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ORIGINAL PAPER

Assessment of surface runoff conditioned by road works and urban settlements in large plain basins

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Abstract
The province of Buenos Aires located in Argentina contains numerous agricultural plain basins of world importance among which the Samborombón river basin stands out, where regular floods affect agricultural activities and urban expansion. This sector has large road works with approach embankments that obstruct the natural drainage, a poorly planned urban growth, and an increase in the rainfall regime in recent decades. The aim of this work is to carry out an analysis and assessment of the surface runoff conditioned by road works and urban settlements in large plain basins, taking the Samborombón river basin as a case study. Satellite images were used to define the floodplain and identify the main road works and urban settlements that develop within it. Subsequently, hydrological simulations were carried out to assess how these anthropic structures modify the surface runoff and the flooded areas. To validate the simulation results, the flooded areas obtained were compared with a similar flood event of a Landsat image. The results show that the road works embankments and urban settlements restrict the floodplain area of the river, generating an increase in the flooded area and delaying the water runoff. This problem, together with the rainfall increase, shows the need to generate a territorial management plan and adopt mitigation measures. The use of sacrificial embankments could be an economic alternative that would prevent the obstruction of water runoff, being able to use the basin as a pilot site for this innovative idea.

Keywords Large road works · Samborombón river basin · Flood risk · Urban settlements

1 Introduction

The great plains of the world are characterized by large river basins, where regular flooding is common (Theiling and Burant 2013; Wang and Plate 2002; Scarpati et al. 2002) and affects these sectors from an economic point of view (Browne and Hoyt 2000). These areas

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have a high demand regarding land use through agricultural activities due to their fertility (Tockner and Stanford 2002; Bardhan and Jose 2012) and, in recent years, due to the occupation of these areas with urban settlements (Penning-Rowsell 1976; Montz 2000; Plate 2002; Chang et al. 2009). On the other hand, a variation of both temperature and rainfall in numerous parts of the world has been recorded in the last decades (Zhang et al. 2007; Trenberth 2011), affecting the volume of water runoff (Zhang et al. 2004; Nohara et al. 2006).

The Buenos Aires Province, located in the central-east part of Argentina, constitutes a productive sector of global importance (Duran et al. 2011), where plain environments with a regional slope in the order of 0.1% dominate (Sala et al. 1983). The climate in the region is humid, being an increase in rainfall recorded in recent decades (Sierra et al. 1995; Kruse and Laurencena 2005; Scarpati and Capriolo 2013), a situation that represents a greater volume of water runoff (van Vliet et al. 2013). In this sense, the increase in rainfall has led to worsening flood issues, a situation that puts the population at risk, due to the recent expansion and growth of urban areas in the floodplain of the rivers, also causing economic losses to the productive agricultural sectors. On the other hand, the embankments of large road works cross the river courses and floodplains, raising above the local topography several meters, obstructing the natural drainage (Auge et al. 2004). These road works date from the early and mid-twentieth century and has been built considering extreme events, records of recurrences and millimeters of rainfall from the period mentioned. Despite this, flood issues have been recorded, resorting to extreme measures such as dynamiting road embankments that have been used to enable the water evacuation (Pereyra 2005). Given the increased rainfall in the region, it is expected that the engineering works which were set up during the beginning of the twentieth century will further hinder the natural drainage of these plain basins.

The Samborombón river basin, located in the northeast of the Buenos Aires Province (Fig. 1), encompasses an area of 5700 km^2 and has an average slope of 0.18%, with an average annual rainfall of 998 mm $year^{-1}$ (period, 1970–2015).

Samborombón river basin presents regular flooding and has had significant agricultural development, and in recent years an urban growth without land use guidelines has developed (Borzi and Carol 2014). Also, there are no studies that contemplate the role of large road works that have been built at the beginning of the twentieth century in plain basins, according to the increase in rainfall recorded in the region. Being a basin with regular flooding that affects agricultural producers and urban centers (Tagle, 1980; Borzi et al. 2016), there is a lack of background studies that comprehensively analyze the anthropic modifications of the basin and the current state of road works, which constitutes a problem for the sustainable management of the basin.

The aim of this work is to carry out an analysis and assessment of the surface runoff conditioned by road works and urban settlements in large plain basins, taking the Samborombón river basin as a case study.

2 Methods and materials

The floodplain of the Samborombón river basin was delimited using a Landsat satellite image of May 2000, in which the largest flooding in the basin was recorded. An analysis of high-resolution satellite images was then carried out using Google Earth Pro software to identify the main road structures that cross the river and its tributary streams. These areas were subsequently analyzed in fieldwork by measuring with measuring tape the width of

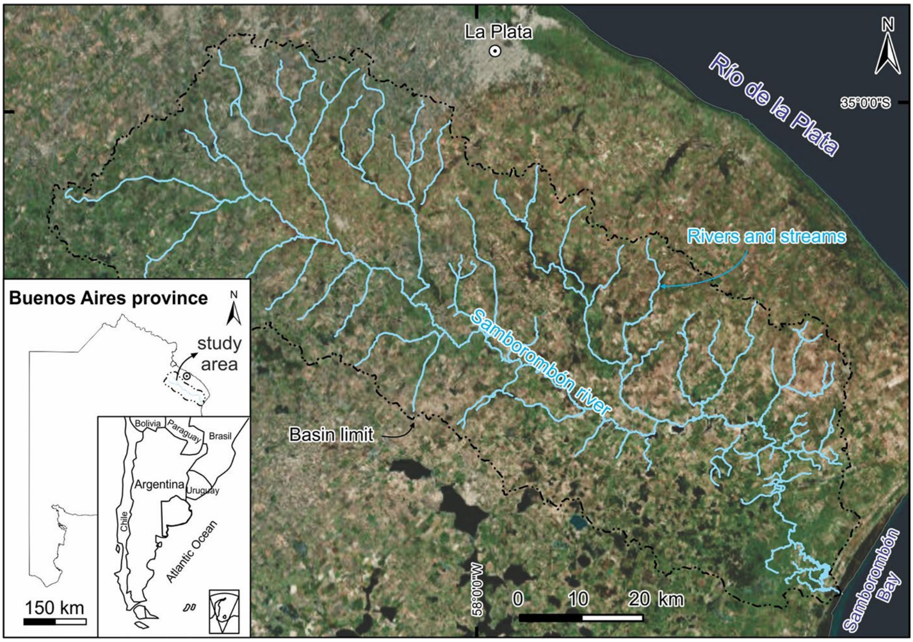

Fig. 1 Location of the study area in the northeast of the Buenos Aires Province, Argentina

the floodplain, the length and the height of the embankments associated with road works, as well as the space left by these road works for the passage of water. Likewise, a description of the current state of the drains was made (cleaning, breakage, silting, etc.). This analysis also allowed the identification of the floodplain areas occupied by urban settlements, classifying these according to the occupation conditions, as well as assessing the distance to the road works.

On the other hand, the behavior of road works was approached from a hydrological simulation using the HEC-RAS v4.1.0 software (USACE 2010) in the middle sector of the basin, where the floodplain presents the greatest expression. For this purpose, a digital terrain model (DTM) was made, based on 1:50.000 scale topographic charts of the National Geographic Institute (IGN) of Argentina using the "Topo to Raster" tool from the software ESRI ArcGIS v10.0. This method is based on the ANUDEM program (Hutchinson 1988, 1989, 1996, 2000; Hutchinson et al. 2011), creating hydrologically accurate DEMs by interpolating contour lines, spot elevation, drainage network and depressions. The DTM was generated using a pixel size of 30 m in order to work with satellite images with a similar spatial resolution (e.g., Landsat images). This pixel size can be further used to obtain 1:50.000 scale to map the results from Landsat ETM+ images, as they are used for urban and land use studies (Sausen et al. 1997). Also, the DTM represents the true height of the terrain and has no interference derived from models generated by interferometry (e.g., buildings, trees, etc.) (Hutchinson and Gallant 2005; Wood 2008; Shingare and Kale 2013; Hirt 2015).

The flooding event simulation was performed in the main river, and subsequently, an area was selected for a more detailed study. Two scenarios were used; The first one is under natural terrain conditions, and the second takes into account roads with embankments. A rainfall event, the largest recorded in the basin, which generated severe flooding was selected, where the flow was 579 m^3/s (Autoridad del Agua, 2014). The results of the simulations obtained, using the HEC-RAS v4.1.0 software, were exported to ArcGIS v10.0 to observe and compare the resulting flooded areas under these two scenarios. The flooded areas obtained, both under natural situation and with road works, were algebraically subtracted to observe the differences in flooded areas which were caused by the presence of the road embankments. With the purpose of validating the simulation results, the flooded areas obtained from the simulation were compared with the Landsat satellite image from May 2000 which represents a flood of similar magnitude to that simulated.

3 Results

3.1 State of the road works

The floodplain of the Samborombón river basin (blue color in Fig. 2) presents numerous roads which have the almost perpendicular direction to the surface runoff of the basin, which can be divided into two groups. Within the first group, larger roads were identified, which contain approach embankments. These embankments constitute an elevated linear morphology that crosses approximately perpendicular the stream and the floodplain. In general, these embankments have few culverts in the floodplain area and the spans are limited to the bridge in the main stream. These types of roads with embankments were mainly

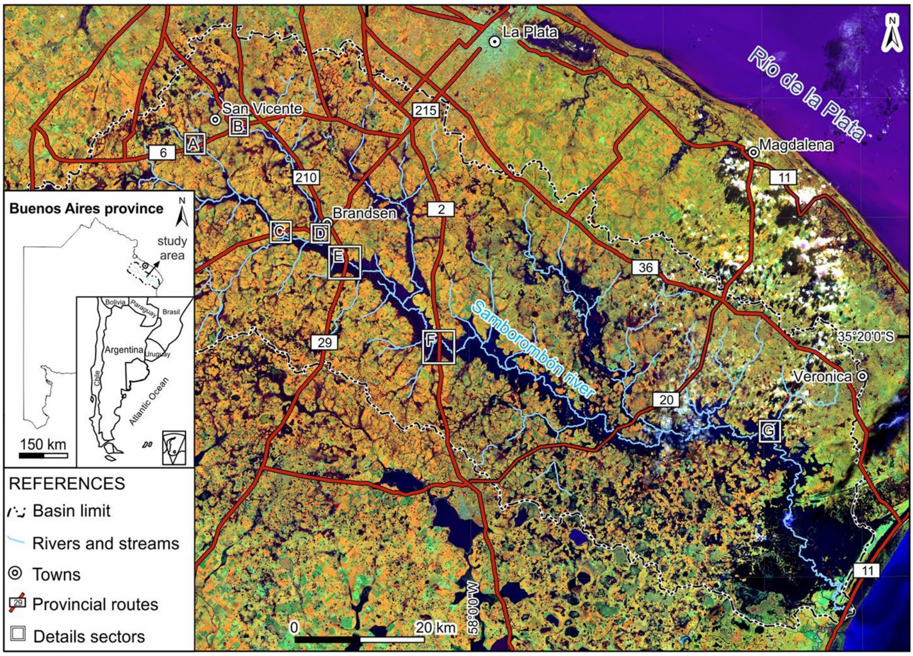

Fig. 2 Landsat image from May 2000, with combination RGB 452; the largest flood recorded by Landsat series is shown in blue. White boxes (from A to G) indicate detailed sectors analyzed in the basin, where the road structures raise several meters above the local topography and/or have characteristics that restrict the width of the natural drainage

identified as provincial routes (PR 2, 6, 29 and 215, represented in red lines in Fig. 2), and six sectors were highlighted where these characteristics were most evident (white boxes from A to F in Fig. 2).

Within the roads of the second group, internal roads which lack embankments or have a low height and consequently do not substantially modify the morphology of the basin were identified. Area G is a site where the road structure, except for those previously mentioned, is not a provincial route, and it used to be an internal road that crossed the Samborombón river (Figs. 2, 3b). This structure, which was built of concrete, had only a small culvert for the passage of water from one side to the other and nowadays is under poor conditions and out of use.

Measurement of these structures allowed to show that the floodplain was reduced by approximately 7% concerning its natural width, due to the restriction generated by road works (Table 1).

During the field work it was verified that, in addition to the scarce space for water runoff that is usually limited to the water course, some of these road works have a conspicuous lack of maintenance (Fig. 3).

Figure 4 represents a scheme of natural terrain with the presence of a stream (Fig. 4a) and the floodplain in a situation in which it is occupied by water (Fig. 4b). At present, the same scenario has the road embankments and bridges of the provincial routes which raise above the local topography and take up most of the floodplain by modifying the natural state (Fig. 4c).

Fig. 3 State of bridges and culverts in different sections of the basin. **a** abandoned bridge in sector G, close to Veronica town, **b** obstructed culverts in PR 6, sector A (see Fig. 2)

Table 1 Width of the floodplain, the bridges and culverts in different sectors of the Samborombón river basin, and width of the main provincial routes that cross the basin and of the span left by these structures

Width in meters					
Road work	Floodplain	Bridge	Total culverts	% Span	Stream (sector) (Fig. 2)
PR29	1993	200	10	10.54	Samborombón river (E)
PR215	1408	60	9	4.9	Samborombón Chico river (D)
PR6	1755	30	16	2.62	San Vicente stream (B)
PR6	870	20	0	2.3	Stream (A)
PR6	630	12	12	3.81	El Portugués stream (A)
PR215	1273	153	0	12.02	Samborombón river (C)
PR2	3749	345	23	9.81	Samborombón river (F)
Average	1669	117	10	7	

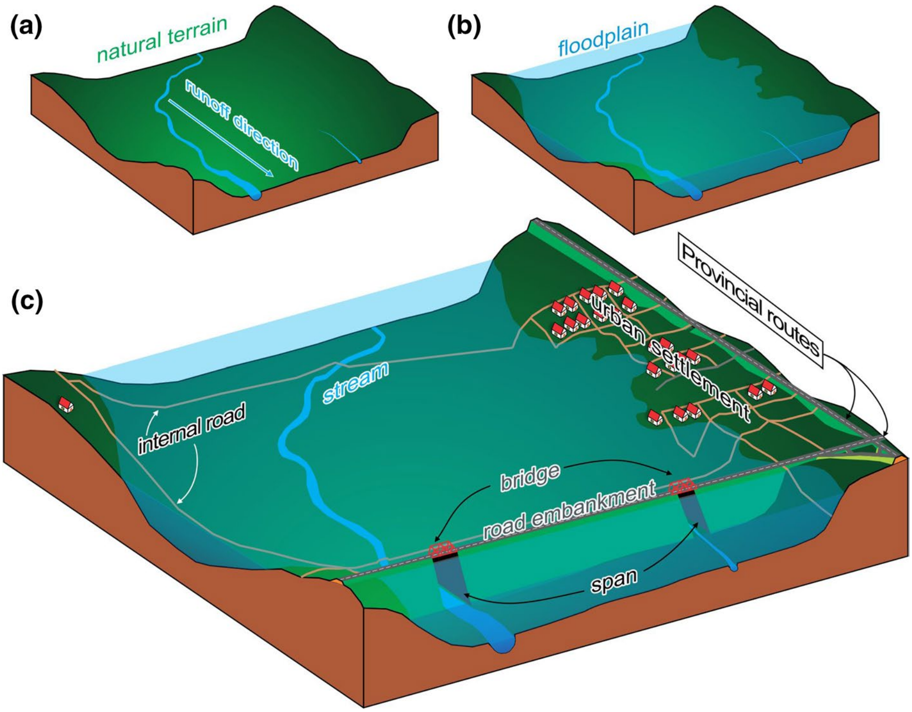

Fig. 4 Schematic representation of **a** natural terrain, **b** floodplain occupied by water, and **c** road embankments and bridges of provincial routes which raise above the local topography and take up most of the floodplain, narrowing the width of natural runoff

3.2 Urban settlements

Urban settlements were recognized in five sites within the floodplain of the river (Fig. 5). These urban settlements are located nearby the provincial routes and not only occupy the floodplain, but they have also modified it by raising with accumulating filler material or by

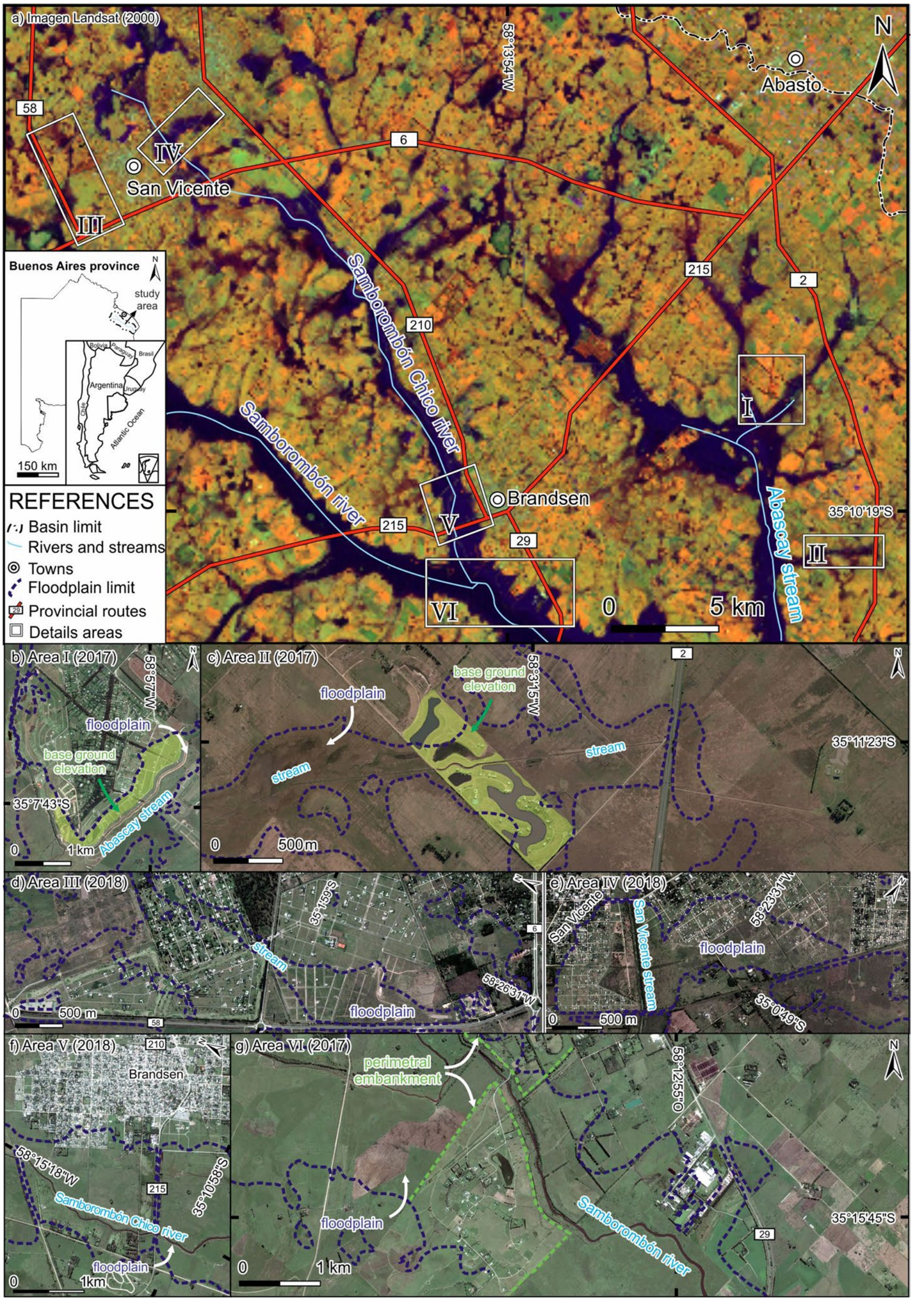

Fig. 5 **a** Landsat image from May 2000, with combination RGB 452; the greatest flood recorded by Landsat series is delimited in blue. White boxes indicate the detailed areas analyzed in the basin, where urban settlements are currently located in flooding areas. The detailed areas shown in figures **b**–**g** correspond to detailed satellite images; **b** and **c** show the houses that were built on the floodplain of the river, and the sectors where the land was raised by accretion of material (green polygons); **d**–**f** show urban areas that were built on the floodplain of courses and rivers; **g** shows urban constructions in the river floodplain surrounded by a perimetral embankment that prevents flooding. The year of capture of each image is indicated in parentheses

perimetral embankment constructions (Figs. 5b, 6d), notably reducing the natural runoff width.

The natural terrain with its floodplain (Fig. 6a, b) was altered by the construction of urban settlements, routes and accretion of material (Fig. 6c). Urban settlements within the floodplain were identified in all sites analyzed in Fig. 5, recognizing that in areas I and II (Fig. 5b, c), the base ground was slightly elevated above the flood level by the accretion of material modifying the natural terrain (left sector in Fig. 6c). On the other hand, within areas III, IV, V and VI (Fig. 5d–g) houses were built on the floodplain without raising the base ground with the accretion of material (right sector in Fig. 6c).

Within the sites described above, the area VI (Fig. 5g) is under a particular condition. The natural terrain (Fig. 7a, b) was altered by the construction of a perimetral embankment to prevent the water entering into the urban settlement during large flood events (Fig. 7c).

3.3 Assessment of road works

The results show that the DTM obtained reflects the smooth relief of the studied basin in a satisfactory way, which is also observed during field surveys.

In sector F (Fig. 2, Provincial Route 2), where the floodplain is best developed, the width for the passage of water in the road work, which was used for the simulation, is

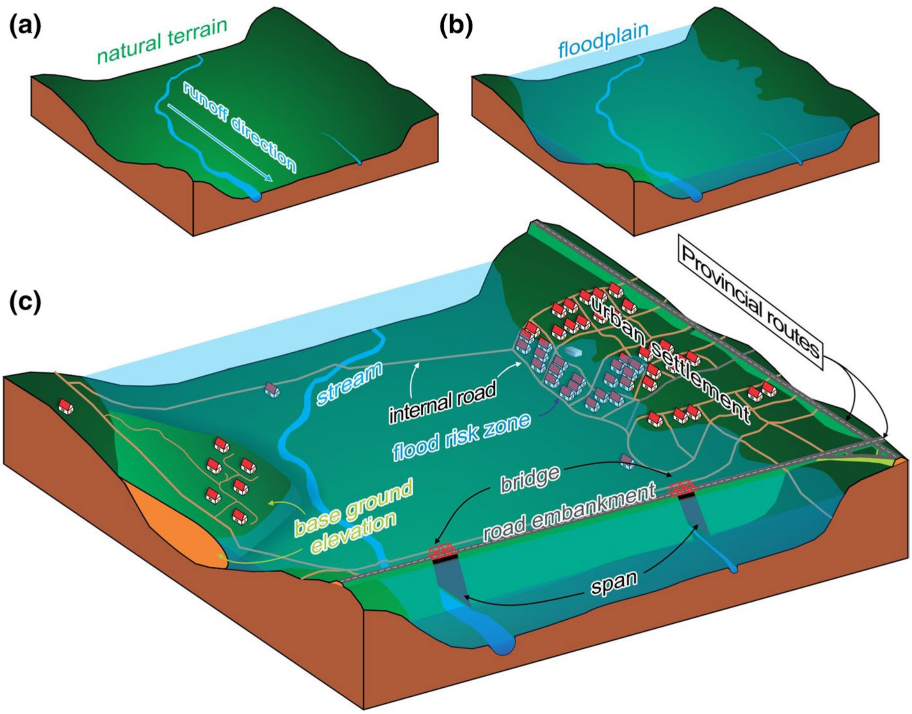

Fig. 6 Schematic representation of **a** natural terrain, **b** floodplain occupied by water and **c** urban settlements occupation within the floodplain (right sector), urban sectors within an area where the base ground was elevated by the accretion of material (left sector) and urbanization without protection against flood events in risk areas

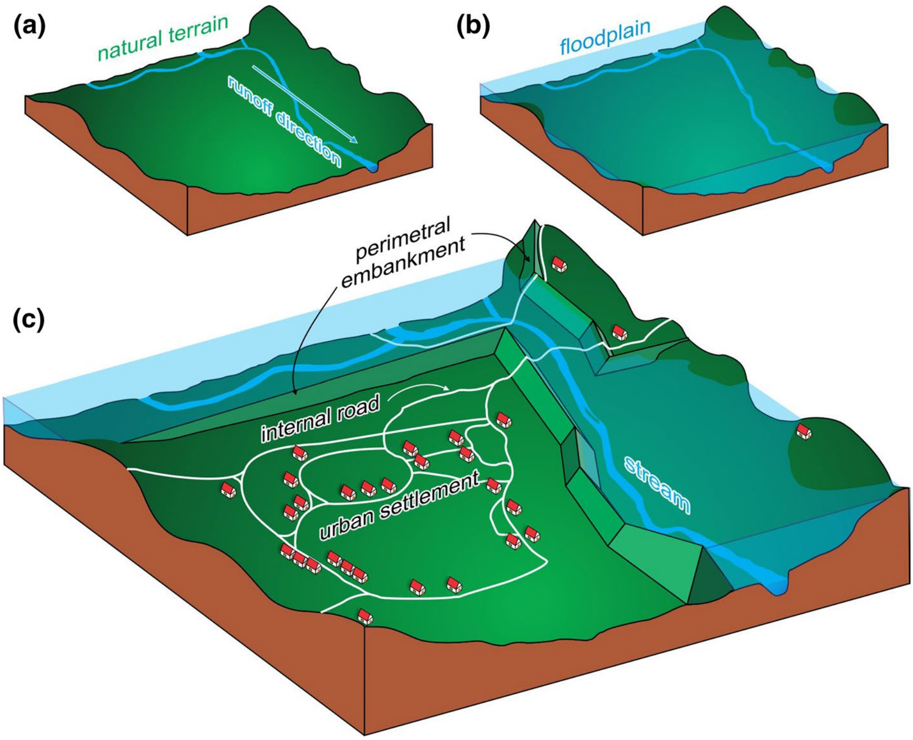

Fig. 7 Schematic representation of **a** natural terrain, **b** floodplain occupied by water and **c** occupation of the floodplain by urban settlements; a perimetral embankment to prevent water entrance into the urban settlement is observed, which reduces the width of natural runoff

345 m and it has two culverts of 23 m of the total extension, registering a floodplain width of 3749 m (Table 1).

Results achieved through simulations using HEC-RAS under natural conditions show that as the river overflow occurs, the exceeding water occupies the floodplain (Fig. 8a) as frequently occurs in plain rivers. If the simulated flooded area is compared with the flood recorded by Landsat satellite images for the same area during a similar flood event, it may be appreciated that there is a good correspondence between both simulated and observed flooded areas, being the simulated one a bit smaller (Fig. 8a).

Regarding the road works embankments which are present in most of the floodplain, field measurements show that these structures enable only almost 10% for the floodplain for water runoff. Simulations generated based on these conditions allow to visualize the accumulation of water that occurs upstream of these embankments as a result of the backwater elevation of 8.97 m a.s.l (2.1 m of total water height) (Fig. 8b, e, Table 2). The backwater elevation is not observed in the simulation generated for natural terrain where road works are not present, and the water level reached 8.45 m a.s.l (1.6 m of total water height) for the same section (Fig. 8a, d, Table 2). This difference, close to 0.5 m, is reflected in an additional flood of more than additional 300 hectares (Table 2) and demonstrates that this variation between the two scenarios is evident up to 5 km upstream of the road work.

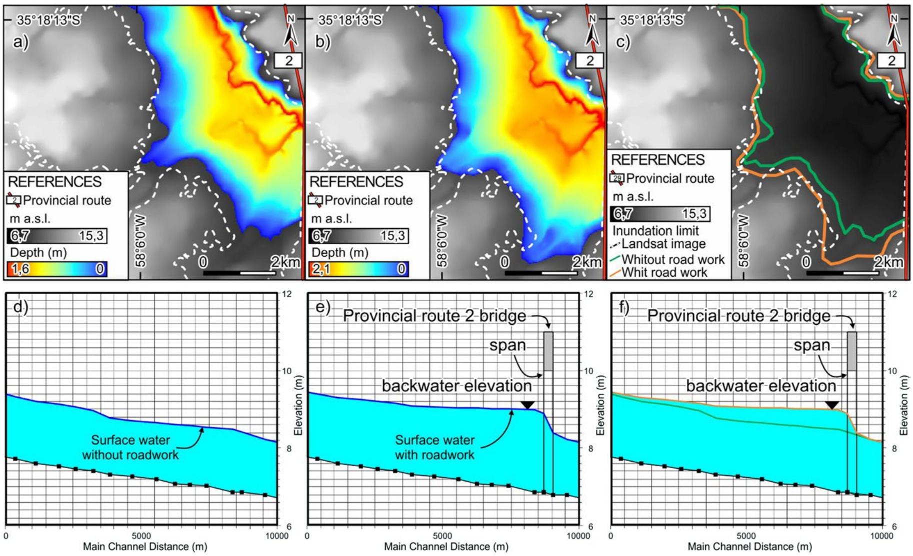

Fig. 8 Simulations performed in the Samborombón river in the Provincial Route 2 (Sector F in Fig. 2); **a** and **d** without road work, **b** and **e** with road work, **c** and **f** comparison between **a**–**d** and **b**–**f**

Table 2 Measurement results obtained with ArcGIS and HEC-RAS

	Provincial route 2 (Fig. 8)
Flooded areas simulated with road works	2857.26 ha
Flooded areas simulated without road works	2494.90 ha
Water column reached with road works	8.97 m a.s.l (2.1 m)
Water column reached without road works	8.45 m a.s.l (1.6 m)
Difference of flooded areas due to road works	362.36 ha
Difference of flooded height due to road works	0.5 m

Table 2 details the number of flooded hectares through simulations for both the natural terrain and the road work and the difference between them due to the accumulation of water upstream of the road structure.

4 Discussion

The increase in flooded areas constitutes a problem in many productive and/or urbanized river basins in the world (Criss and Shock 2001; Sanyal, 2017; Jemberieet al. 2008). Studies carried out in plain basins found that the floodplain restriction not only generates an increase in flooded areas (Brown et al. 2008), but also water takes longer to drain from the basin due to the extent of road embankments (Lee et al. 2000) and behaves similarly to a reservoir (Zimmerman et al. 2001; Moruzzi et al. 2009). The permanence of water in these sectors for a considerable period leads to economic losses for the agricultural producers since their production is strongly affected (Nelms and Twedt 1996). On the other hand, the inhabitants located in the floodplain also suffer material damage and have to be relocated in urban areas not affected during the floods (Plate 2002).

The hydrological simulations obtained for the Samborombón river basin allow us to corroborate the observations respect to the presence of road embankments and their bridges and how these structures obstruct the natural drainage and generate the accumulation of water in the upstream sector. Likewise, the occupation of the floodplain through urban settlements not only puts the inhabitants at flooding risk, but also highlights the floodplain restriction through perimetral embankments. The perimetral embankments may have a similar effect as road embankments, delaying the water runoff and generating a rise in the water level upstream of the perimetral embankment by modifying the natural hydrodynamics. These results constitute the first antecedent that analyzes the increase in flooded areas regarding the influence of road works and urban settlements. The proposed methodology also constitutes an important tool to be used in other basins in the region where the studies carried out are mainly based on field observations (Euillades et al. 2002; Auge et al. 2004; Ferreira and Rodríguez 2013; Quiroz Londoño et al. 2013). Flooding is a problem that, in the study area and in general throughout the world, has been traditionally addressed through the construction of canals that tend to evacuate surplus water. However, it has been observed that this measure does not always achieve the expectations (Carol et al. 2014) and only recently structural measures such as the extension of bridges and culverts are considered (Bandano 2010; Ministerio de Obras Publicas 2019).

It is widely accepted that climate variability and changes in land use or occupation are critical drivers for watershed hydrological changes (Wei et al. 2013). The increase in the volume of rainfall recorded in the Pampean Region (Scarpati and Capriolo 2013) contributes to greater water runoff (Jiang et al. 2007), which worsens the situation of the anthropic activities that are developed in the floodplain of the Samborombón river basin and leads to a greater flooding risk (Trenberth 2011).

The situation described demonstrates the need to make a review of the hydraulic working of engineering structures which have been built at the beginning of the twentieth century that contemplate the current increase in rainfall and the economic development of the basin. Similar problems, in other parts of the world, have led to consider the realization of new engineering road works aimed at complementing or replacing previous road works (Galisteo del Río 2004; Hernández 2018; Nasr et al. 2019). In a plain sector as studied in this work, the construction of a bridge with a floodplain width of approximately 3 km could make these new engineering road works excessively expensive. It is proposed that the use of "sacrificial embankments" or "fuse plug" would be a low-cost option for large floodplains, where the road embankments are lower than the bridge and would be flooded during large floods, facilitating water runoff (Martín Vide 2006; Brand et al. 2017; Thomason 2019), avoiding the bridge scour. Despite this alternative, during great magnitude flood events, the low height of the road embankments may make them not to be passable, which generates the need of looking for an alternative route (Martín Vide 2006; Brand et al. 2017). The natural functioning of a river and its floodplain, unlike those anthropized by road embankments that resemble control dams, favors the runoff of large volumes of water in less time (Moruzzi et al. 2009), avoiding both economic and human losses. In this sense, it is important to note that engineers consider "sacrificial embankments" as an innovative idea. However, it is necessary to conduct pilot studies mainly in rural areas with the purpose of that this idea be applied, where the population is scarce constituting a low risk for the inhabitants (Brand et al. 2017). The study area fulfills the aforementioned characteristics, so this could be a strategic site where the "sacrificial embankments" may be implemented.

5 Conclusions

The study of flood events using satellite images and hydrological simulations, together with field surveys of the state of the floodplain in road works areas and urban settlements, constitute an appropriate methodology to evaluate the influence of these anthropic modifications in the flooded areas. Road works embankments and urban settlements constitute a restriction of the river floodplain area, leading to an increase in the flooded area and a delay in the drainage. Given the antiquity of these road works, which have been built at the beginning of the twentieth century and the lack of maintenance, the unplanned urban development, as well as the increase in the rainfall regime in recent decades, it is expected that this problem will get worse over time. In this sense, it is necessary to make a structural update of these engineering road works, as well as to carry out a territorial management plan that considers the occupation of natural runoff areas according to the climate change which is being registered in the region. The use of sacrificial embankments is an innovative low-cost alternative that can be used in this plain basin and also constitutes an example for sites with similar characteristics.

The data provided in this work are relevant not only for being the first study carried out on the topic for the study area but also for providing methodological procedures applicable to other hydrographic basins worldwide.

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