Analysis of urban flooding from a meteorological perspective applied to two temperate climate cities in Argentina

Campo, Alicia María[1,3], Zapperi, Paula[1,3], Aldalur, Beatriz [2], Ramos, Ma. Belén[1]

[1] *Departamento de Geografía y Turismo - UNS, 12 de Octubre 1098, Bahía Blanca, Argentina, amcampo@uns.edu.ar,*
[2] *Departamento de Ingeniería- UNS, Av. Alem 1253, Bahía Blanca, Argentina, baldalur@uns.edu.ar,*
[3] *Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), 12 de Octubre 1098, Bahía Blanca, Argentina, paula.zapperi@uns.edu.ar*

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1. Introduction

In urban areas, flooding is considered the main environmental impact of heavy rains. The IPCC fourth assessment report (2007) mentions that heavy rainfalls will become more frequent in most of the earth's surface. Thus, the associated processes that affect cities such as floods and landslides will be exacerbated by the predicted increase in rainfall intensity and, in coastal areas by the sea level rise. Under this scenario, knowing in advance the synoptic conditions that can generate these types of events might contribute to the mitigation of damage.

The city of Bahía Blanca and the coastal town of Ingeniero White, in the Southwest of Buenos Aires province, Argentina, are characterized by a template semi-arid climate (Fig. 1). The town of Ingeniero White is emplaced at an altitude between 3 to 10 m above the sea level with origin at the adopted level by the National Geographic Institute (NGI), taking as the southern limit of Bahía Blanca estuary. The whole area forms a lower zone, surrounded by nonpermanent water channels which pass through passable land with sparse and little vegetation. (Benedetti, 1997) describes it as a coastal area covered with halophytic vegetation, with large flat land, with the presence of plants and shrubs, interspersed with bare and whitish spaces. The coast of the estuary, to the height of 10 m, is occupied by halophytic steppe composed of shrubs, subshrubs and herbs halophytes, which become confused with species of the pampean steppe and dry forest (Verettoni and Aramayo, 1976). Bahía Blanca city is emplaced also in the Southwest of Buenos Aires province, in the lower basin of the Napostá Grande creek at 5 km away from the coast. This location contributes to receive the runoff that is generated upstream and increases the flooding risk. It has a population of 301.501 inhabitants (National Institute of Statistics and Surveys, 2010). The altitude range is about 80 m from the shore area to the highest point of the city which corresponds to a 76 m terrace at the northern zone. The urban drawing pattern involves the highest building density in the centre while parks and disperse urbanization are emplaced in the surroundings.

The study area is mainly affected by the maritime tropical (mT) and continental polar (cP) air masses. The first one is warm and humid and generated in the subtropical anticyclones emplaced over the oceans white the last one is generated in the polar zone and provides cold and dry air (National Weather Service, 1987). There are 6 meteorological phenomena that cause rainfalls in the area (Celemín, 1984; Zapperi *et al., 2007)*:

a) Cold front: rainfalls in the region are mainly due to this type of fronts. Generally, rains occur behind the front in the cold air brought by winds from the south, southwest and southeast. The interaction of the named pressures center generates typical weather systems that involve an advancing cold front that brIngs rain. That is the case of the *Pampero*, which consists in a cold or warm wind, according the season, but always dry. Its speed is above 40 km/h and blows with gusts from the south and southwest. It is always associated with the passage of a cold front which causes sudden drops in temperature, atmospheric pressure rise and heavy storms, mainly during the summer season. The other weather system is locally called *Sudestada.* It is a meteorological phenomenon common to a large region of the South and Southeast of Buenos Aires province. It is characterized by cold or cool and intense winds from the southeast quadrant with speeds above 35 km/h, rainfall of different intensity, low temperature and moisture in successive days from the ocean (Campo de Ferreras *et al.*, 2004; Gentili and González*,* 2011).

b) Warm front: rainfalls caused by this weather system occur at any time of year but less frequently in summer. The warm front produced thunderstorms, rains and fogs. The duration of rainfall is usually 3-63 hours.

c) *Instability line:* they consist of thunderstorms, heavy downpours, southern or southwestern winds and occasional hail storms. These systems of bad weather are often formed ahead of a cold front and move quickly (20-60 km/h) from southwest to northeast and are frequent from October to March. The duration of the precipitation ranges from half an hour to 6 hours.

d) Frontal wave (Cyclogenesis): this meteorological situation is identified as disturbance current formed by a low pressure centers generated by the pushing of air within a stationary front: cold air pushed to the north while warm air is pushed to the south. The wave moves from east to west and frequently consist of cold fronts. However this type of disturbance current can be caused by a succession of warm fronts. The rain duration varies between 6 and 36 hours.

e) Convective Storms: In hot weather, storms and scattered thunderstorms are formed due to the instability of the air and strong ground warming. The duration of rainfall tends to fluctuate between half an hour and 3 hours.

f) Rains caused by a low pressure system: These rains occur when low pressure centers or West-East channels are formed in height (3-10 km). In the forward area, heavy rains are generated. The duration of rainfall is 6 to 36 hours.

The existence of these weather systems and the different types of rainfall generated led to the goal of this work which is to map and analyze the effects of rainfall in Bahía Blanca city and Ingeniero White town considering the synoptic conditions that generated the precipitation events in May 2008 - September 2014 period.

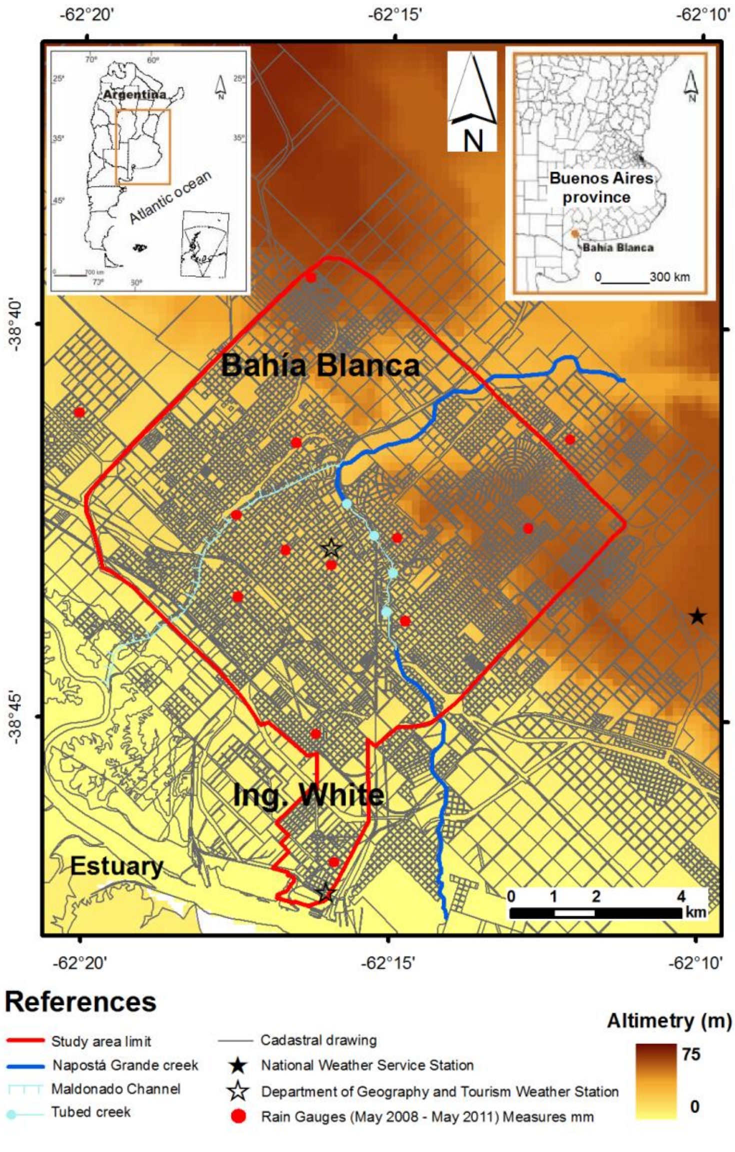

Fig. 1 Study area location.

2. Data and Methods

The synoptic climatology is interested in describing local or regional climates in terms of the properties and motions of the atmosphere rather than monthly intervals. There are two stages in a synoptic climate study: the determination of categories of types of atmospheric circulation (usually called weather systems) and the establishment of statistical parameters such as mean, mode, etc. of meteorological elements on these categories. (Sala Sanjaume and Batalla Villanueva, 1996). To carry out this work, weather conditions were analyzed through synoptic charts published by the National Weather Service of Argentina. From May 2008 to May 2011 rainfall amounts across the study area were measured by means of a network of 11 rain gauges covering both towns. In addition, meteorological data was registered by the Department of Geography and Tourism weather stations located in Bahía Blanca downtown and the Ingeniero White coastal area. Additionally, the amounts of rainfall provided by the National Weather Service were used. These daily values of rainfall recorded in different parts of the cities were averaged. Also, to know the intensity of the event, the value obtained was compared with the duration of the precipitation event.Additionally, to ascertain the effects caused by rainfall in these cities and having previously selected certain areas, the type of impact was assessed once the precipitation event has finished. This was supplemented with the review of the local press articles in which the different problems caused by the heavy rains episodes are mentioned.

3. Results and Discussion

The review of the weather charts and the effects of heavy rains during the study period showed for Ingeniero White only two events of urban flooding. It is important to point out that due to its coastal location, the tidal influence is very important. In fact, on July 29th 2009, streets of the flatter area where flooded (Fig. 2) because of the entry water through the storm drain system when the tide reached 5.30 m ("The New Province", July 29th 2009), while the mean level is about 2.59 m (Hydrography National Service, 2000). In that opportunity, southerly wind was moderate wand no rainfalls were registered. In Ingeniero White floods were historically related to the occurrence of *Sudestadas* whose effects are magnified by the tidal action, the low slope and the railways and roads that leads to reduce flow rates (Aldalur *et al.,* 2013). Aldalur (2011) studied though press articles the main events of urban floods in Ingeniero White from 1934-2007 and found that gusts of south and southeastern direction, higher than 100-120 km/h, were always present. Moreover, April and August were the months of highest frequency of these events. From a total of 22 urban floods, 7 of them (32 %) weren't caused by rainfall of less than 35 mm or it didn't rain at all. However, in most cases the wind was from the south and southeast. Local press defined 9 of these events (41 %) as *Sudestadas*, while the rest was defined as a consequence of heavy rains. During the studied period, it was identified one case of *Sudestada* that affected the town. It lasted from February 28th to March 2nd 2013 and rained 102 mm with gusts of southeastern winds at 60 km/h.

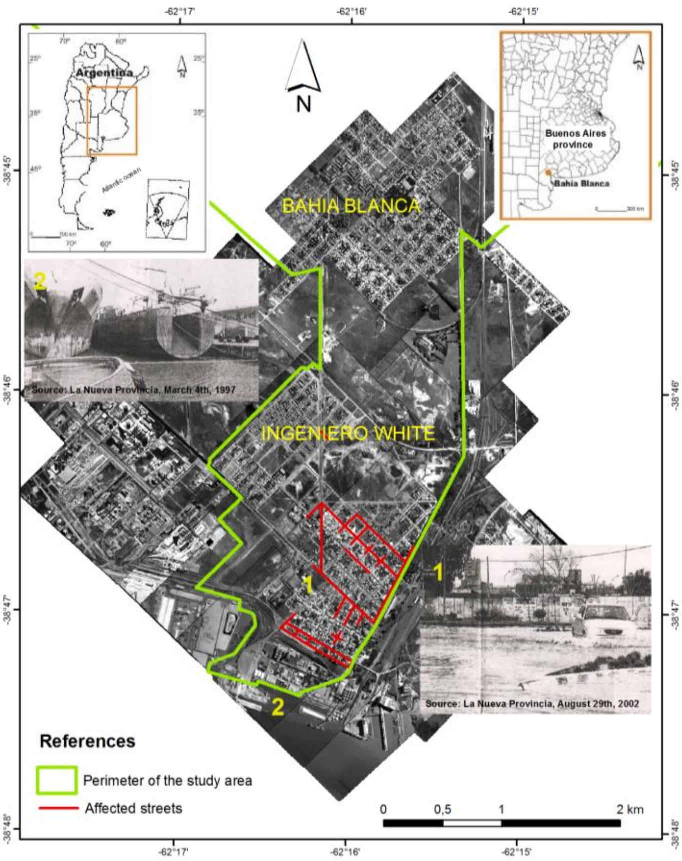

Fig. 2 Mapping of the most affected places by flood and waterlogging in the town of Ingeniero White.

Rainfall intensity is a major factor in determining the type of problem that might be developed. Sequeira (2006) studied the ranges of this parameter in Bahía Blanca considering the relationship between the intensity, duration and frequency of rainfall events in the city. A return-period of more than 2 years and an hourly amount of 10.2 mm define a heavy rain for this town. According to this value and the occurrence of floods there were selected the events of precipitation to analyze the synoptic conditions that generated them. In Table 1 the results of the analysis are presented. Cold fronts rainfalls are the most frequent cause of urban flooding. From a total of 26 events, half of them were generated by this weather system. However, in these cases floods took a short time to runoff, as it happens in the streets of the center of the city that have storm drain system. Otherwise, over the alluvial plain of the Napostá Grande creek and flat areas, the unpaved streets, lacking of drainage system can be flooded taking more than a day to drain and disrupting traffic. Also, in those areas is where there are the most cases of evacuees (Fig. 3). Regarding the synoptic conditions associated with these problems in the city, not only cold fronts are triggers but also instability lines and frontal waves (Cyclogenesis). The analysis of the weather maps and the meteorological data indicates that heavy rainfalls are related to the convective processes resulting from the succession of warmer days. By the occurrence of these meteorological situations, in the north of the city, the sloped streets favor the runoff concentration. However, in recent years there has been the most significant process of urban growth. Besides flooding, other effects of heavy rains over the unpaved streets that lay over the steepest area are the erosion and the sediment removal. The alluvial activity begins with the erosion in the higher zones and continues by the descending streets until the removed material is deposited on the changing slope. Moreover, the urban development of the area leaded the pavement of the street which helps to concentrate the flow. The accumulation of sediments is not only an inconvenience to vehicular traffic during the days of the rain event; it also hinders the entry of the runoff to the storm drains system and rises the flood risk of the property.

Date	Rainfall amount (mm) and duration (hour and minutes / days)	Effects over the city *Main Source*: field work and research of the archive of the newspapers “The New Province” and “The Compass”	Synoptic condition
Sept. 27th, 2008	25 mm in 7 h15 min	- No effects registered	Cold front
Nov. 10th, 2008	14 min 4 h 30 min	- No effects registered	Cold front
December 18th, 2008	25 mm in1 h	- Evacuees citizens in the flat zones - Flooding of quick drainage	Frontal wave (Cyclogenesis)
February 2nd, 2009	12 mm in 1 h	- Flooding of quick drainage	Cold front
March 2nd, 2009	18 mm in 1h 30 min	- Flooding of quick drainage	Cold front
March 5nd, 2009	19 mm in 1h 30 min	- Flooding of quick drainage	Cold front
July 29 th, 2009	No rain registered. Extreme high tide.	- Flooded streets in Ingeniero White	High pressure system over de area
Nov. 16th, 2009	6 mm in 20 min	- Flooding of quick drainage in the flood plain zone	Cold front
Nov. 23rd 2009	30 mm en 4h in 20 min	- Evacuees citizens in the flat zones - Flooding of quick drainage	Instability Line
December 18th, 2009	50 mm in 3 h	- Floods - Evacuees	Instability Line
January 11th, 2010	25 mm in 2 h	- Floods - Evacuees	Instability Line
February 2nd, 2010	24 mm in 30 min	- Floods - Evacuees - Erosion of unpaved streets - Eroded material deposit	Warm Front
February 3rd, 2010	36,5 mm in 30 min	- Floods - Evacuees - Erosion of unpaved streets - Eroded material deposit - Flooding in the Napostá Grande flood plain	Cold front (Pampero)
February 18th, 2010	22 mm in 30 min	- Floods of quick drainage - Evacuees	Instability Line
March 18th, 2010	35 mm in 2 h 15 min	- Flooding of quick drainage	Instability Line
March 29th, 2010	36 mm in 2 h	- Urban flooding of quick drainage	Cold front (Sudestada)
Sept. 11 th, 2010	36 mm in 1 h 30 min	- Floods of quick drainage in the central area - Unpaved streets flooding - Erosion of unpaved streets - Eroded material deposit	Cold front (Pampero)
Oct. 29th, 2010	44 mm in 2 h	- Evacuees - Unpaved streets flooding - Erosion of unpaved streets - Eroded material deposit	Cold front
Nov. 4th 2010	60 mm in 1:30 h	- Evacuees - Unpaved streets flooding	Cold front (Sudestada)
February 23rd, 2011	31 mm in 1 h 15 min	- Evacuees - Unpaved streets flooding - Erosion of unpaved streets - Eroded material deposit	Frontal wave (Cyclogenesis)
Nov. 8th 2011	30 mm in 4 h 30 min	- Evacuees - Unpaved streets flooding	Instability Line
Feb. 28th – March 2nd, 2013	120 mm in 3 days	- Fallen trees (strong winds: 60 km/h) - Evacuees in Ingeniero White	Cold front (Sudestada)
March 30 th, 2013	30 mm in 30 min (gusts of wind of 87 km/h and hail storm)	- Fallen trees - Floods in streets of the lower areas and houses	Frontal wave (Cyclogenesis)
Sept. 28th-30th, 2013	70 mm in 3 days	- Overflow in the Napostá Grande floodplain	Frontal wave (Cyclogenesis)
March 30 th, 2014	55 mm in 3 h	- Fallen trees - Floods of quick drainage in the central area	Cold front
April 7 th, 2014	60 mm in 10 hours	- Floods of quick drainage in the central area - Floods in flat areas because of the storm drains overflow	Frontal wave (Cyclogenesis)

Table 1. Rainfall events, their effects over Bahía Blanca and the synoptic conditions associated.

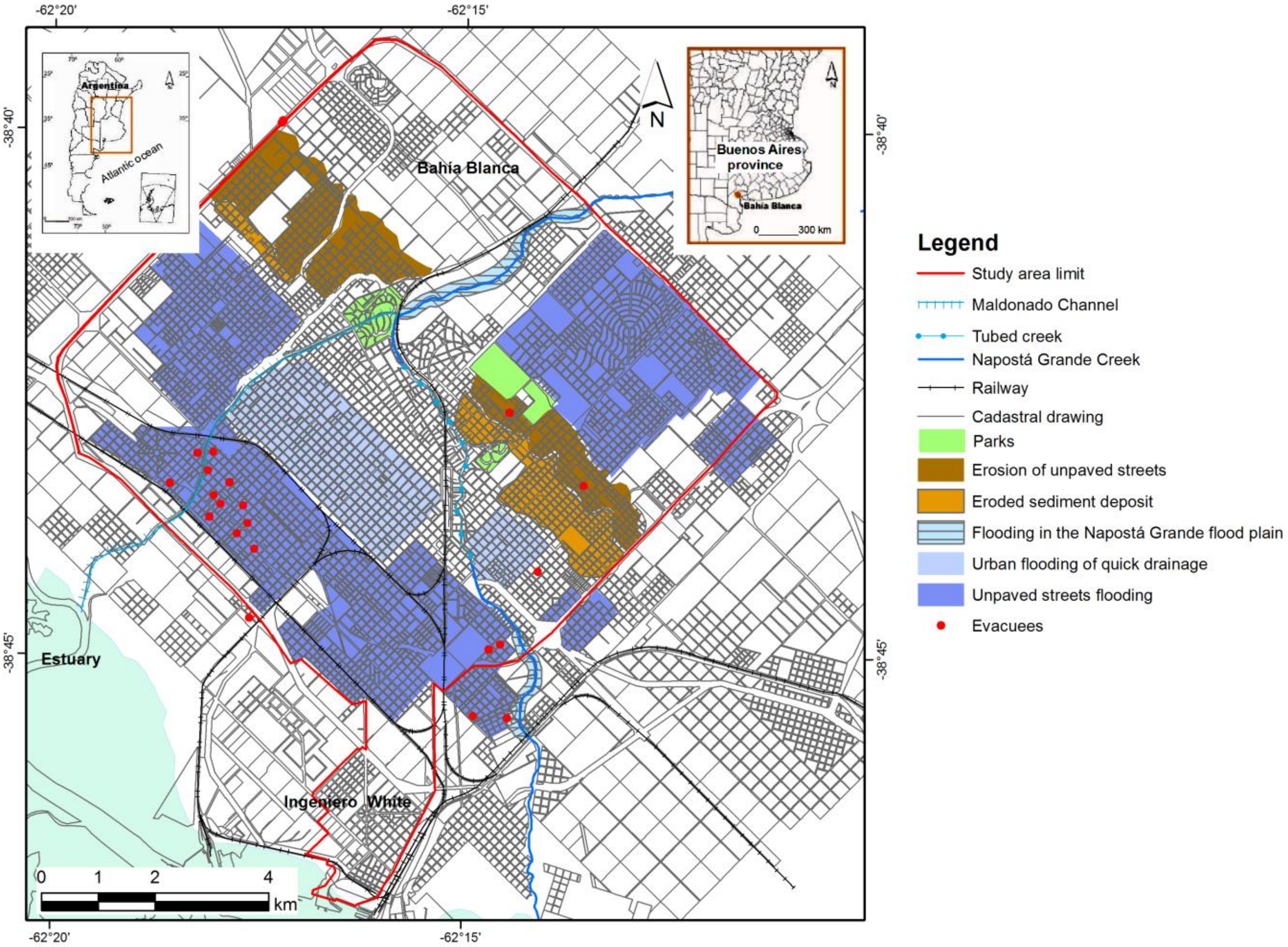

Fig. 3 Effects of heavy rainfall in Bahía Blanca.

4. Conclusions

Most of the heavy rains events were generated by the convective instability preceding cold fronts that reached the area after warm days. With regard to the effects of such events, the main impact is due to floods not only in flat areas, but also in downtown area when sewer drainage capacity overflows. Besides, these storms affect sloped non-paved streets by causing erosive processes which make traffic difficult. That is why it is so important to improve the functioning of the existing storm drains system and keep them clean. In addition, another proposal is to promote green spaces and the use of porous materials to facilitate the infiltration capacity and reduce the runoff during storms.

In the town of Ingeniero White the problems of flooding and waterlogging arises when heavy rains happen in conjunction with the increase in tidal heights and the occurrence of *Sudestadas*. Under those conditions the evacuation of any water excess is hindered. These results lead to the proposal of deep the existing output channel that drains to the estuary so it can evacuate the largest flow. This should be complemented with the placement of pumping stations.

Acknowledgment

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