Heliyon 6 (2020) e04517

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

A basin-level analysis of flood risk in urban and periurban areas: A case study in the metropolitan region of Buenos Aires, Argentina

Andrea Pamela Flores [a], Leandro Giordano [a,b], Carlos Alberto Ruggerio [a,c,*]

[a] Instituto del Conurbano, Universidad Nacional de General Sarmiento, J. M. Gutiérrez 1150, Los Polvorines (B1613GSX), Prov. de Bs. As., Argentina
[b] Dirección de Sistemas de Información y Alerta Hidrológico, Instituto Nacional del Agua, Au. Ezeiza–Cañuelas, tramo Jorge Newbery Km 1,620, C.C. 46 1802 (Aeropuerto), C.P. 1804, Ezeiza, Prov. de Bs. As., Argentina
[c] Centro de Investigaciones en Geografía Ambiental, Universidad Nacional Autónoma de México, Campus Morelia. Antigua Carretera a Pátzcuaro No. 8701, Morelia C.P. 58190 Michoacán, Mexico

ARTICLE INFO

Keywords:
Lowland river basin
Supervised classification
Impervious surface
Flooding risk
Flood vulnerability
Environmental management
Environmental risk assessment
Geography
Hydrology
Natural hazard
Environmental science

ABSTRACT

Flooding in urban and periurban areas is a complex phenomenon that results from the interplay between urban expansion and the dynamics of the hydrological system. Understanding both processes is essential to manage flood risk. This study aimed to analyze the flood risk in urban and periurban areas of the upper and middle basin of the Luján River (Metropolitan Region of Buenos Aires, Argentina) between 1985 and 2015. We assessed the factors that affect flood frequency by analyzing the precipitation variations obtained from meteorological data and applying hydrological models. We also used supervised classification of remote sensing imagery to detect increases in impervious surface areas that could enhance flooding. Furthermore, we combined both analyses to identify flood risk situations in the region. Our results indicated that maximum precipitation and hydrometric values remained stable during the study period, with a marked interannual variability due to the presence of dry and wet phases. During the dry phase (2011–2015), when flooding events were infrequent, there was a steady urban sprawl in the floodplain area and, as a result, more people would have subsequently become exposed to flood risk. Our results evidence the lack of regional policies to regulate the urban sprawl in flood risk regions.

1. Introduction

Floods have become a serious problem worldwide, causing loss of life and economic damage (Gao et al., 2019; Kundzewicz et al., 2014, 2013; Svetlana et al., 2015). In urban and periurban areas, flood events may occur at different times and places and vary in intensity, duration, and spatial extent, thus constituting complex phenomena that result from a link between urban expansion and the dynamics of the hydrological system (González, 2006; Lindón, 1989; Minciardi et al., 2006; Pascale et al., 2009).

. For this reason, flood risk assessment requires a robust approach to determine the nature and extent of disaster by analyzing possible flood events and evaluating existing exposure conditions (UNIDSR, 2016).

Although floods are recurrent phenomena, they exhibit changes in periodicity due to several factors. These factors are either predictable or unpredictable (chaotic) climatic and hydrologic factors, whose variation is usually analyzed using rainfall–runoff transformation models, which can be contrasted with the observed hydrograph or limnograph (Perrin et al., 2003; Beven, 2012; Crooks et al., 2014; Elga et al., 2015; Coron et al., 2017; Douben, 2006). Difficulties in assessing water surplus are dealt with using a soil moisture accounting approach, while flow propagation through the river network can be simulated by applying hydrological and hydrodynamic methods (Muskingum method, cascade of linear reservoirs, St. Venant equations) (Beven, 2012; Chalfen and Niemiec, 1986; Eagleson, 1972; Liu et al., 2015; Moussa and Bocquillon, 1996).

In both urban and periurban areas, urban expansion may replace vegetation cover and increase the imperviousness and soils compaction, thus reducing infiltration and increasing the volume and velocity of runoff (Kundzewicz, 2001; Vogel et al., 2011). Combined, these alterations affect the temporal structure of flooding and waterlogging (Hollis, 1975; Tucci, 2005; Vogel et al., 2011). These changes may be monitored and evaluated by means of remote sensing applications and techniques involving aerial and satellite-based imagery of the earth (Miller and Small, 2003). In particular, many multi-temporal studies using multi-spectral satellite imagery have proved to be useful for the analysis

* Corresponding author.
E-mail address: cruggerio@campus.ungs.edu.ar (C.A. Ruggerio).

https://doi.org/10.1016/j.heliyon.2020.e04517
Received 3 June 2019; Received in revised form 15 January 2020; Accepted 17 July 2020

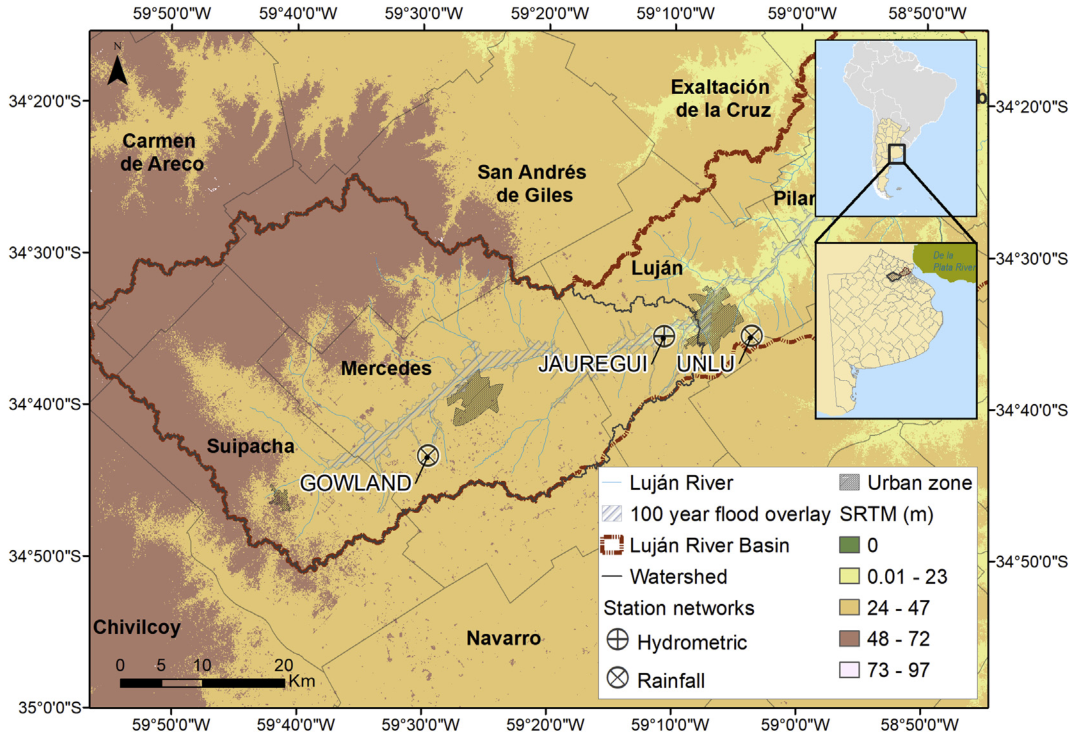

Figure 1. Map of the study area showing Lujan River basin, hydrometric and rainfall stations (National University of Luján (UNLu)), Gowland and Jauregui), urban zones, and topographic information from the Shuttle Radar Topography Mission (SRTM).

of changes in land use patterns in urban and periurban areas (Angel et al., 2005; Taubenböck et al., 2012; Benza et al., 2016; Kantakumar et al., 2016; Shahtahmassebi et al., 2016; MacLachlan et al., 2017) and for the modeling of urban growth patterns (Shi et al., 2017). Understanding the dynamics of variation in climatic factors and the production of geographical space is essential to determine the flood risk. Natural precipitation fluctuations may affect the hydrological regime, leading to exceptional flooding or water logging, which poses a threat to both urban and rural settlements.

Based on the fact that urbanization may affect social vulnerability to flooding, management measures aim to mitigate the negative impacts by means of infrastructure (defense systems, waterway diversion and construction of dams for water storage, among others), without taking into account the complex functioning of the Socio-Ecological System. Indeed, to reduce flood vulnerability, it is mandatory to evaluate the human-made environmental changes driven by political, social and economic factors (Kundzewicz, 2001; Minciardi et al., 2006; Pascale et al., 2009; Takeuchi, 2001).

In the metropolitan region of Buenos Aires (RMBA), one of the most populated areas in the world, with approximately 14 million people, floods are a recurrent problem. More than 1,075 flood events were recorded from 1970 to 2012, with over 300,000 people being evacuated (Bertoni, 2006; Barbier et al., 2012). On May 31st 1985, the city of Buenos Aires suffered an extreme flood event, in which the highest volume of precipitation accumulated over 24 h was 310 mm; this extreme event caused 15 deaths, over 100,000 people evacuated and total economic losses of over U$S 246,000,000 (Barbier et al., 2012). Other relevant flood events in the region occurred in January 2001, April 2013 (which affected mainly La Plata city), October 2014, and August 2015 (INA, 2014; SMN, 2013; UNLP, 2013; Valverde, 2017).

Floods in this region occur principally in the floodplains of three of the rivers of the region: Matanza-Riachuelo, Reconquista and Luján Rivers. In particular, recurrent flooding affects the urban and periurban areas located along the coasts of the upper and middle basin of these rivers, causing important economic losses and representing a public health hazard. The upper and middle basin of Luján River is widely

Table 1. Physical, hydrological and climatic characteristics of the study area.

Parameter	Value*
Drainage area (km^2)	~1997
Mean topographic slope (m/km)	1
Flow module (m^3/s)	12
Mean annual rainfall (mm)	1012
Annual runoff coefficient	~0.2

* Information obtained from analysis of data from the Instituto Geográfico Nacional (National Geographic Institute of Argentina) and the Shuttle Radar Topography Mission (SRTM). Data are available in https://alerta.ina.gob.ar/pub/gui/apibase.

Table 2. Pluviometric and hydrometric stations, and time intervals.

Variable	Gauge station	Location (Easting, Northing)	Weight (%) (mean areal rainfall)*	Time interval
Precipitation	UNLu	-59.07–34.60	3.73	Jan 1st 1989 to Mar 1st 2014
Precipitation	Gowland	-59.58–34.63	96.27	May 2nd 1982 to Dec 31st 2014
Water Level**	Puente Jáuregui	-59.18–34.59	-	Jun 9th 1988 to Aug 12th 2005

* Mean areal rainfall was estimated using the nearest neighbor method (Thiessen method).
** Flood events: 2012, 2014 and 2015.

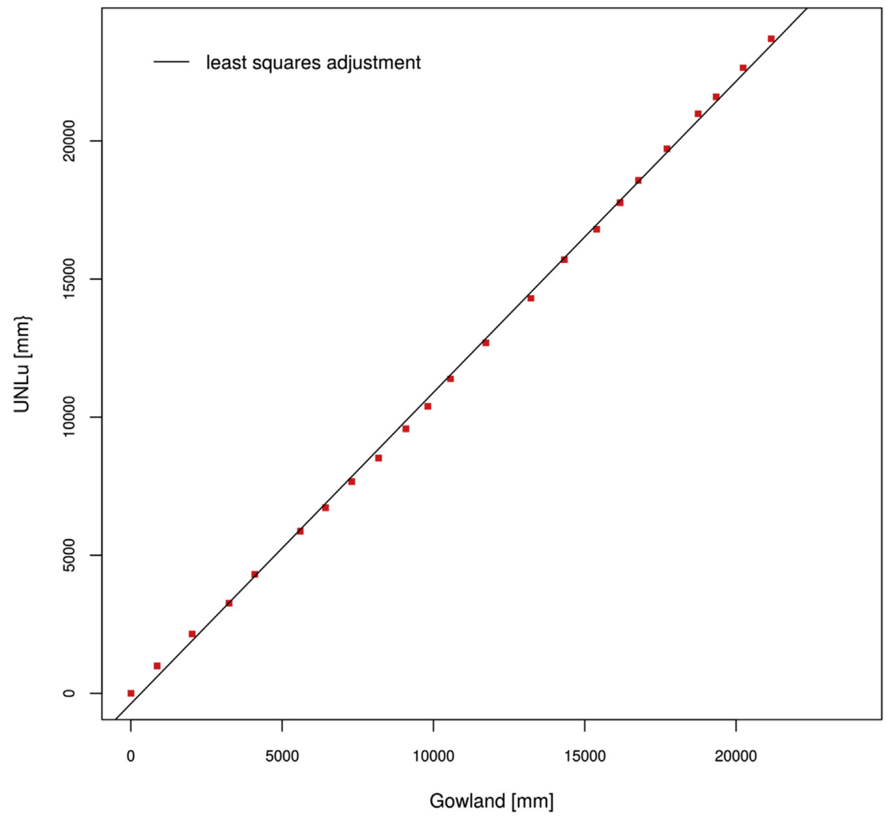

Figure 2. Double mass analysis showing total accumulated rainfall for Gowland gauging station and National University of Luján gauging station (UNLu). Time interval: Jan 1st 1989 to March 14th 2014. Least squares adjustment shows that both gauging stations are affected by the same trends ($R^2 = 0.99$). Kolmogorov-Smirnov test on annual recordings suggests that each recorded data comes from the same parent population (p value >0.1).

representative of this situation and the management of the flood risk responds to the logics of land use planning in the region. In 2015, local media reported that floods affected 10,000 people,1,500 had to be evacuated, and only 20% of the families were relocated after the event (Valverde, 2017).

Based on the above, the main objective of our study was to analyze the flood risk in urban and periurban areas of the RMBA to facilitate the decision-making processes to mitigate the damages caused by floods. Our working hypothesis is that flood risk in the region is managed without policies of land-use planning aimed to prevent urbanization in floodplains.

We tested this hypothesis by assessing: 1) the factors that affect flood frequency and 2) the processes involved in urban expansion. First, we focused on the analysis of variation in precipitation by using hydrometric information and hydrological models, then applied supervised classification of remote sensing images to detect land cover changes, and finally combined both analyses to identify and characterize the main drivers of the process of urbanization-related flood risk.

2. Materials and methods

2.1. Study area

The study area was the upper and middle basin of the Luján River and included the municipalities of Suipacha, Mercedes, Luján and San Andrés de Giles (Figure 1). The activities developed in the area are related to agricultural production, industrial production and urban centers. Data collected from the last Argentine National Census of Population indicated a sustained population growth from 144,296 people in 1991 to 162,766 in 2001 and to 179,638 in 2010 (INDEC, n.d.), with most inhabitants being concentrated in the cities of Suipacha, Mercedes and Luján. The rural areas are located along the Luján River and tributaries, thereby being exposed to high flood risk.

Hydrologically, the study area is a plain watershed (mean topographic slope of 1 m/km) with a well-defined drainage system of 1997 km^2, a flow module of 12 m^3/s and an annual runoff coefficient of 0.2 (Table 1). The system is characterized by wide annual fluctuations in surface runoff mainly caused by rainfall (mean annual for the period 1980–2015: 1012 mm). The climate is temperate sub-humid, with mild winters and hot summers. Proximity to the sea and to the Río de la Plata estuary accounts for thermal amplitude, intense rainfall (mean annual: 986 mm) and high relative humidity (about 75% of mean annual value). Climate conditions are influenced by winds from the South Atlantic anticyclone, among which the most important ones are the "Sudestada" and the "Pampero". The basin is one of the three basins of the RMBA and is situated in the Pampa region.

2.2. Characterization of floods

We constructed and examined precipitation annual maxima series on a daily, weekly and fortnightly basis, as well as cumulative monthly precipitation anomalies and their integration. Data were obtained from the rainfall gauge stations of Gowland, Mercedes and of Universidad Nacional de Luján (National University of Luján; UNLu) (Table 2). Consistency between different sources of rainfall data was checked by means of the double mass curve method (Figure 2).

We tested the stationary hypothesis (null hypothesis of constant mean and constant variance) by means of the regression between precipitation annual maxima series and time, and estimated the significance of the slope of the linear fit (i.e. under the null hypothesis of constant mean, slope = 0 mm/year). The Breusch-Pagan test was used to assess heteroscedasticity (Breusch and Pagan, 1979).

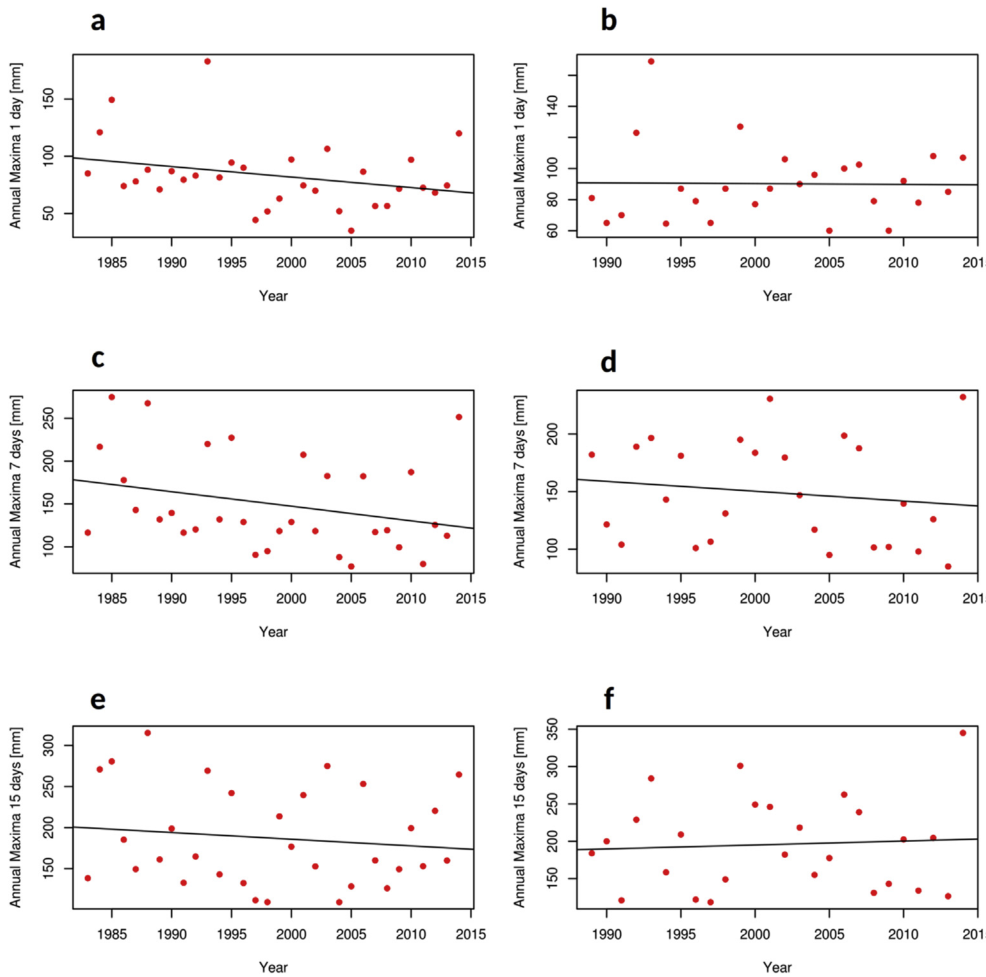

Figure 3. Annual maxima values of daily precipitation (a. Gowland station, b. UNLu station), weekly precipitation (c. Gowland station, d. UNLu station), and fortnightly precipitation (e. Gowland station, f. UNLu station).

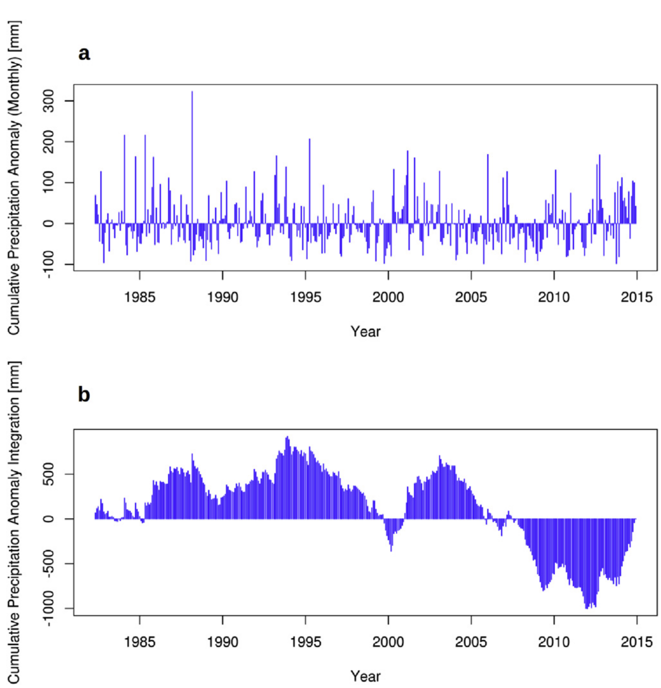

Figure 4. (a) Series of cumulative monthly precipitation anomalies and (b) cumulative precipitation anomaly integration.

To identify and characterize traits related to rainfall seasonality and interannual variability, we used the series of cumulative monthly precipitation anomalies (deviation of the monthly accumulated value from the mean monthly accumulated) and their integration. We assumed that the local trend of the integration of the cumulative monthly precipitation anomaly is associated with variations in the position of the phreatic level, as it is known to be a key factor in generating water surplus in lowland river basins with humid or sub-humid climate (Kruse and Zimmermann, 2002).

In these types of hydrological systems, the dynamics of the water balance is notoriously vertical. Indeed, the predominance of vertical flows over horizontal ones is due to topographic and edaphic factors that lead to an intense relation between groundwater and surface water storage (Kruse and Zimmermann, 2002). Periods of excess water or positive cumulative monthly precipitation anomalies are associated with periods of water recharge.

We also analyzed the temporal trend and variance of the hydrometric level by using annual maxima series. Water levels were recorded at the hydrometric station installed on the Puente Nuevo-Jaúregui bridge, corresponding to the section of the Luján River (Table 2). Available records for the 1988–2005 period were provided by the Ministry of Infrastructure of Buenos Aires province (MOSP), whereas those for 2012, 2014 and 2015 were provided by the Instituto Nacional del Agua (National Institute of Water; INA) and the UNLu. Since the data from the MOSP have gaps and the data from the INA and UNLu are restricted to punctual events, we performed rainfall-runoff modeling for the 1988–2015 period. We used two spatially lumped and time-continuous

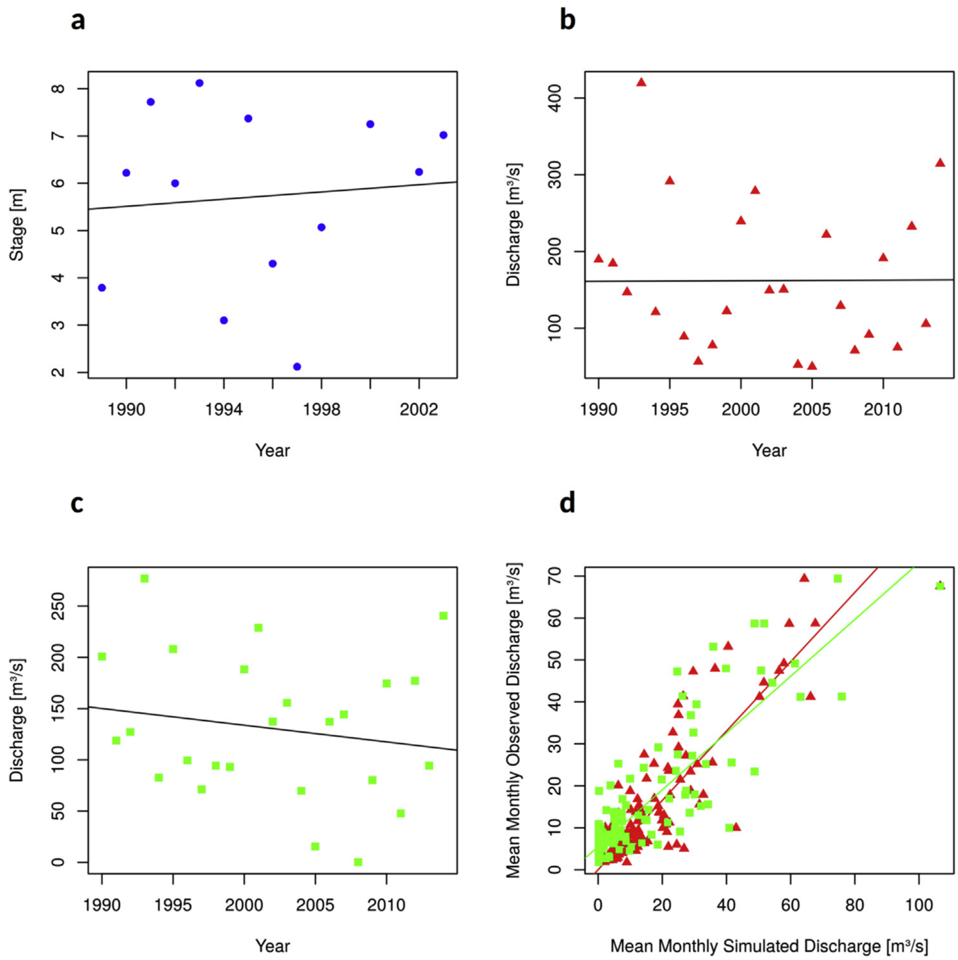

Figure 5. (a) Annual maxima series of the hydrometric level (observed vs simulated) for the 1990–2005 period and monthly values, (b) annual maxima series of simulated discharge of the Sacramento Model, (c) simulated annual maxima flow series from HIDROSAT, and (d) observed vs simulated mean monthly flow values from the SacMod/ea model (red triangles, $R^2 = 0.76$, Rns~0.6) and the HIDROSAT model (green squares, $R^2 = 0.75$, Rns~0.6).

hydrological models: the Sacramento model modified with the effective area parameter 'SacMod/ea' (Sánchez Caro and Bianchi, 2014) and the HIDROSAT model (Giordano, 2014), both set at a daily time step (Model description in the Annex).

The 1988-2012periodwas used for calibration and validation. The model performance was assessed using the coefficient of efficiency (R_{ns}) proposed by Nash and Sutcliffe (1970), the coefficient of determination (R^2), and the root-mean-square error (RMSE). Taking into account that precipitation is the main input for these models and that the analysis was carried out at constant parameters obtained from information corresponding to the 1988–2005 period, the experiment also allowed contrasting the hypothesis of changes in the hydrological regime by the "pure effect" of precipitation (i.e. changes in the hydrological regime due to fluctuations in the pluviometric regime, assuming stationary parameters for the entire 1988–2015 period).

Finally, we tested for possible changes in the internal structure of the hydrological system by comparing the outputs of the hydrological models (daily time step) with available records of important recent floods provided by the INA and UNLu.

2.3. Land-use change analysis

Impervious surface expansion was used as an indicator of land-use change. This variable was identified using supervised classification techniques applied on LANDSAT (USGS) satellite images. LANDSAT is the most widely used satellite data sources because it is the longest-running program to observe global land use and has a multispectral scanner system for more accurate land cover classification (Estoque and Murayama, 2015; Gao et al., 2012; Guindon et al., 2004; Jiang et al., 2017; Luo et al., 2014; Reynolds et al., 2017; Ridd and Liu, 1998; Schneider, 2012; Song et al., 2016; Zhang et al., 2017). We selected one cloud-free image per year between 1985 and 2015. Before 2011, images were first acquired from the THEMATIC MAPPER sensor and then from the Operational Land Imager (OLI) sensor. A normalized spectral difference vector (NDSV) was constructed prior to the classification to maximize differences in reflectance between land cover classes (Eq. 1) (Angiuli and Trianni, 2014; Patel et al., 2015).

$$NDSV_{ij} = (b_i - b_j)/(b_i + b_j) \quad (1)$$

where b_i and b_j are the band pairs for each image.

The NDSV images were supervised classified applying the algorithms: Classification and Regression Tree -CART- (Breiman et al., 1984), Random Forest (Breiman, 2001), and Support Vector Machine -SVM-(Burges, 1998). These classification tools are considered to be expert systems because they allow determining-non-parametrically- statistical relationships between many data layers, which are then converted into binary decisions (Angiuli and Trianni, 2014; Luo et al., 2014; Patel et al., 2015). Both the Landsat imagery derived from measured values of reflectance at the top of the atmosphere and the algorithms were obtained from the Google Earth Engine platform (Gorelick et al., 2017).

The training areas were obtained using very-high-resolution images, provided by Quick Bird satellite imagery extracted from Google Earth Pro (2002–2014); we assumed that the areas with some kind of building or

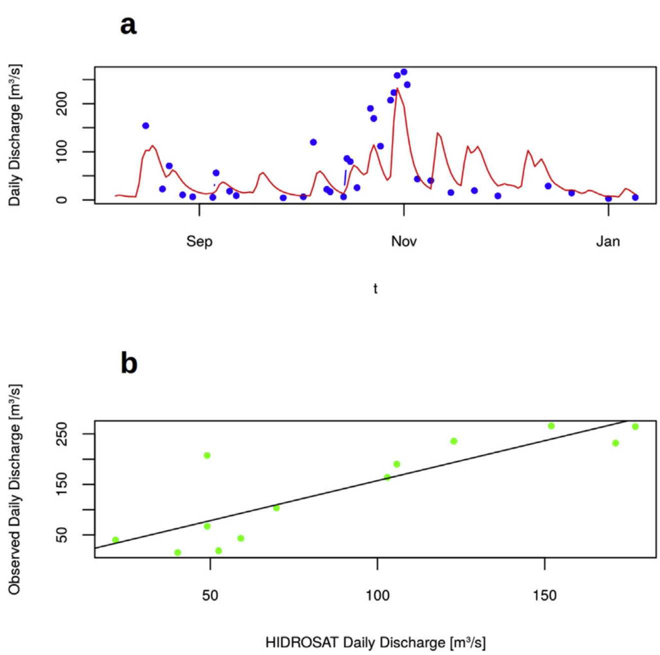

Figure 6. (a) Simulated flow vs. observed flow in the Luján River with the Sacramento Model, centered on the flood wave event of October–November 2012 ($R^2 \approx 0.72$); (b) simulated (obtained by using discharge rating curve on simulated discharge values) and observed hydrometric levels with HIDROSAT, on the flood wave event of October–November 2012 ($R^2 \approx 0.71$).

street layouts observed in past images were still present. To confirm that these areas had the same type of land cover from 1985 to 2001, we obtained official information on land cover/use during this time period. Satellite-based remotely-sensed images were regrouped into five classes: 1) impervious surface (household roof made of tiles, concrete blocks, corrugated zinc sheets, or radiant barrier, pavement and parking lot), 2) tree, 3) herbaceous vegetation, 4) water body and 5) bare soil (including unpaved road). To identify the pervious surface (classes 2–5), we examined the complete imagery catalog and selected areas that remained unchanged during 1985–2015 (Luo et al., 2014). As a result, 65% of the samples were selected for training and the remaining samples were used to validate the classification obtained.

To determine the temporal variation in surface imperviousness, images were reclassified according to the binary categories pervious (value = 0) and impervious (value = 1). To reduce error variability, we considered four periods: 1985–1991, 1992–2001, 2002–2010 and 2011–2015.

The analysis of variation of impervious surfaces was focused in the urban zones. The urban zones were delimited by the Zoning Code of Buenos Aires province (Decree-Law 8912/77) and the Argentine urban census units (INDEC, n.d.).

Finally, we estimated the increase in urban impervious surface in flood areas by overlying the 100-year flood extent (Reyna et al., 2007). Geoprocessing was performed using ArcGIS 10.0 (ESRI); vectors and imagery were previously projected onto the local coordinate system (EPSG 22185).

3. Results and discussion

3.1. Analysis of flood risk and related components

The precipitation annual maxima obtained at different time intervals (daily, weekly and fortnightly) from the stations of Gowland and UNLu are shown in Figure 3. The dispersion of values indicates randomness. The p-values of the Breusch-Pagan test for homoscedasticity were higher than 0.1 in all cases, thus indicating homogeneous variability/dispersion. Likewise, none of the slopes differed significantly from 0 ($p>=0.1$ in all cases) and therefore the hypothesis of simple stationary annual maxima could not be rejected. These results indicate that daily, weekly and fortnightly annual maxima precipitation showed no significant changes during the study period (1985–2015). Therefore, our results do not support the hypothesis that the change in the hydrological regime is the main forcing factor for flooding. It is possible that significant differences would be detected at shorter time scales (e.g. within daily, weekly or fortnightly intervals), but these are not expected to affect a large hydric system such as the drainage basin of the Luján River in Jáuregui.

The cumulative monthly precipitation anomalies and their integration are shown in Figure 4. The analysis of the trends in the integration of the precipitation anomalies revealed a long period of water deficit between 2005 and 2012 (dry phase), followed by a predominance of positive anomalies from 2012 onwards (wet phase). This interannual variability is characteristic of the Pampean systems (Ameghino, 1984).

The slope of the linear model fitted to the annual maxima series of the hydrometric level (H) obtained at the hydrometric station for the 1988–2003 period did not differ significantly from zero (Figure 5). On the other hand, both the Sacramento model modified with the effective area parameter (SacMod/ea) (Sánchez Caro and Bianchi, 2014) and the HIDROSAT model achieved a satisfactory performance ($R_{ns} \approx 0.6$). The results obtained through hydrological modeling showed no significant trend in the hydrological regime with the patterns of cumulative monthly precipitation anomalies, while a wet phase was detected after 2012, in line with the floods occurring at the end of the period. Therefore, there is no clear evidence supporting the hypothesis of change in the hydrological regime due to variations in the precipitation regime.

Table 3. Impervious surface in the urban zones.

Urban area (km^2)	Period	Surface area (km^2)	Relative increase (%)
Suipacha (3.70)	1985–1991	0.89	-
	1992–2001	0.95	6.7
	2002–2010	1.05	10.5
	2011–2015*	1.37	30.5
Luján (30.47)	1985–1991	8.92	-
	1992–2001	9.09	1.9
	2002–2010	9.22	1.4
	2011–2015*	10.82	17.3
Mercedes (24.34)	1985–1991	5.18	-
	1992–2001	5.98	15.4
	2002–2010	6.46	8.0
	2011–2015*	7.65	18.4

* Images for 2012 were not available because the TM sensor failed and the OLI sensor had not been launched yet.

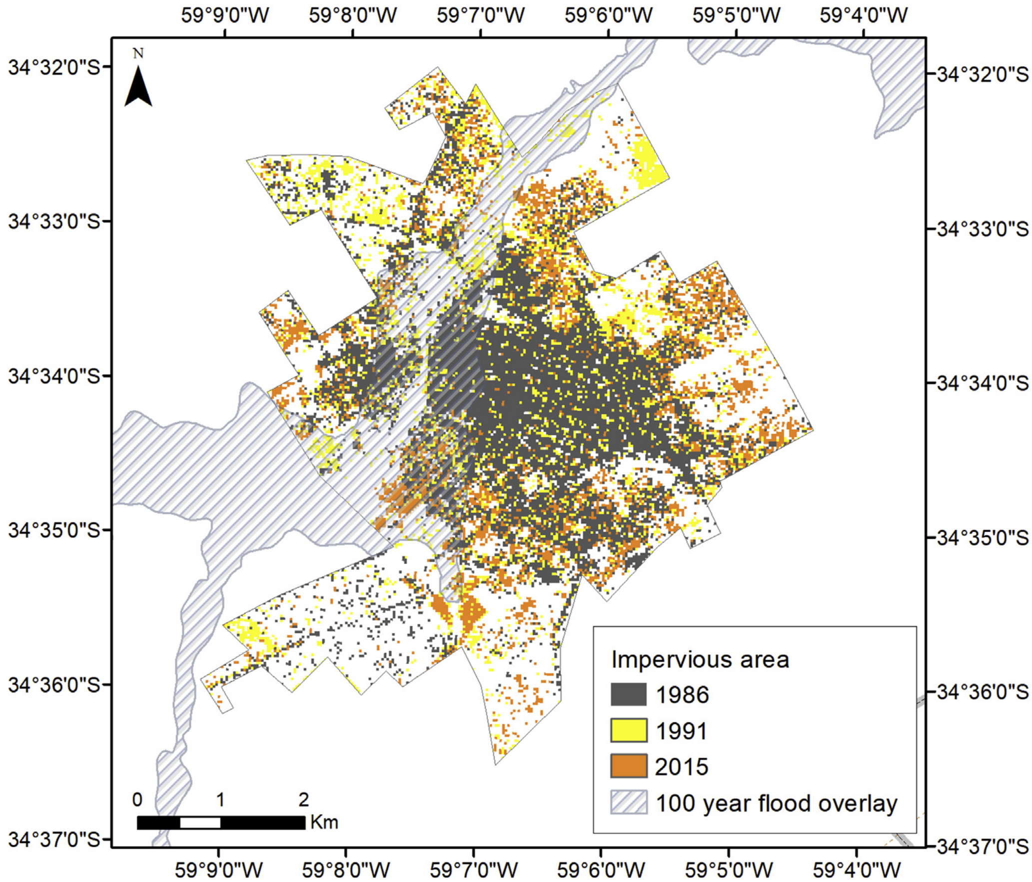

Figure 7. Impervious surface in Luján urban zone.

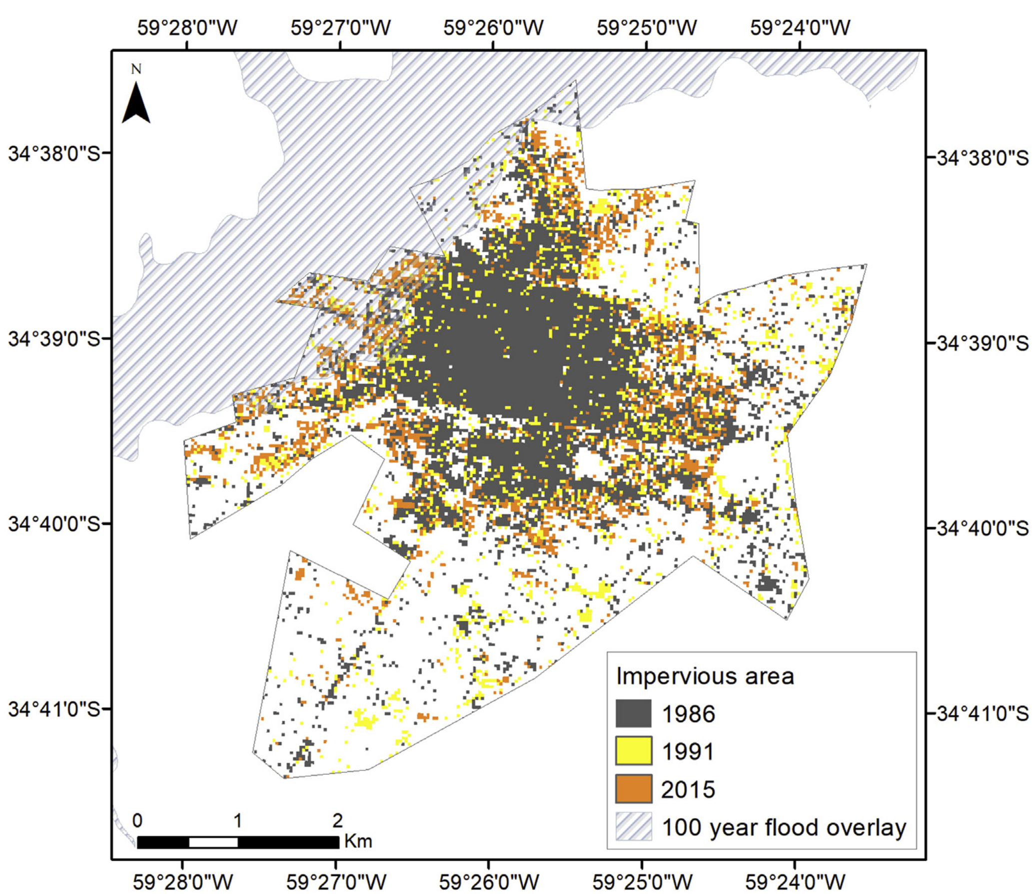

Figure 8. Impervious surface in Mercedes urban zone.

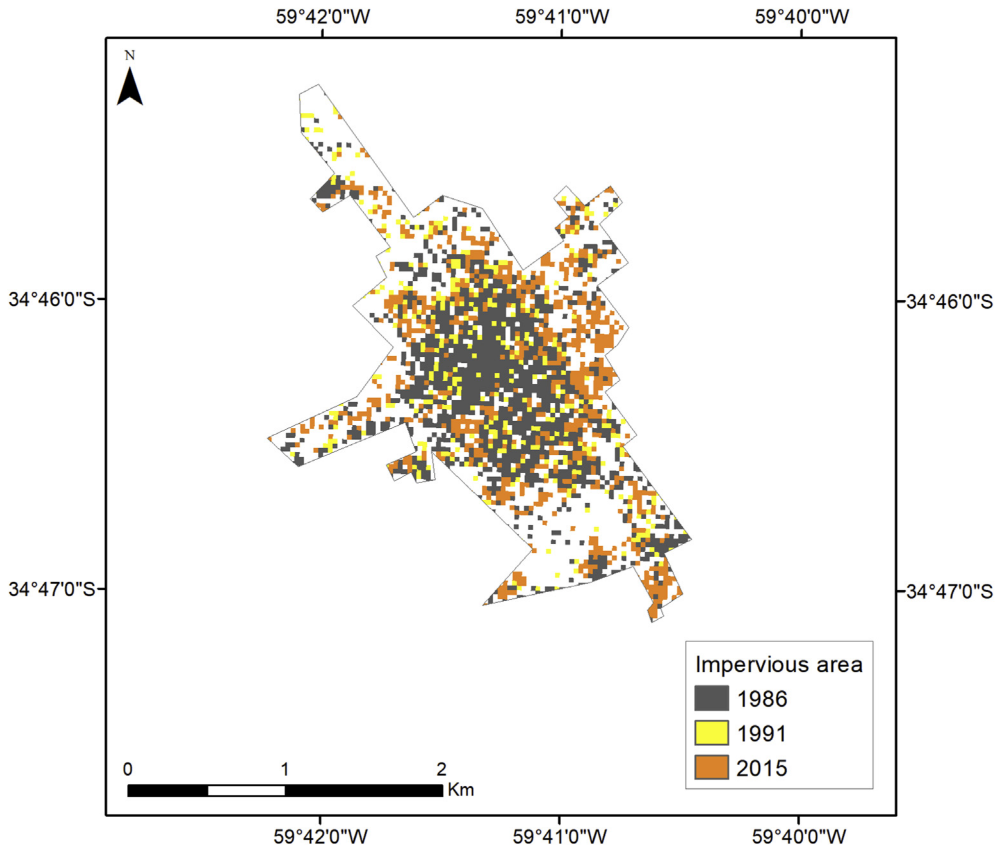

Figure 9. Impervious surface in Suipacha urban zone.

Table 4. Estimated impervious surface in flood-prone areas of the municipalities of Mercedes and Luján.

Municipalities	Period	Impervious surface in flood-prone areas		Proportion of impervious surface in flood-prone areas (%)
		Totally impervious surface (km^2)	Relative increase (%)	
Mercedes	1985–1991	0.08	-	4.13
	1992–2001	0.17	109.9	8.67
	2002–2010	0.23	35.3	11.73
	2011–2015	0.46	100.0	23.46
Luján	1985–1991	1.87	-	30.81
	1992–2001	1.92	2.7	31.63
	2002–2010	1.97	2.6	32.45
	2011–2015	2.12	7.6	34.92

Modeling and efficiency showed a similar bias for the floods of 2012, 2014 and 2015 in comparison to the 1988–2005 period of evaluation and calibration (Figure 6). We found no evidence to reject the hypothesis of stationary parameters. Therefore the combined effect of factors not included in the models may be assumed constant at modeling resolution level. Moreover, the modeling error showed no significant trend indicating changes in the parameter values of SacMod/ea and HIDROSAT for the 1988–2005 period in comparison to the 2005–2015 period. This indicates that the statistical structure of the modeling error remained stable, implying that there were no significant changes in the internal structure of the hydrological system that could explain the flood events in the last 4 years of the study.

In sum, the simple rainfall-runoff models used in our study indicate that: (a) a great amount of the information obtained after 2005 can be summarized without assuming changes in model parameters, meaning that the internal structure of the hydrological model remained invariable; (b) no changes were observed in the combined effect of the factors not included in the modeling process; and (c) the system was subjected to quasi-periodic fluctuations of dry and wet phases, with low hydrological activity during the 2005–2012 period and high recharge rate and surplus water from 2012 to 2015, in coincidence with above-average rains.

3.2. Extraction of impervious surfaces

Regarding the impervious surface mapping, satisfactory results were achieved using LANDSAT remote sensing images at medium resolution. In comparison to Random Forest and SVM, the algorithm CART had an overall accuracy of extraction of impervious surfaces between 79.9% and 98.03%. Table 3 shows the quantification of impervious surfaces in the projected urban area and the percentage of relative increase for each period.

The results indicate that the three urban areas studied underwent a continuous impervious surface expansion during the period under consideration. The highest increase in impervious surfaces was recorded during the last 4 years of the study (2011–2015), with the highest value being estimated for Suipacha (30.5%). Figures 7, 8, and 9 show the impervious surfaces obtained in 1986, 1991 and 2015 for the main urban zones in the municipalities of Luján, Mercedes and Suipacha.

3.3. Land occupation in flood extent

The 100-year flood extent represents 4.1 % of the total surface area of the three municipalities (2764.4 km^2). In Suipacha, the flood extent did not overlap with the urban zone, whereas in Mercedes and Luján, the flood extent overlapped the urban zone, covering 1.96 km^2 and 6.07 km^2, respectively. Table 4 shows the increase in impervious surface in the urban zone and flood extent.

The results exhibited a continuous increase in the impervious surface of Mercedes (from 4.13% in 1985 to 23.46% in 2015) and Luján urban zones, overlapped with the flood extent (from 30.81% in 1985 to 34.92% in 2015). We also detected that 79.0% of the surface in the upper Luján River basin remained pervious. Although an increase in impervious surfaces was detected in the rest of the study area, these showed a dispersed distribution and did not affect the internal structure of the hydrological system. In non-urban flood areas (107.45 km^2), pervious surfaces are represented by different types of land use involving agriculture and poultry production, among others.

4. Conclusions

The strategy of governments to solve the problem here exposed has been based on structural measures to prevent floods. However, floods seem to be more recurrent, having much more negative impacts. The situation in the Luján River basin has the same logics and evidences the lack of land use planning and policies to prevent the flood risk in the region. The integration between the hydrological analysis and the process of urbanization reveals that the increase in urban growth observed in the last period coincides with a period of low hydrological activity between 2005 and 2012. Such information may serve as a warning to urban land managers about preventing land occupation in flood-prone areas.

Declarations

Author contribution statement

Andrea Pamela Flores: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Leandro Giordano: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Carlos Alberto Ruggerio: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported by Universidad Nacional de General Sarmiento, Buenos Aires, Argentina as part of the project "Sustentabilidad hídrica en cuencas hidrológicas de la región metropolitana y el noreste de la provincia de Buenos Aires" (Code 30/2095).

Competing interest statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2020.e04517.

Acknowledgements

We would like to thank Professor Rubén Lombardo for the revision and contributions to the work.

References

Ameghino, F., 1984. Las secas y las inundaciones en la Provincia de Buenos Aires. Obras de retención y no obras de desagüe 1884-1984. Ministerio de Asuntos Agrarios. Provincia de Buenos Aires, La Plata.
Angel, S., Sheppard, S., Civco, D.L., Buckley, R., Chabaeva, A., Gitlin, L., Kraley, A., Parent, J., Perlin, M., 2005. The Dynamics of Global Urban Expansion, first ed. The World Bank, Washington D.C.
Angiuli, E., Trianni, G., 2014. Urban mapping in Landsat images based on normalized difference spectral vector. Geosci. Rem. Sens. Lett. IEEE 11, 661–665.
Barbier, J.L., Respighi, E., Etchichury, L., Moscardini, O., Zaballa, C., González, S., Torchia, N., Pallares, U., Clarembeaux, C., Manchiola, J.I., Fernández, S., Ferrari, C., Bonadé, A., Tomasini, D., Bottino, G., García, A., Martorell, A., Bruno, P., Remes, S., 2012. Documento País 2012 Riesgo de desastres en la Argentina.
Benza, M., Weeks, J.R., Stow, D.A., López-Carr, D., Clarke, K.C., 2016. A pattern-based definition of urban context using remote sensing and GIS. Remote Sens. Environ. 183, 250–264.
Bertoni, J.C., 2006. Inundaciones urbanas en Argentina, first ed. Editorial Científica Universitaria, Córdoba, Argentina.
Beven, K., 2012. Rainfall-Runoff Modelling: the Primer, second ed. Wiley-Blackwell, Chichister, UK.
Breiman, L., 2001. Random forests. Mach. Learn. 45, 5–32.
Breiman, L., Friedman, J., Stone, C.J., Olshen, R.A., 1984. Classification and regression trees. In: The Wadsworth and Brooks-Cole Statistics-Probability, first ed. Routledge, New York.
Breusch, T.S., Pagan, A.R., 1979. A simple test for heteroscedasticity and random coefficient variation. Econometrica 47, 1287.
Burges, C.J.C., 1998. A tutorial on support vector machines for pattern recognition. Data Min. Knowl. Discov. 2, 121–167.
Chalfen, M., Niemiec, A., 1986. Analytical and numerical solution of saint-venant equations. J. Hydrol. 86, 1–13.
Coron, L., Thirel, G., Delaigue, O., Perrin, C., Andréassian, V., 2017. The suite of lumped GR hydrological models in an R package. Environ. Model. Software 94, 166–171.
Crooks, S., Kay, A., Davies, H., Bell, V., 2014. From catchment to national scale rainfall-runoff modelling: demonstration of a hydrological modelling framework. Hydrology 1, 63–88.
Douben, K.-J., 2006. Characteristics of river floods and flooding: a global overview, 1985–2003. Irrigat. Drain. 55, S9–S21.
Eagleson, P.S., 1972. Dynamics of flood frequency. Water Resour. Res. 8, 878–898.
Elga, S., Bronders, J., Batelaan, O., 2015. Hydrological modelling of urbanized catchments: a review and future directions. J. Hydrol. 529, 62–81.
Estoque, R.C., Murayama, Y., 2015. Classification and change detection of built-up lands from Landsat-7 ETM+ and Landsat-8 OLI/TIRS imageries: a comparative assessment of various spectral indices. Ecol. Indicat. 56, 205–217.
Gao, F., de Colstoun, E.B., Ma, R., Weng, Q., Masek, J.G., Chen, J., Pan, Y., Song, C., 2012. Mapping impervious surface expansion using medium-resolution satellite image time series: a case study in the Yangtze River Delta, China. Int. J. Rem. Sens. 33, 7609–7628.
Gao, L., Tao, B., Miao, Y., Zhang, L., Song, X., Ren, W., He, L., Xu, X., 2019. A global dataset for economic losses of extreme hydrological events during 1960-2014. Water Resour. Res. 5165–5175.
Giordano, L., 2014. Elaboración, calibración y verificación de un modelo hidrológico, agregado y continuo, sobre la base de información hidrológica provista mediante Teledetección. Presented at the Actas Congreso Internacional de Hidrología de Grandes Llanuras, Santa Fe, Argentina.
González, S., 2006. O planejamento urbano e a construção do risco por inundações na cidade de Buenos Aires. In: Alessandri Carlos, A.F. (Ed.), Geografias Das Metrópoles. Contexto, San Pablo, Brasil, pp. 467–484.
Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google earth engine: planetary-scale geospatial analysis for everyone. Remote Sens. Environ. 202, 18–27.
Guindon, B., Zhang, Y., Dillabaugh, C., 2004. Landsat urban mapping based on a combined spectral–spatial methodology. Remote Sens. Environ. 92, 218–232.
Hollis, G.E., 1975. The effect of urbanization on floods of different recurrence interval. Water Resour. Res. 11, 431–435.
INA, 2014. Estudio de Inundabilidad del Conurbano Bonaerense. Informe de Diagnóstico. Cuencas Arroyos Luján, Sarandí, Santo Domingo, Jiménez y Las Conchitas. Instituto Nacional del Agua, Laboratorio de Hidráulica.
INDEC, n.d. Censo Nacional de Población, Hogares y Vivienda de 2010. URL https://redatam.indec.gob.ar/argbin/RpWebEngine.exe/PortalAction?&MODE=MAIN&BASE=CPV2010B&MAIN=WebServerMain.inl&_ga=2.41599207.452715235.1528478382-1678520482.1528478382.
Jiang, M., Tian, S., Zheng, Z., Zhan, Q., He, Y., 2017. Human activity influences on vegetation cover changes in Beijing, China, from 2000 to 2015. Rem. Sens. 9, 271.
Kantakumar, L.N., Kumar, S., Schneider, K., 2016. Spatiotemporal urban expansion in Pune metropolis, India using remote sensing. Habitat Int. 51, 11–22.
Kruse, E., Zimmermann, E., 2002. Hidrogeología de Grandes Llanuras: particularidades en la Llanura Pampeana (Argentina). In: Presented at the Groundwater and Human Development. IAHS Congress), Mar del Plata, Argentina.

Kundzewicz, Z., 2001. Non-structural flood protection and sustainability. In: Simonovic, S.P. (Ed.), Non Structural Meassures for Water Management Problems. PHI-UNESCO, pp. 8–27.
Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G.R., Kron, W., Benito, G., Honda, Y., Takahashi, K., Sherstyukov, B., 2014. Flood risk and climate change: global and regional perspectives. Hydrol. Sci. J. 59, 1–28.
Kundzewicz, Z.W., Pińskwar, I., Brakenridge, G.R., 2013. Large floods in europe, 1985–2009. Hydrol. Sci. J. 58, 1–7.
Lindón, A., 1989. La problemática de las inundaciones en áreas urbanas como proceso de ocupación, un enfoque espacio-temporal. El caso de la ciudad de Buenos Aires. In: Actas Encuentro de Geógrafos de América Latina.
Liu, H., Wang, H., Liu, S., Hu, C., Ding, Y., Zhang, J., 2015. Lattice Boltzmann method for the Saint-Venant equations. J. Hydrol 524, 411–416.
Luo, J., Du, P., Alim, S., Xie, X., Xue, Z., 2014. Annual Landsat Analysis of Urban Growth of Nanjing City from 1980 to 2013. In: 2014 Third International Workshop on Earth Observation and Remote Sensing Applications (EORSA). Presented at the 2014 Third International Workshop on Earth Observation and Remote Sensing Applications. EORSA), pp. 357–361.
MacLachlan, A., Biggs, E., Roberts, G., Boruff, B., 2017. Urban growth dynamics in perth, Western Australia: using applied remote sensing for sustainable future planning. Land 6, 9.
Miller, R.B., Small, C., 2003. Cities from space: potential applications of remote sensing in urban environmental research and policy. Environ. Sci. Pol. 6, 129–137.
Minciardi, R., Sacile, R., Taramasso, A.C., Trasforini, E., Traverso, S., 2006. Modeling the vulnerability of complex territorial systems: an application to hydrological risk. Environ. Model. Software 21, 949–960.
Moussa, R., Bocquillon, C., 1996. Criteria for the coice of flood-routing methods in natural channels. J. Hydrol. 186, 1–30.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I: a discussion of pinciples. J. Hydrol. 10, 282–290.
Pascale, S., Giosa, L., Sdao, F., Sole, A., 2009. Assessment of Systemic Vulnerability in Flood Prone Areas, pp. 933–942.
Patel, N.N., Angiuli, E., Gamba, P., Gaughan, A., Lisini, G., Stevens, F.R., Tatem, A.J., Trianni, G., 2015. Multitemporal settlement and population mapping from Landsat using Google earth engine. Int. J. Appl. Earth Obs. Geoinf. 35, 199–208.
Perrin, C., Michel, C., Andréassian, V., 2003. Improvement of a parsimonious model for streamflow simulation. J. Hydrol. 279, 275–289.
Reyna, J., Spalletti, P., Brea, J.D., 2007. Riesgo de inundaciones en el Río Luján. Presented at the Tercer Simposio Regional sobre Hidráulica de Ríos, Córdoba, Argentina, p. 13.
Reynolds, R., Liang, L., Li, X., Dennis, J., 2017. Monitoring annual urban changes in a rapidly growing portion of northwest Arkansas with a 20-year Landsat record. Rem. Sens. 9, 71.
Ridd, M.K., Liu, J., 1998. A comparison of four algorithms for change detection in an urban environment. Remote Sens. Environ. 63, 95–100.
Sánchez Caro, A., Bianchi, J.F., 2014. Modelación hidrológica a paso diario de la cuenca del río Luján, Provincia de Buenos Aires. Actas del IIdo Encuentro de Investigadores en Formación en Recursos Hídricos.
Schneider, A., 2012. Monitoring land cover change in urban and peri-urban areas using dense time stacks of Landsat satellite data and a data mining approach. Remote Sens. Environ. 124, 689–704.
Shahtahmassebi, A.R., Song, J., Zheng, Q., Blackburn, G.A., Wang, K., Huang, L.Y., Pan, Y., Moore, N., Shahtahmassebi, G., Sadrabadi Haghighi, R., Deng, J.S., 2016. Remote sensing of impervious surface growth: a framework for quantifying urban expansion and re-densification mechanisms. Int. J. Appl. Earth Obs. Geoinf. 46, 94–112.
Shi, Y., Wu, J., Shi, S., 2017. Study of the simulated expansion boundary of construction land in shanghai based on a SLEUTH model. Sustainability 9, 876.
SMN, 2013. Características meteorológicas del evento de precipitaciones intensas ocurridas el 2 de Abril de 2013 en La Plata. Servicio Meteorológico Nacional, Buenos Aires.
Song, X.-P., Sexton, J.O., Huang, C., Channan, S., Townshend, J.R., 2016. Characterizing the magnitude, timing and duration of urban growth from time series of Landsat-based estimates of impervious cover. Remote Sens. Environ. 175, 1–13.
Svetlana, D., Radovan, D., Ján, D., 2015. The economic impact of floods and their importance in different regions of the world with emphasis on europe. Proc. Econ. Finance 34, 649–655.
Takeuchi, W., 2001. Flood management in Japan - from rivers to basin. In: Simonovic, S.P. (Ed.), Non Structural Meassures for Water Management Problems. PHI-UNESCO, pp. 37–44.
Taubenböck, H., Esch, T., Felbier, A., Wiesner, M., Roth, A., Dech, S., 2012. Monitoring urbanization in mega cities from space. Remote Sens. Environ. 117, 162–176.
Tucci, C., 2005. Gestión de inundaciones urbanas, first ed. Global Water Partnership, Porto Alegre, Brasil.
UNIDSR, 2016. Report of the Open-Ended Intergovernmental Expert Working Group on Indicators and Terminology Relating to Disaster Risk Reduction (No. A/71/644), Sustainable Development: Disaster Risk Reduction. General Assembly United Nations.
UNLP, 2013. Estudio sobre la Inundación ocurrida los días 2 y 3 de abril de 2013 en las ciudades de La Plata, Ensenada y Berisso. Universidad Nacional de La Plata (UNLP), Facultad de Ingeniería, Departamento de Hidráulica., Buenos Aires.
Valverde, A., 2017. Inundaciones, vulnerabilidad social y participación ciudadana en la gestión del riesgo. La cuenca superior del río Luján como caso de estudio (Bs. As., Argentina). In: Presented at the XII Jornadas Cuyanas de Geografía: Huellas y Perspectivas., Mendoza, Argentina.
Vogel, R.M., Yaindl, C., Walter, M., 2011. Nonstationarity: flood magnification and recurrence reduction factors in the United States1: nonstationarity: flood magnification and recurrence reduction factors in the United States. J. Am. Water Resour. Assoc. 47, 464–474.
Zhang, L., Wei, Y., Meng, R., 2017. Spatiotemporal dynamics and spatial determinants of urban growth in suzhou, China. Sustainability 9, 393.