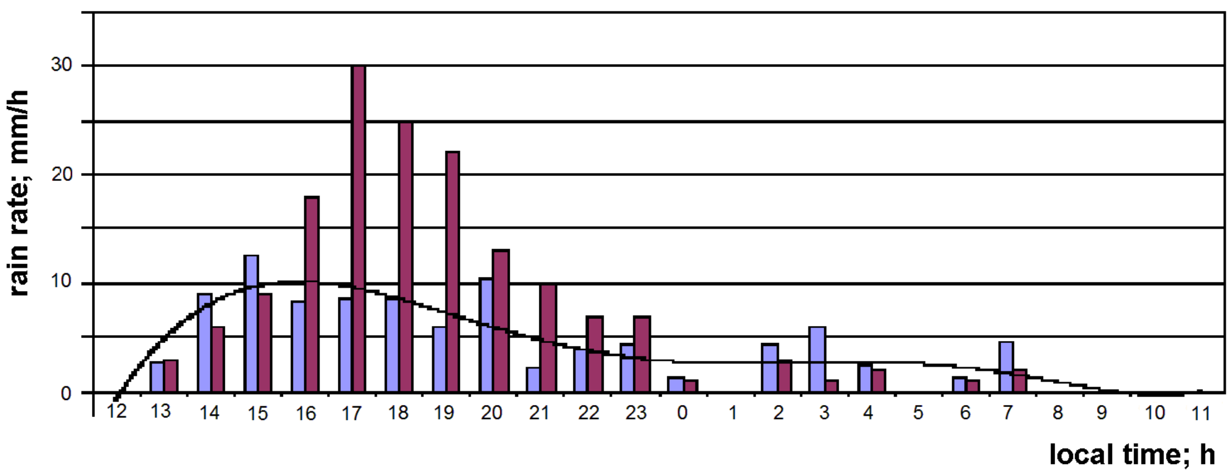
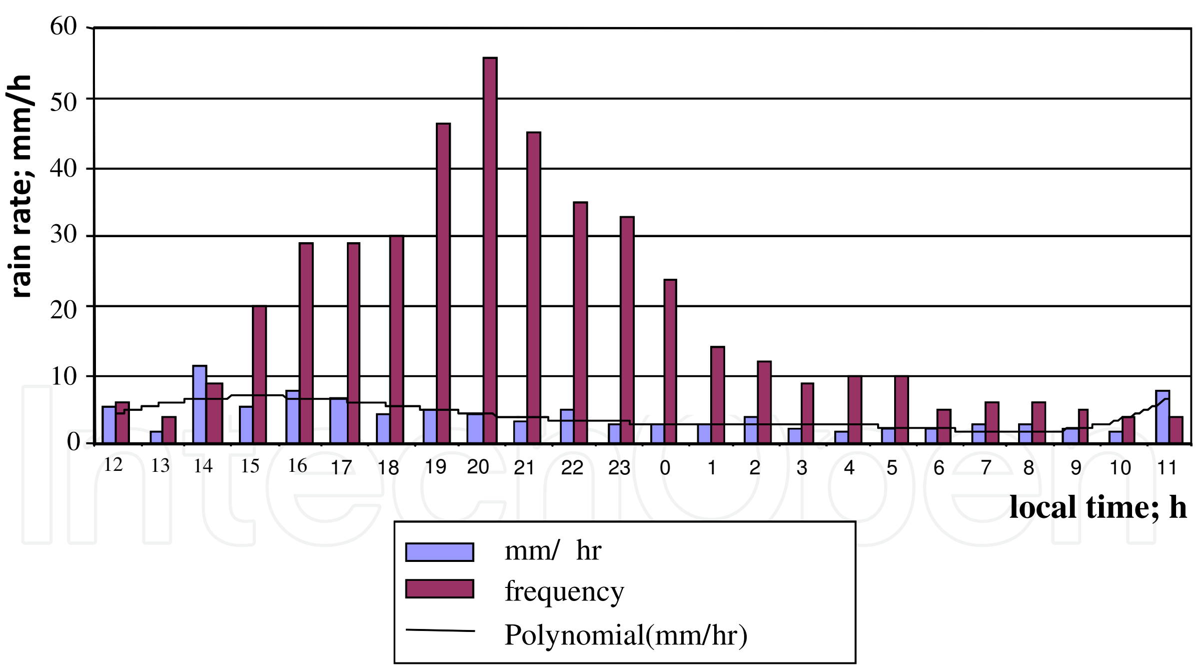


Fig. 2. Threshold values to determine daily extreme precipitation event. Topography (m) is shown in color.



(a)



(b)

Fig. 3. Precipitation intensity, frequency and occurrence time histograms; (a) northern and (b) southern Mexico basin; (1993-2001).

Antenna diameter (m)	4.2.
Antenna Gain (dB)	44.7
Beamwith (")	0.9
Polarization	Linear hor/vert
Frequency (GHz)	5.60-5.65
Wavelenght (cm)	5.30-535
Peak power (kW)	250
Pulse lenght (μs)	0.5 - 2.0
PRF (Hz)	250, 900, 1200
MDS (dBm)	-114, -110, -109

Table 1. Cerro Catedral weather radar (Ericsson UBS 103 04, upgraded by Sigmet/Vaisala technology) technical characteristics.

Such elevation has effects over the precipitation estimated at low level on Mexico Valley Watershed. In order to get a good coverage of shallow rain, originating close to ground, it is necessary to settle the elevation angles to negative value of around –1.5 degree. This has the inconvenience of blockage, clutter and loss of signal. The weather radar usually suffers partial or total blockade operating in mountain zones due to the complex topography around it. This effect can limit the coverage of the radar when it use negative degrees and affect the precipitation measurements (Joss & Waldvogel, 1990; Sauvageot, 1994; Collier, 1996 and Smith, 1998). The application of some blockage corrections to the observations radar is worthwhile, in order to get quantitative estimation of the precipitation and it can be combined with elimination of spurious echoes by two and three-dimensional analysis of the topography and the storm (Krajewski &Vignal, 2001; Steiner & Smith, 2002). A promising development in this field is related to the gradual change of weather radar concept, from a tool for qualitative rainfall estimation to a tool for more quantitative rainfall measurement (Borga et al., 1997).

Despite the drawback of the radar height site (1500 m above Mexico City) to follow stratiform precipitation system, convective systems are adequately monitored. In fact, the radar is capable of doing the full scan within convective clouds but no precipitation estimates in clouds with a base height of less than 3500 m (Fig. 5).

Figure 6 shows the monitoring of three storm events within range of radar coverage. In addition to tracking the storms, which would support decision makers in a warning system in these figures one can see the fixed echoes caused by the presence of volcanoes on the eastern side of Mexico City. This represents a serious problem in estimating precipitation, both qualitatively and in its distribution and location, as it provides information on areas where there is rain. Considering that the fixed echoes, whether caused by the interception of the land or effect of the lateral lobes, they can be largely eliminated with the Doppler radar function. However, despite all the Mexican radar, including that of Cerro Catedral, have this feature is not used to remove these echoes.

The Doppler radar function is a great help to eliminate this kind of echo and it is important for a better estimation of rainfall fields for hydrological or/and alert purposes. The cost of sending false warning alerts to users, when these echoes are not removed, is high, because once lost confidence in warnings of severe storms is difficult to recover it.

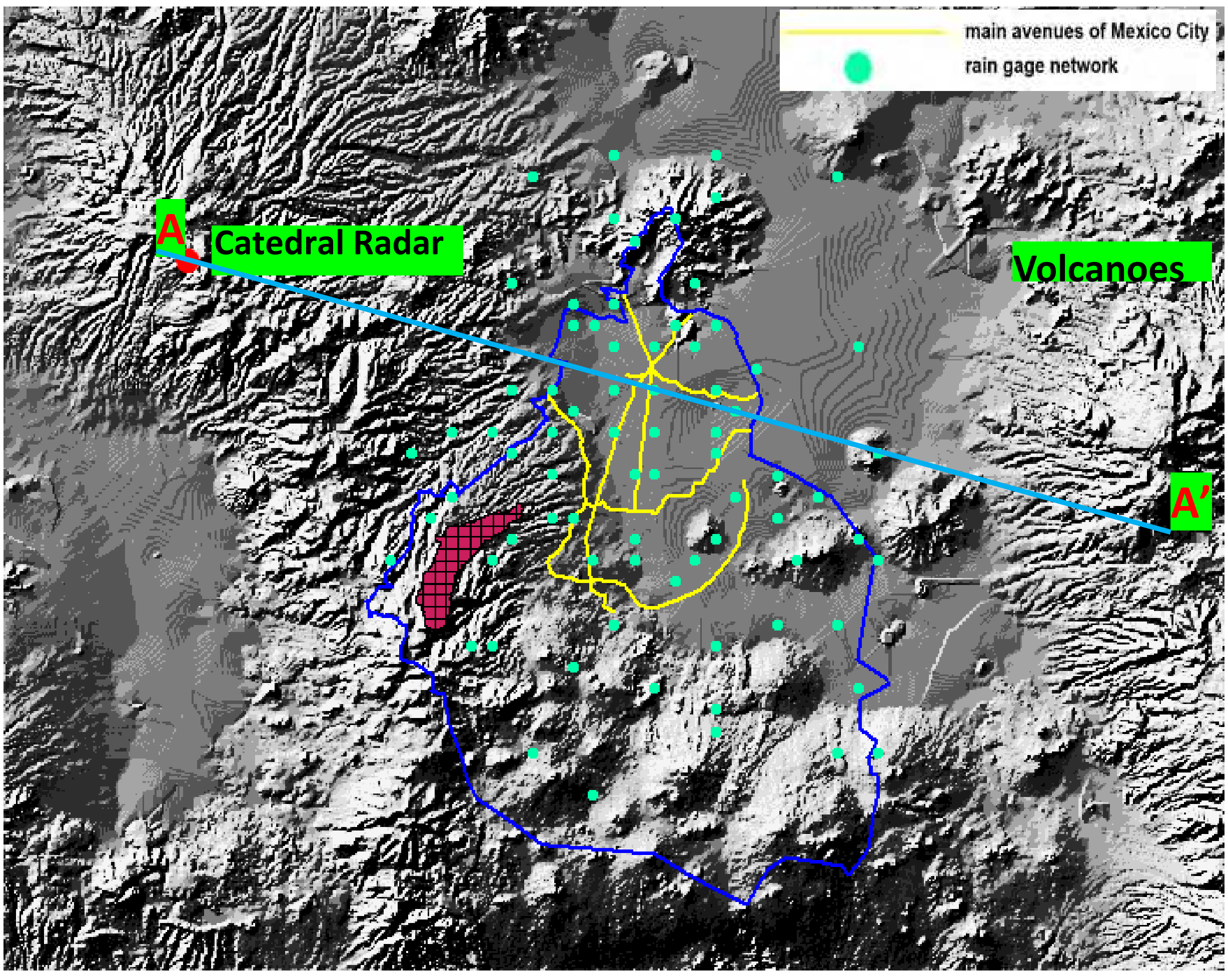


Fig. 4. Mixcoac River Basin (pink shaded area), Cathedral radar site and main avenues of Mexico City and rain gauges network.

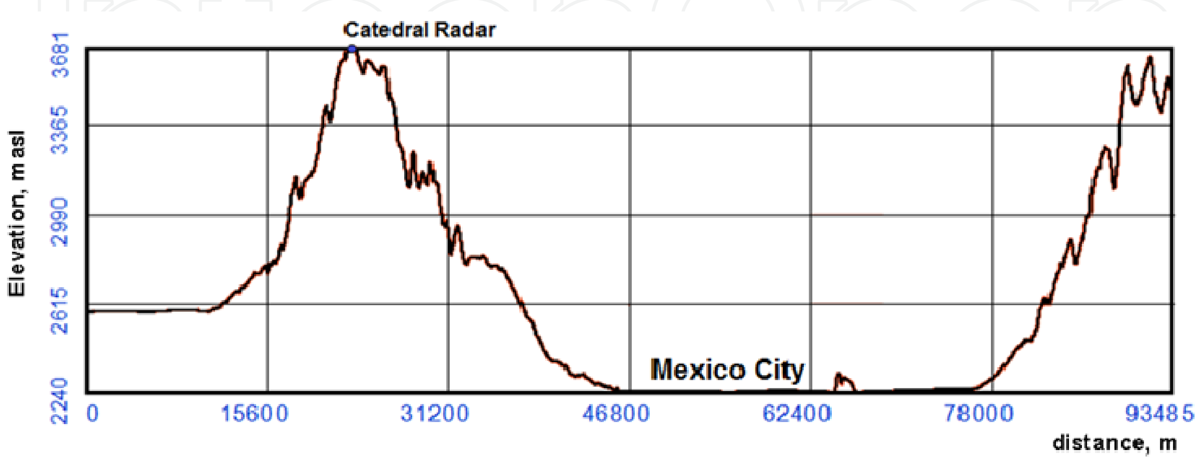
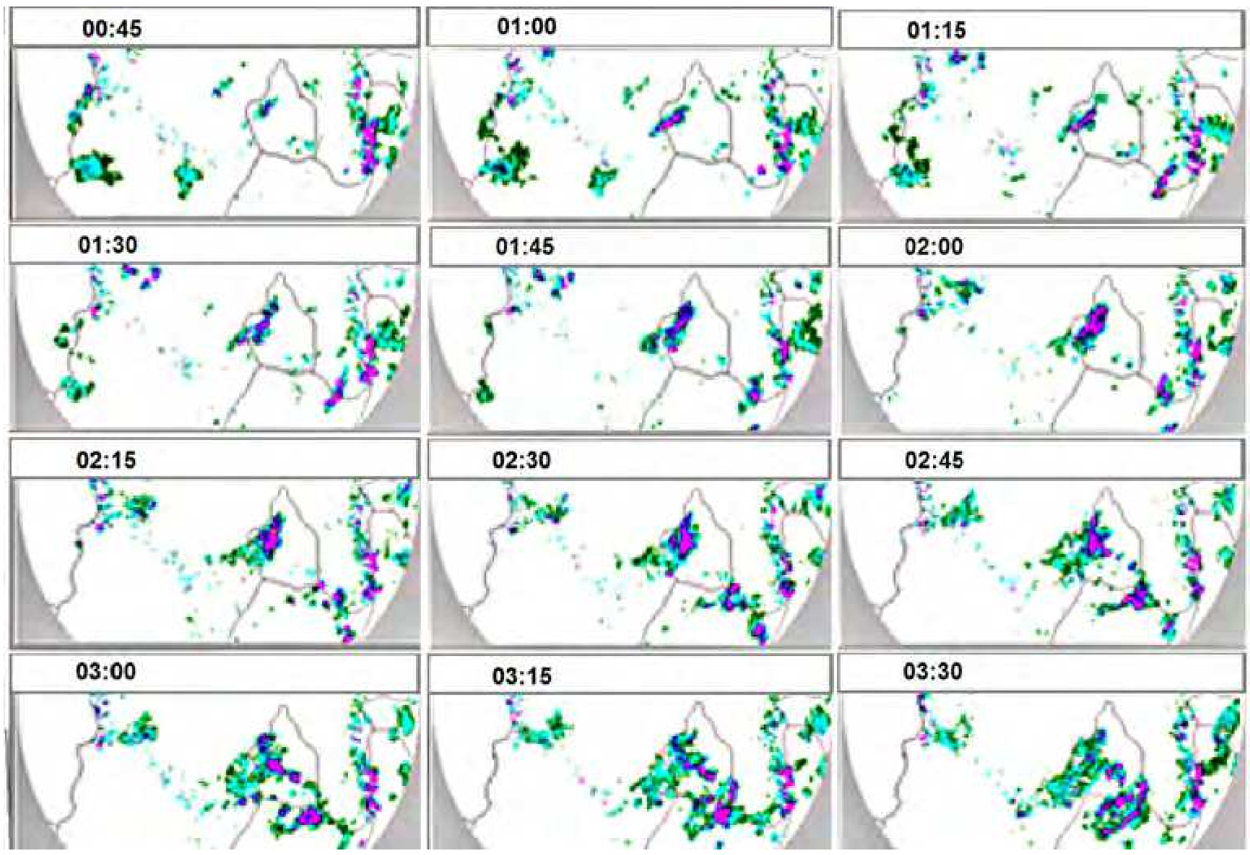


Fig. 5. Relief cross section A-A' of the Mexico Valley basin (see Fig. 4).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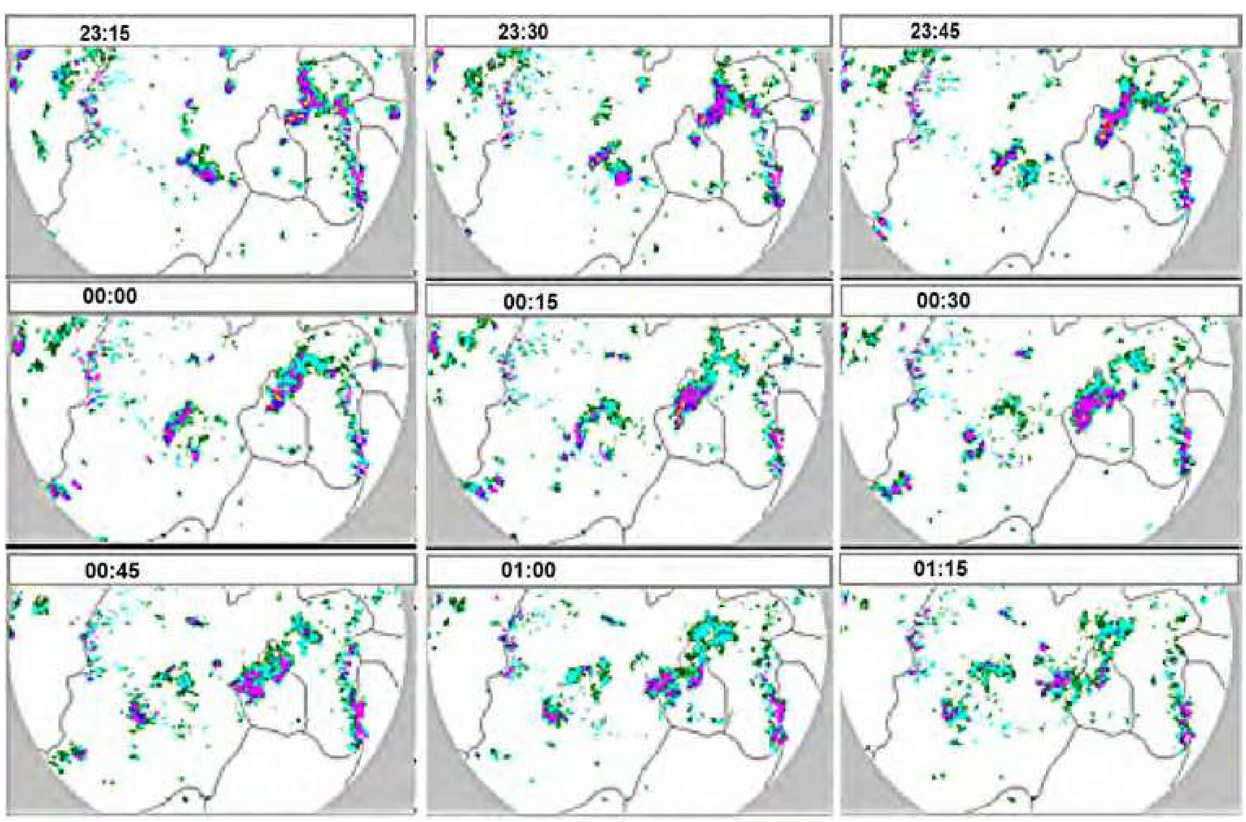
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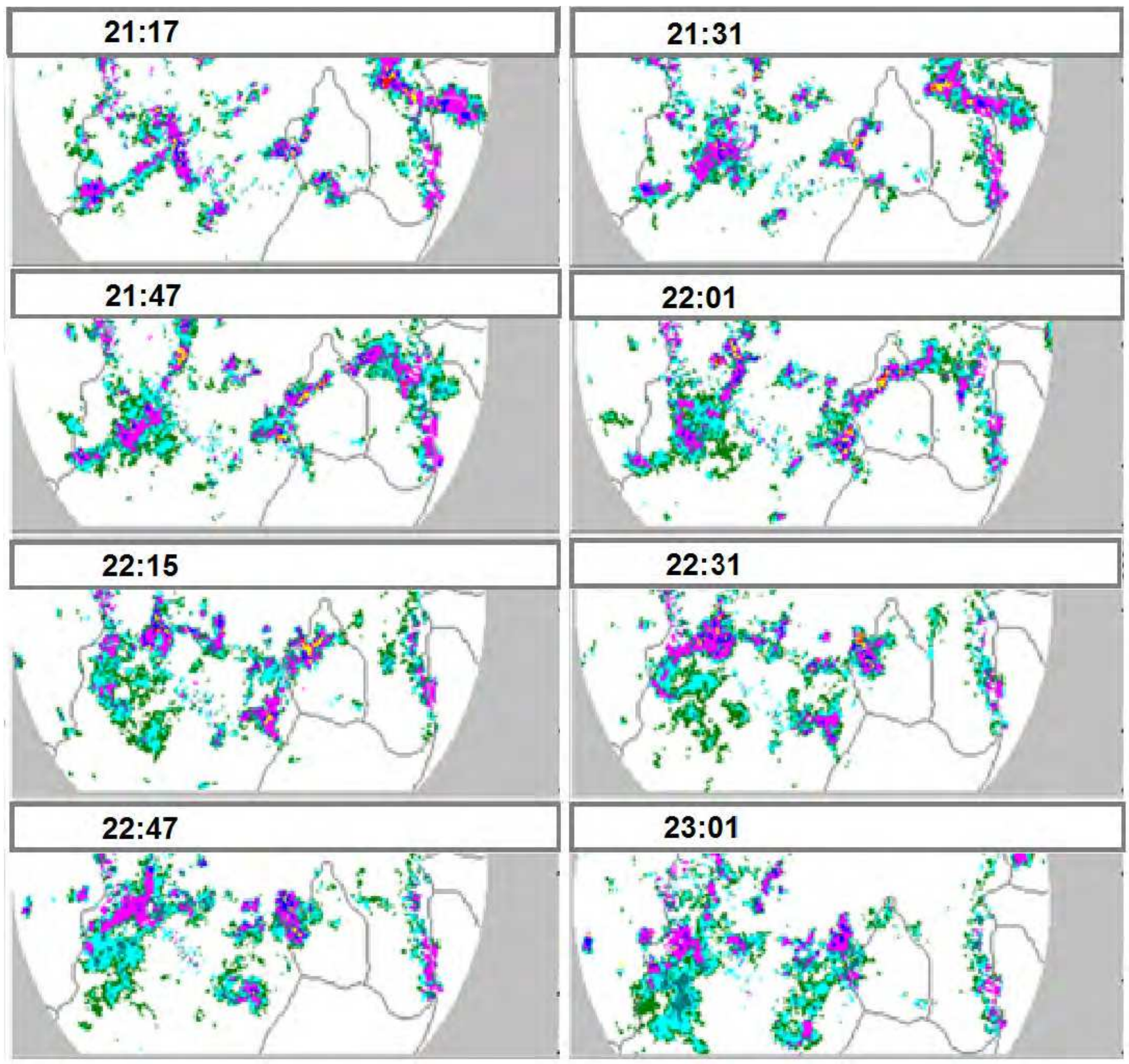

(c)

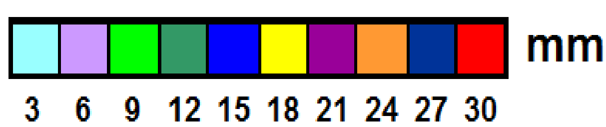

Fig. 6. Examples of storm radar monitoring over the Valley of Mexico basin and identification of fixed echoes caused by the interception of the radar beam with volcanoes located eastern Mexico City: a) 15 June; b) 13 July and; c) 19 September 1998.

4. Case study

Mendez (2005) and Mendez et al. (2009) using reflectivity radar data for the period of 1995-1998, selected 13 intense precipitation events to examine the rainfall patterns over México City, determined by the Cerro Catedral radar, by looking at spatial characteristics (shape, position and magnitude) of precipitation across the valley. The analysis also constitutes a first step towards an improved understanding of storms over urban areas, particularly during the summer rainy season.

Méndez et al. (2011) developed a lumped model of the rainfall-runoff type with input from radar and pluviograph (rain gauge network of Mexico City water management system) data for calibration, applied to the microwatershed of Mixcoac River located at western Valley of Mexico basin, over an area of 31.5 km² (Fig. 4).

Currently all Mexican radar precipitation estimatives use the Marshall-Palmer equation (Marshall and Palmer, 1948), which presents certain discrepancy for tropical regions (Fig. 7). However, the precipitation underestimation could also be associated to beam overshooting, attenuation or hardware calibration issues. A local calibration was performed in order to improve the rainfall estimation taking into account characteristics of precipitation system over Mexico (Mendez et al., 2006). The resulting local calibration improves the estimation of rain (Fig. 7). Although false echoes treatment is not yet done, one might think that it can improve even more if they are removed.

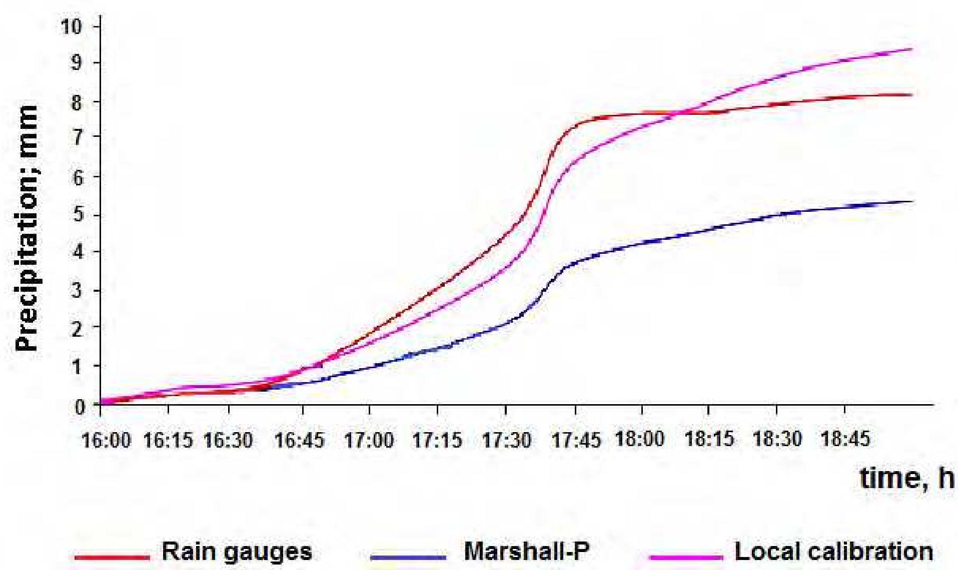

Fig. 7. Storm rainfall of 27 September 1998.

It should be mentioned the radar estimates reproduce well the precipitation patterns in time but not quantitative ones. This new calibration distribution improves this estimate.

4.1 Hydrological analysis

The improvement in the unitary hydrograph of the basin is clear (Fig 8). This is an expected result if one notices that the radar initially reproduce the temporal variability of rainfall and subsequently, after calibration hydrology, quantitative estimate improves. It is obvious that the radar properties would be underused in aggregated hydrological models because the ability to detect the precipitation spatial variability usually are not take into account in these models and, thus the analysis of the hydrological processes within the basin. However, an analysis of the aggregated model applied here is performed to detect the advantage of the radar data for hydrological model in an experimental urban catchment.

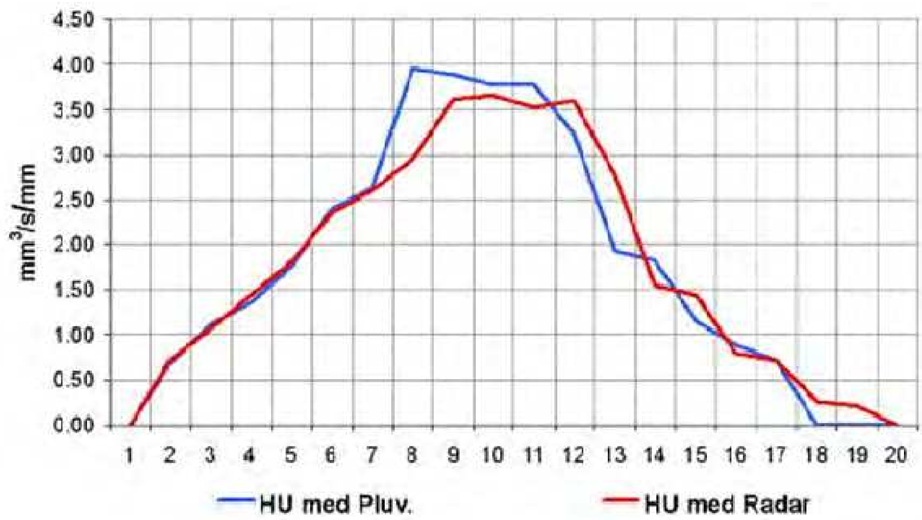

Fig. 8. The unit hydrograph estimated from radar data and pluviographs.

Additionally, in order to obtain a methodology to determine the distributed parameter hydrologic model in other watersheds, the experimental basin of the river Mixcoac and the technique Distributed Unit Hydrograph (Clark, 1943) is used. The conceptual model obtained (Fig. 9) is similar to Maidment model (Maidment, 1993). The model obtains the isochrones to Mixcoac River Basin (Fig. 10), which is then used to estimate the outflow hydrograph of the basin. The comparison between the observed and estimated with the distributed hydrological model fed with precipitation data obtained from the radar is showed in the figure 11.

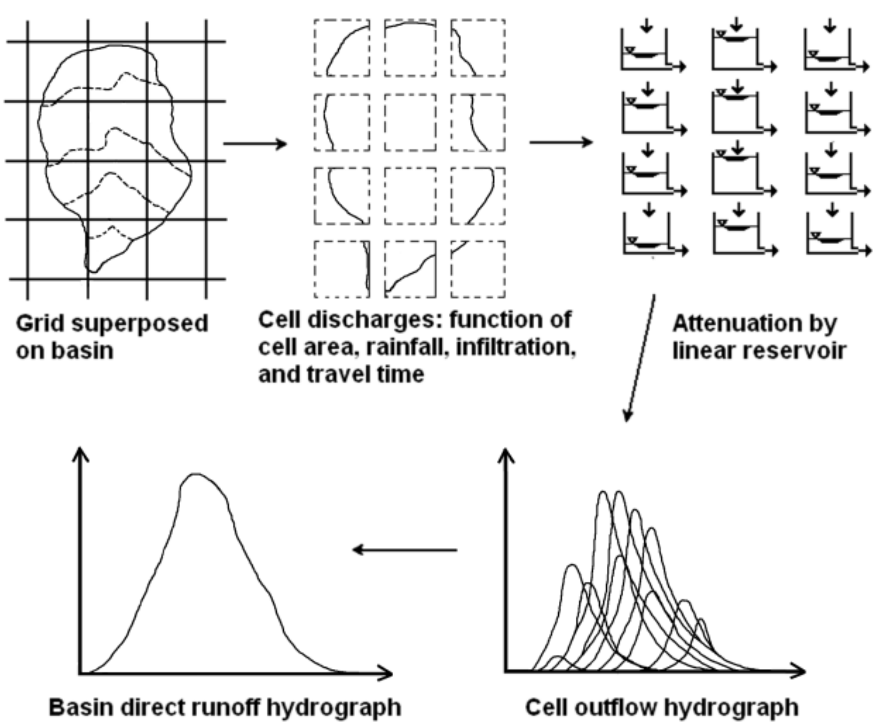

Fig. 9. Conceptual model of the distributed hydrologic model known as the Modified Clark (Source: Kull & Feldman, 1998).

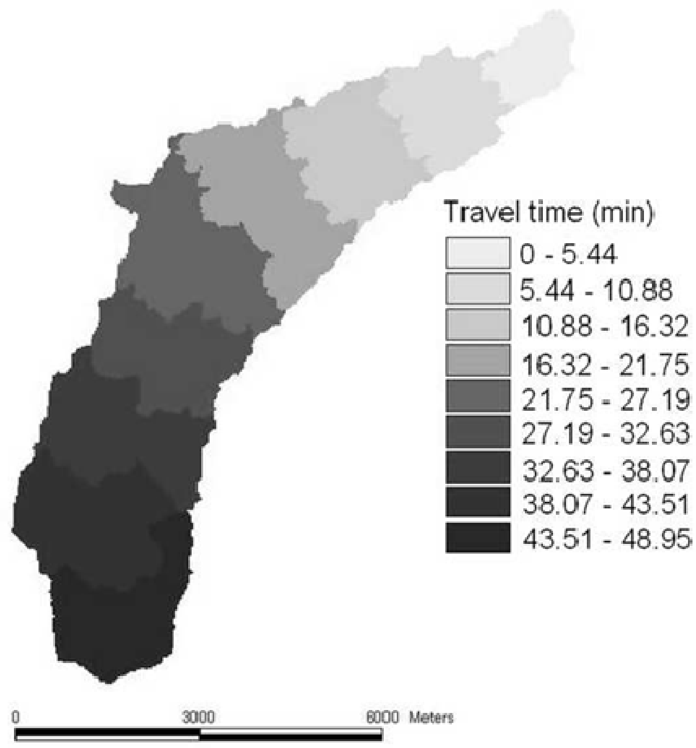

Fig. 10. Mixcoac watershed Isochronous.

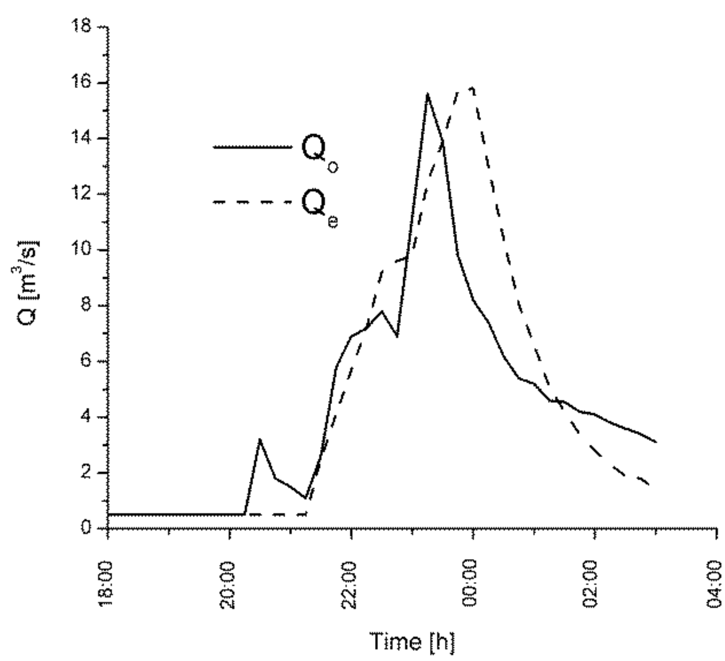

Fig. 11. Hydrological response of Mixcoac river basin, observed (Q_o) and estimated (Q_e) with radar rainfall data.

The observed and estimated response using radar rainfall data demonstrate a fairly agreement and creates the confidence to apply the methodology used in this analysis, in other watersheds. It is important to establish how to estimate correctly the radar rainfall data by eliminating false echoes, using Doppler mode techniques to filter those echoes caused by the interception beam (principal and/or secondary lobes) with the terrain. This will give greater confidence to hydrologists that the data used were carefully treated before feeding to their models.

Aiming to use the radar hydrological information with operational purposes, a short hydrological forecast system should include the following components integrated components: a) Automatic meteorological stations network (pluviographs); b) Weather Radar; c) Satellite products and; d) Mesoscale numerical weather prediction model. The main feature of each of these components is to provide real time and hours/days in advance (forecast) rainfall data, which is a necessary condition for implementing an operational hydrological system.

5. Weather forecast system

In most cases, the fire department response facing intense rainfall events over Mexico basin is a merely emergency procedure. Its work would be greatly improved and lead to more efficient use of human and material resources available by the city government by taking advantage of weather information that is, diagnoses and forecasts of weather and climate. Unfortunately, the information prepared by the National Weather Service lacks the detail and quality required for making decisions as presented in general terms, without data, in order to one can acquire confidence in the forecast. This problem is particularly severe when it comes to prediction of severe storms considered as a danger to the water system in Mexico City. Requirements to take the first steps in the right direction are the improvement of surface measurement networks, radar and satellite information, forecasting deadlines to produce hydrometeorological information useful in decision making for disaster prevention and development of an early warning system that includes not just the danger or threat, but also the vulnerability facing to severe weather.

Any centre that generates meteorological information for decision making is based on the following required elements (Fig. 12):

1. Data Collection
2. Assimilation and display of information. Very short-term prognosis based on radar and satellite estimates of rainfall and rain gauge information.
3. Weather Forecast Systems
4. Post-processing of weather forecasting in the short term to prepare products tailored to user needs
5. Scheme for submission of information to the user or decision maker, including an early warning system useful for the Water System of Mexico City
6. Seasonal climate forecasts for water management in the long run

Although all components are equally important, the main focus to be discussed here is the radar network to be implemented in the system. Méndez et al. (2009) presented a proposal for a new radar system for Mexico Valley based on precipitation analysis estimated by the existing Cerro Catedral radar. They found an underestimation in the amount of precipitation over the western mountains of the valley, at the foothills, while rainfall rates tend to be overestimated over the eastern parts, resulting of the blockage effect of mountains between the current radar position and the basin. The weather radar usually suffers partial or total blockade when it is located in mountainous regions. The current location of the Cerro Catedral radar can limit the coverage of the radar when it requires negative angles in the vertical measurements to monitor the valley, affecting the precipitation estimates (Joss and Waldvogel, 1990; Sauvageot, 1994; Collier, 1996; Smith, 1998).

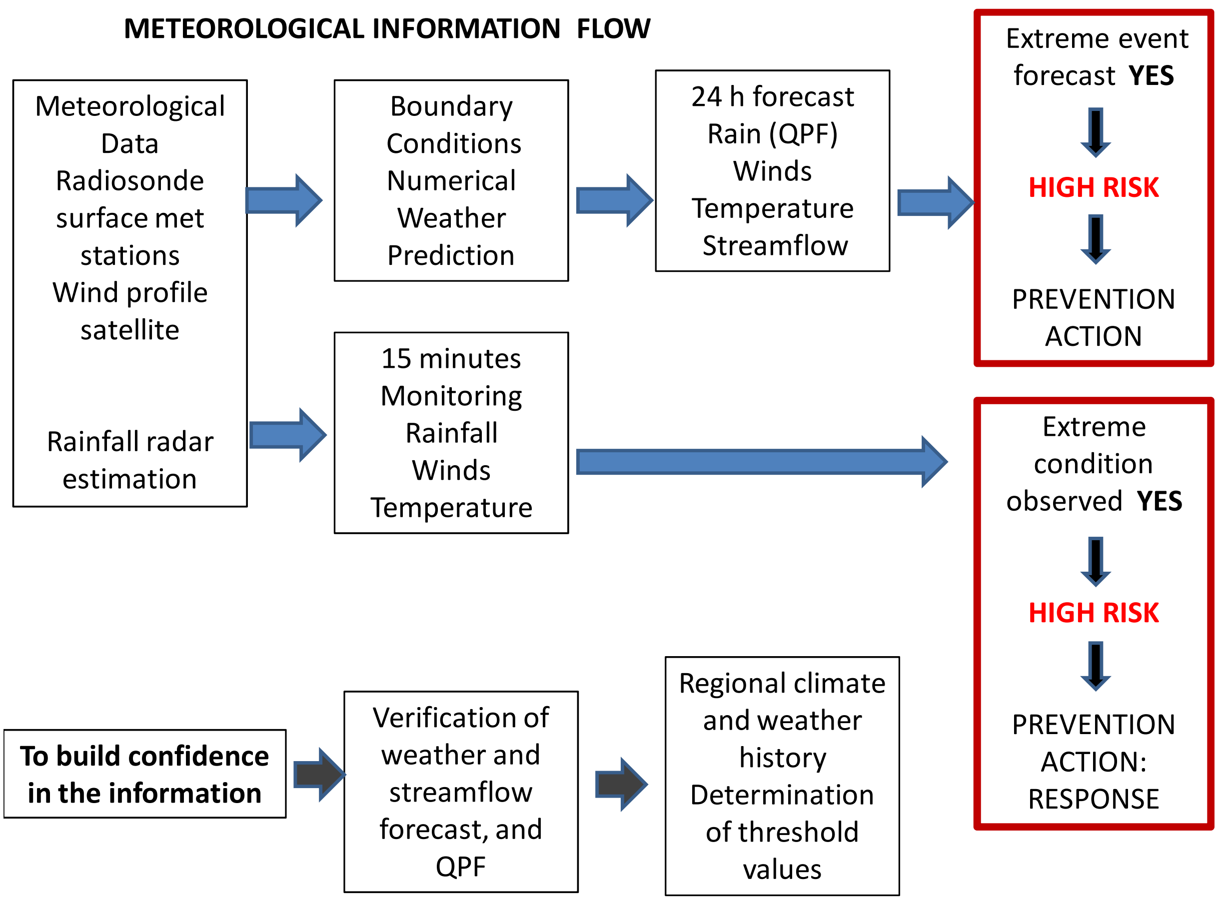

Fig. 12. Meteorological information flow of Early Warning System.

In order to achieve a complete three-dimensional coverage of México City a second radar deployment in the opposite extreme of the basin is required. Several conditions of propagation either from the present radar or from others possible positions (Fig. 13a) were attempted to get the greater coverage area (Méndez et al., 2009). The site selected was the Cerro de la Estrella located at the central eastern of Mexico Valley (Fig. 13b) had shown more adequate. The Cerro de la Estrella is at an approximate elevation of 300 m above the City of Mexico and therefore is able to scan both stratiform and convective precipitation (Fig. 14). The radar coverage was obtained from a Geographic Information System.

Fig. 13. a) Proposed sites in Mexico Basin for the new radar deployment. Black line is the political boundary of Mexico City: b) View of the Valley of Mexico basin from the Cerro de la Estrella.

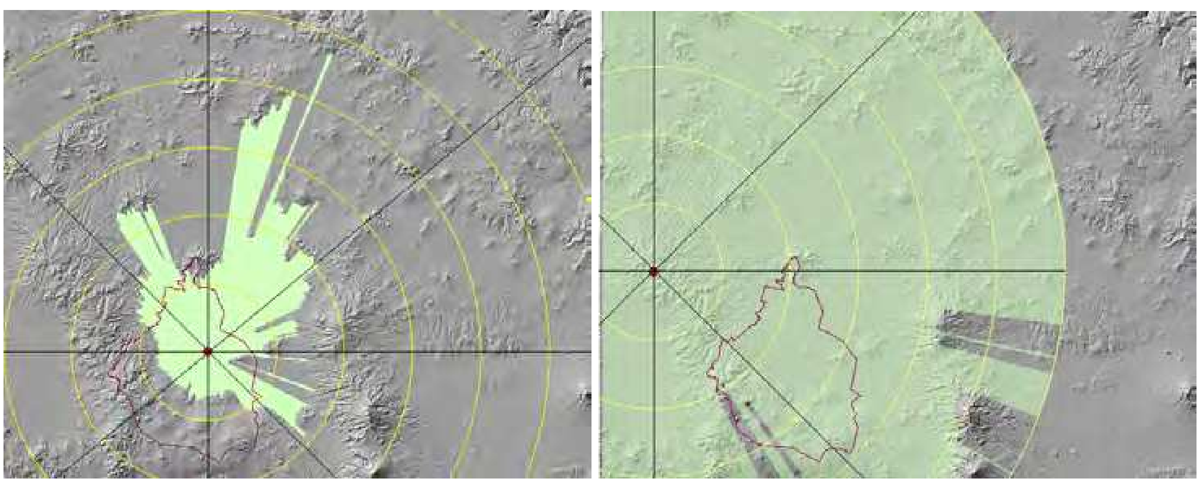

Fig. 14. Radar scan at 0 deg.: Left, The Cerro de La Estrella (2450 msl) and; right the Cerro Catedral site (3785 msl). Red line is the political boundary of Mexico City.

The Mexico Basin rain gauge network (Méndez et al. 2009) is very dense (Fig. 4) and the new Mexico Valley radar system should take advantage of this to implement quantitative precipitation estimation schemes as one of main products generated by the early warning system. To achieve this, a proper processing of radar data must implemented in order to develop methodology to prevent beam blockage due to orography (Bech et al. 2003), ground clutter (Fornasiero et al., 2006), which can produce frequent false alarms and affect the precipitation estimative. These effects can be mitigated through the application of the decision-tree method proposed by Lee et al. (1995) for a dual-polarized system, which able to provide additional parameters such as differential reflectivity, correlation coefficient (and their texture) that can be used to further reinforce the traditional techniques.

All products generated by the early warning system (graphic, data image, text, bulletin) will be integrated into a display system based in GIS system. This will permit produce better quality graphic resolution and generate tailor made products for specific needs to stake holders and general public.

6. Conclusion

Hydrological applications of meteorological radars have become an important branch of remote sensing in meteorology and disaster preparedness activities. The high temporal and spatial resolution precipitation fields generated by meteorological radars meet the requirements of the hydrological modeling (Sempere-Torres et al., 2004). Furthermore the radar covers large areas and is of rapid access for real time hydrological applications and, therefore an adequate blending of radar and rain gauge data results in better estimates of real time precipitation (Collier,1996; Joss & Waldvogel, 1990). Méndez et al. (2009) has pointed the capacity of the Doppler radars to scan storm gives a big advantage for runoff and precipitation prediction and may be fundamental to understand the physics of storm intensification in complex orography as México Valley.

The system of weather/hydrological forecasting and monitoring storms enable user and stake holders to have information of more severe events in advance and establish risk management policies for their mitigation. The scheme for dissemination of information must contemplate to present the results of diagnostic scheme and weather forecasting as clearly as possible in order that users and stake holders have relevant elements to incorporate objective vulnerability assessments to more closely meet the facing risks. To achieve this the continuous results display in a color system associated with critical values of risk, using a Geographic Information System, is a powerful tool for prevention and response prevention or emergency in accordance with the Mexico City government interests. Further improvements in the short term precipitation forecast, or quantitative precipitation forecast (QPF), can be achieved by blending Doppler radar products and output of numerical weather prediction models (Atencia et al. 2010)

The results of this study and Méndez et al. (2011) assess the value of using weather radar data as input distributed hydrological models. These models are adequate for applications in regions of strong slopes and heavy rainfall with complex draining networks for which reason it would be very useful in early warning systems.

Early warning systems, widely used in the world, aim to provide relevant information for making decisions within a framework of prevention. This type of action has proved to be much more helpful, even under weather forecasts uncertainties, than a system based only an emergency response.

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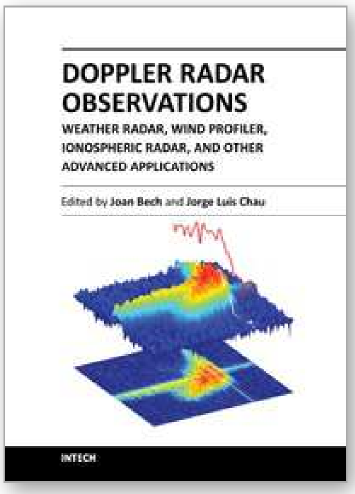
DOPPLER RADAR OBSERVATIONS
WEATHER RADAR, WIND PROFILER, IONOSPHERIC RADAR, AND OTHER ADVANCED APPLICATIONS
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