Hydrological consequences of land use changes on a dammed urban basin

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Abstract

Anthropic interventions on a territory tend to affect the hydrological dynamics and the surface runoff process. This work was aimed to analyse the spatial and temporal changes in land use and land cover (LULC) as well as their incidence on surface runoff in Lago del Fuerte reservoir basin (Argentina). This basin is located in the main tourist area of the region. In recent years it has experienced a significant population increase, which has not been accompanied by water and sewer services and lacks territorial planning. This situation can alter the hydrological dynamics of the lake's contribution basin and of the reservoir itself. Geographic Information Systems tools were used for the morphometric characterization of the basin, LULC mapping, and for the identification of the hydrological soil groups. Curve Number (CN) method was applied to estimate the surface runoff for the years 2003 and 2020. Rock outcrops (30%) remained unchanged. In 2003, brush-forbs-grass dominated (30%), followed by grassland (12%), and open spaces (8%). However, grassland and open spaces were the most affected LULC by 2020, because their areas were partially replaced by high (7%) and low density (2%) residential uses. The study evidenced that replacement of vegetation by urbanisation increased the CN values, while CN decreased in renatured lands. Therefore, the average CN values in the basin were similar due to the compensation between zones. This work contributes to the integrated water resource management of the basin in order to protect its environmental quality and the functionality of the reservoir.

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Introduction

Land use has generally been considered as a local environmental issue, but it is becoming a force of global importance (Foley et al. 2005). Rates of deforestation, agriculturalization, urbanisation, wetlands drainage, and several other types of land use changes have accelerated as a function of the growth of human populations and economic development (Eshleman 2004).

Land use and land cover (LULC) changes strongly affect catchment hydrology. Additionally, studies have also demonstrated that the environmental effects of LULC changes have potentially large impacts on hydrologic processes such as sediment load and nutrient concentration, evapotranspiration, groundwater recharge, base flow, and runoff (Aghsaei et al. 2020; De Oliveira Serrão et al. 2022).

The factors that influence surface runoff in a basin are many and varied and can be classified into two general

groups: natural characteristics and anthropic interventions. The first group involves shape and extension of the basin, geology, morphology, slope, depth of the water table, vegetation cover, and previous humidity of soil (Davis and De Wiest 1971). The second group of factors involves streets, hydraulic works, urbanisation, and landscape alteration for agriculture, among others. Urbanisation and other anthropic interventions tend to increase surface runoff by creating more impermeable surfaces. The opening of streets as well as the changes in land use to less dense vegetation cover change the dynamics of runoff and increase their volume (Shuster et al. 2005). According to Foley et al. (2005), the surface runoff and river discharge generally increase when natural vegetation (especially forest) is cleared. The lack of planning regarding the use and occupation of basins increases the problems of water availability and demand, as well as its quality (Barbosa et al. 2019). Therefore, an assessment of the impacts of anthropogenic LULC alteration on hydrology is crucial for sustainable river basin management (Woldesenbet et al. 2017; Aghsaei et al. 2020).

The study of the morphometric parameters of a basin, namely shape, relief and drainage, allows for a correct and broader interpretation of the general functioning of the hydrological system. In addition, knowledge of runoff processes is essential to respond to environmental problems such as water erosion and floods. Both issues are key elements when considering the planning of land use and an integrated management of water resources. In this respect, one of the most widely used methodologies to study changes in hydrological processes caused by human activities is the Curve Number method (CN) (Guo et al. 2019).

The study area is hilly and consists of the upper zone of a drainage basin. In order to prevent flooding in nearby areas, resulting from the rapid and abundant concentration of rainfall, a dam was built at the mouth of Lago del Fuerte basin (Ruiz de Galarreta et al. 2010). Over time, the area has become a site of commercial, urban, and tourist interest, thus turning into one of the main expansion areas of Tandil city.

Lago del Fuerte is one of the main tourist attractions of the region. In recent years, the area near the lake has experienced a significant population increase, mainly due to the growth of residential land use and the settlement of tourist-recreational enterprises (Rodríguez 2014). However, this growth has not been accompanied by water and sewer services, except in one small sector of the basin, nor by a comprehensive territorial planning, generating impacts on the dynamics of the basin and associated environmental problems (Rodríguez et al. 2013; Guerrero et al. 2015; Cifuentes et al. 2022a).

As mentioned above, urban growth and its associated interventions, such as changes in land use and cover, tend

to increase surface runoff by creating more impermeable surfaces. This situation can alter the dynamics of the water resources of the lake's contribution basin and of the reservoir itself. Therefore, without proper planning and management of LULC, the reservoir's responsiveness could be compromised, further exacerbated by the accumulation of sediments (Rodríguez et al. 2008; Cifuentes 2020; Cifuentes et al. 2022b).

Several researches about the study area have been carried out, especially on the lake basin, which described and characterised the hydrogeology of the area (CINEA 2009) as well as the changes in land use and urban expansion and their associated environmental impacts (Ulberich 2007; Miranda del Fresno and Ulberich 2010, 2011; Rodríguez 2014). Creparula (2006) focused on the relationships between land uses and diatom algae communities in one of the lake sub-basins while Bogetti (2015) carried out an environmental diagnosis of the dynamics and quality of water in the two contributing streams of the reservoir. La Macchia (2014) conducted a modelling of urban drainage in the city of Tandil which includes the area of study as the head basin. Other studies on Lago del Fuerte reservoir focused on water quality and eutrophic level (IHLLA 1995; 2005a, 2005b; Albornoz et al. 2009; Cifuentes 2012; 2020), bathymetry and sediment volume (Rodríguez et al. 2008), nutrient balance, especially phosphorus, and phytoplankton (Cifuentes 2020) and ichthyological characters (Grosman 1999; Berasain and Padín 2014; Bertora et al. 2016).

Although there are studies that have applied GIS tools for the analysis of changes in land use and land cover and their implications for surface runoff in the region (Gaspari and Bruno 2003; Vagaría et al. 2012; Delgado et al. 2013, 2020; Senisterra et al. 2015), this has not been developed in Lago del Fuerte basin. Furthermore, there are some studies by the working group in the area (Rodriguez 2014; Cifuentes 2020; Cifuentes et al. 2022a, b) which constitute partial advances because they have not jointly analysed the impact of territorial changes on surface runoff and the reservoir.

The objective of this study was to perform a spatial and temporal analysis of the changes in land use and land cover and their incidence on surface runoff in Lago del Fuerte basin (Tandil, Argentina). This work represents a contribution to environmental territory planning, and is useful for decision makers towards the integrated water resources management in a basin.
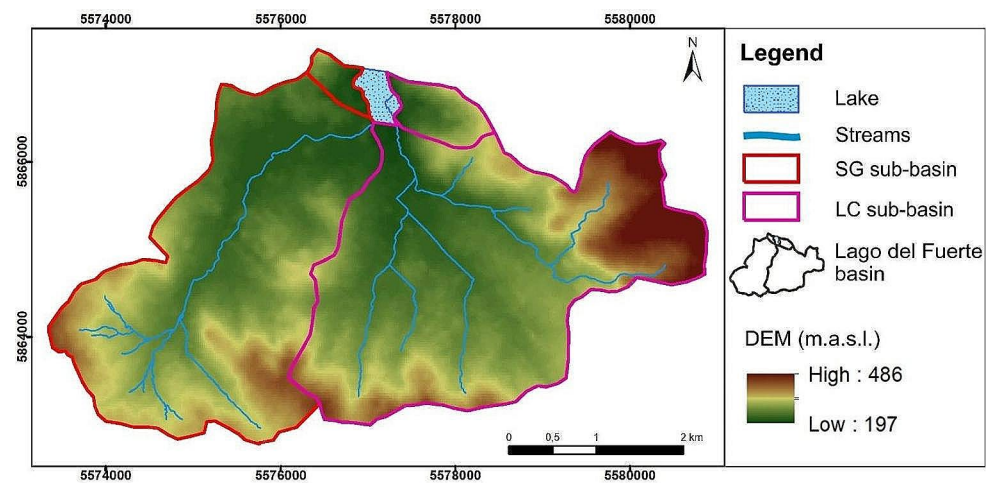
Study area

Lago del Fuerte basin (Fig. 1) is located on the North face of the Tandilia hilly system, at the South of Tandil city, in the South-East of Buenos Aires province (Argentina). It covers

Fig. 1 Location of Lago del Fuerte basin and the sub-basins San Gabriel and La Cascada
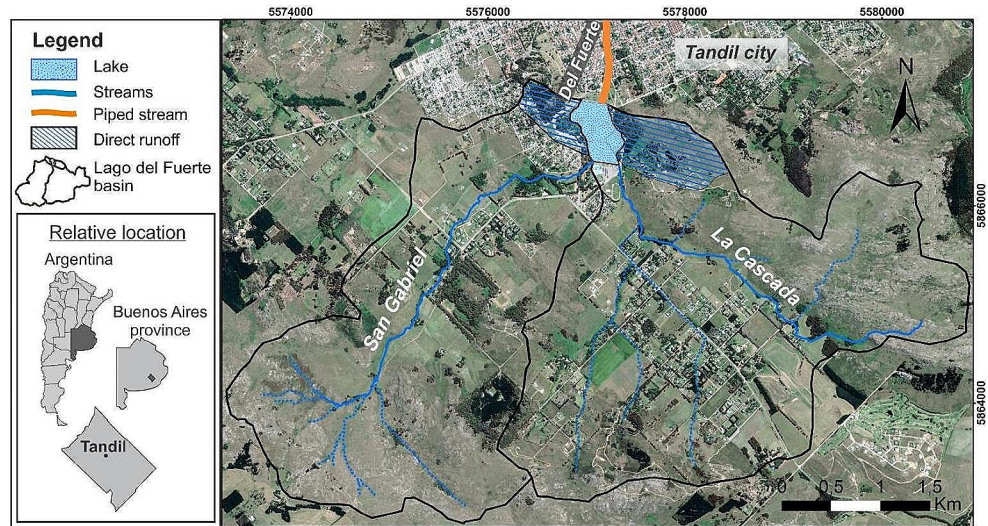
Fig. 2 Digital Elevation Model (DEM) of the study area

an area of 2,000 hectares and has a defined and integrated surface drainage. The direction of runoff is towards the North-East, according to the region slope (Ruiz de Galarreta et al. 2010).

The Tandilia system includes two geological units: the crystalline basement consisting of plutonic igneous rocks, and the sedimentary cover which includes Pampean sediments of the loessoid silt type (Teruggi and Kilmurray 1980).

Regarding the regional geomorphology, three morphological units are distinguished within the Tandilia system: mountains, piedmont, and plains (Ruiz de Galarreta 2006). The mountainous sector is characterised by pronounced relief, isolated hills, and valleys with the occurrence of faulted blocks. Watersheds are recognizable, and the valleys of the streams are well-defined. The study area is partially located in this geomorphological region, where the crystalline basement is shallow, and significant outcrops are observed in certain areas. The hills are followed by the piedmont with a gentler slope and the presence of large blocks

and alluvial cones. The flat zone has low slopes and extends towards the North-East. The elevation of the study ranged from 197 to 486 m above sea level (Fig. 2).

According to the geology and geomorphology of the region, the soils can be classified in three subregions. The first, corresponding to mountainous morphology, is characterised by rocky outcrops, surface stoniness, and areas with a thin layer of loess, where Lithic Hapludolls and Petrocalcic Hapludolls predominate. The piedmont subregion, which occupies the largest area of the watershed, includes hilly areas and small plain sectors, primarily represented by Typical Argiudolls. The third zone corresponds to the plain with the presence of Tapto Natric Hapludolls and Typical Natracuols (INTA 1989).

The region presents a typical subhumid-humid, mesothermal climate, with a low water deficit in summer (Ruiz de Galarreta et al. 2010). Tandil city had an annual average rainfall of 849 mm for the period 1900–2016. The precipitation is distributed as follows: 29.1% in summer, 27.8% in autumn, 26.7% in spring, and 16.4% in winter for the period

under consideration (Fig. 3). The month with the lowest average monthly precipitation is July (< 43 mm), while March experiences the highest precipitation levels (98 mm) (Cifuentes 2020).

Lago del Fuerte basin is composed of two sub-basins of San Gabriel (SG) and La Cascada (LC) streams (Fig. 1). Both streams flow into the Del Fuerte lake, which constitutes an artificial reservoir of 19 hectares originated by the construction of a dam aimed to regulate the floods that affected the city. The dam, called Dique del Fuerte, was built between 1957 and 1962 (Ruiz de Galarreta et al. 2010). From the exit of the dam, the water flows through Del Fuerte stream which crosses the city piped (Fig. 1).

The reservoir has two direct runoff zones on both East and West banks. Thus, surface water and groundwater drain directly into the lake instead of contributing to the streams (Fig. 1).

Materials and methods

Morphometric parameters

Calculations of the morphological features of Lago del Fuerte basin (shape, relief and drainage parameters) were developed, focusing on their influence on the surface runoff (Table 1). The Arc Hydro Tools extension for ArcGis (v 10.5) was used together with cartographic support for those calculations. This software has specialised tools for territorial, topological, and hydrological analysis.

Digital Elevation Models (DEM) provided by the Geological Service of the United States (USGS 2014), type SRTM 1 Arc-seg (spatial resolution of 30 m), were used, which were compared with the Topographic Chart Nº 3760-29-2 Sierras del Tandil, scale 1: 50.000 (IGN 1957). Direct observation was carried out in the field in order to identify

and solve inconsistencies between the DEM and the chart detected during the analysis of the sub-basins. The layers were georeferenced by a reference system based on the IGN Posiciones Geodésicas Argentinas network (POSGAR '07 zone 5), which uses a metric system.

### Curve number (CN) calculation

The Soil Conservation Service Curve Number method (CN; USDA, 1972) was used to estimate the runoff. CN is an empirical method useful for computing the transformation from rain into runoff according to the following properties: hydrologic soil type, use and soil treatment, surface condition of the soil, and moisture condition antecedent (Ponce 1989). CN ranges from 1 to 100, where higher values of CN refers to greater levels of runoff.

The CN method has been developed for more than 50 years and has been applied as well as reviewed in numerous research (Ponce and Hawkins 1996). According to Hawkins et al. (2009), the CN method has undergone a series of unavoidable adjustments, improvements, redefinitions and clarifications over the years. High positive correlations ($p \leq 0.05$) between the runoff estimated by the CN methodology and the observed values have validated the use of this methodology (Nonglait and Tiwari 2016).

CN method was applied for the years 2003 and 2020 on Lago del Fuerte basin to analyse and compare the surface runoff generated by a reference precipitation, according to the modifications of the land cover and land uses in the basin under study. The period was chosen for the availability of satellite images needed to identify the land use and land cover and also for the LULC changes evidenced in previous studies.

In order to calculate the CN, a HEC-GeoHMS extension for AcrGis was applied (Fleming and Doan 2003). Georeferenced vector shapes were carried out with the surveyed

Fig. 3 Average monthly precipitation and temperatures of Tandil city (1900–2016) (Cifuentes 2020)
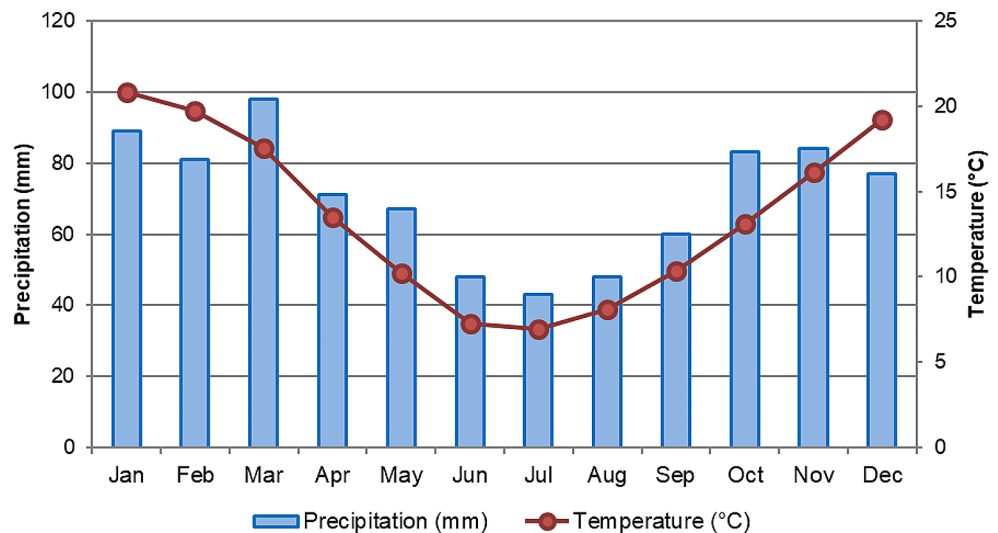
Table 1 Morphometric parameters for Lago del Fuerte basin. (Sources: Chow et al. 1994; Henaos 1988; Horton 1945; Kirpich 1940; López Cárdenas de Llano 1998; Llamas 1993; Patton 1988; Romero Díaz and López Bermúdez 1987; Schumm 1956; Strahler 1964)

Caracter	Morphometric parameters	Description
Shape	Area (A), Perimeter (P), 3D Perimeter (P_3D)	Basic characteristics of the polygon that forms the basins
	Axial Length (AL)	Distance between the water effluence and the furthest point in the basin
	Length of main course (L)	Distance from spring to main stream effluence
	Total length of drain (Ln)	Sum of the lengths of all the watercourses that drain through the basin
	Total sinuosity coefficient (S)	Relationship between real L and the length in a straight line or curve of the stream
	Average width (Aw)	Ratio A/Al
	Form Factor (IF)	It indicates how the concentration of surface runoff in the basin is regulated. Ratio Aw / Al
	Gravelius Coefficient (Kc)	It relates the perimeter of the basin with the perimeter of a theoretical circle of equivalent area to the basin
	Elongation ratio (Re)	Ratio between the diameter of a circle with equal area of the basin and the axial length (Al)
Relief	Hypsometric Curve	Graphic explaining maturity of the basin
	Slope map	Thematic mapping that expresses in % the slope for each pixel in the DEM
	Roughness coefficient (Ra)	It relates the slope of the basin and its drainage density (Dd)
	Slope orientation map	Thematic mapping that expresses the orientation (cardinal points) of the slope for each pixel of the DEM.
Drainage	Drainage classification	Stream order
	Drainage Density (Dd)	Ratio Ln / A of the basin
	Average slope of the stream	Slope in m / m or % of the main stream channel
	Concentration Time (Ct)	Theoretical time it would take for a drop of water from the furthest point in the basin to the point where it exits the basin
	Torrentiality Coefficient (Tc)	Ratio of the number of sections of order 1 of the stream and the total area of the basin

Fig. 4 Methodological steps for CN calculation
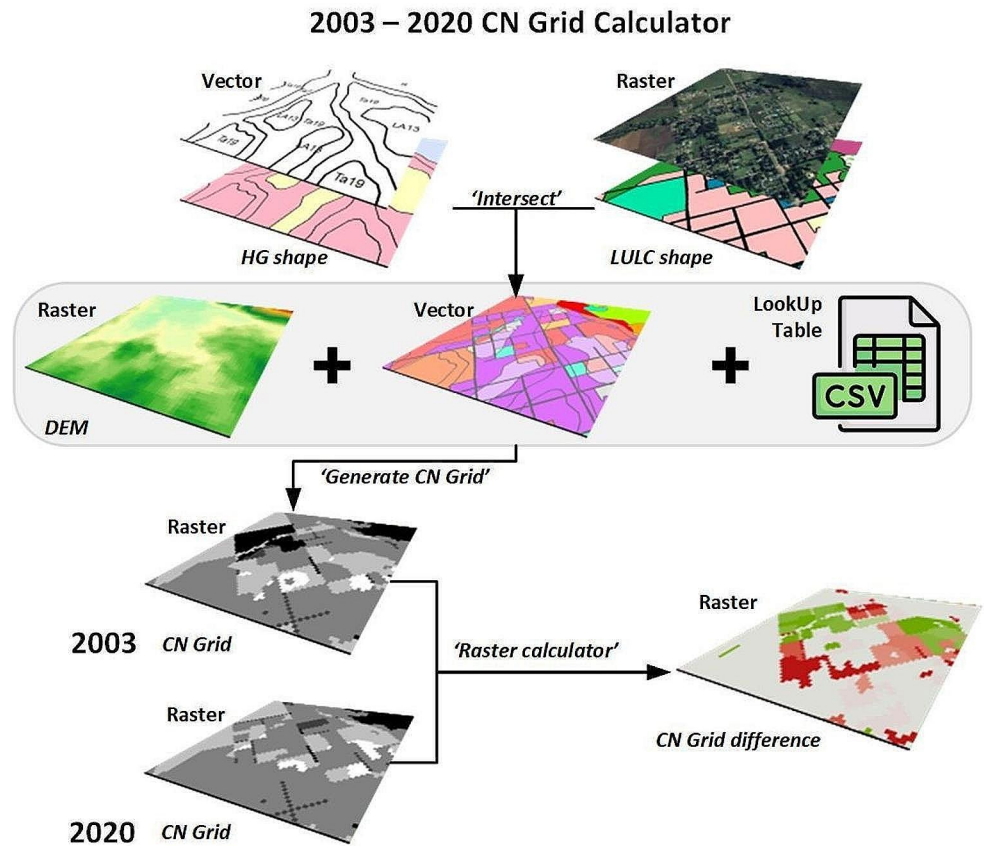
territorial information. The information layers developed were Hydrological Group (HG), land use and land cover (LULC), and digital elevation model (DEM) (Fig. 2):

a) Hydrological Group (HG). The CN method requires classifying soil types according to their permeability or infiltration capacity, in order to indicate their capacity for surface runoff. Thus, four hydrological soil groups were established (USDA 1972):

Group A: Soils with low potential for surface runoff. Water is easily transmitted in the edaphic profile. They are sandy or sandy-loamy soils.
Group B: Soils with a moderately low potential for runoff. Infiltration has no impediments. They are medium-depth sandy loam soils or deep loamy soils.
Group C: Soils with moderately high runoff. The permeability of the profile presents limitations or impediments. The texture has clay loam characteristics or with some impervious soil horizon.
Group D: Impervious soils with high surface runoff. The typical texture of this group is clay type, or with lithological characteristics that totally or partially restrict water infiltration in the event of events.
The edaphological characterization was carried out considering the Instituto Nacional de Tecnología Agropecuaria (INTA) Soil Chart Nº 3760-29-2 (Sierras del Tandil) and the elaboration of the textural triangle from the edaphic profile (Villaroya et al. 2013). The rocky outcrop in mountains was considered as areas with great restrictions to the infiltration of the water resource. Each type of soil was assigned to a HG according to its characteristics.

b) Land use and land cover (LULC). This research considered CN values as used by different authors who adapted them to land use and vegetation cover (Ponce 1989; Chow et al. 1994; Gaspari et al. 2013). Thus, a land use and land cover mapping was carried out using satellite images provided by Google Earth for the periods of May 2003 and June 2020. This process was complemented by field visits, photographic documentation, and georeferenced surveys, providing greater specificity and precision to the LULC maps. The minimum mapping area was 0.1 ha. Based on the data collected, 13 types of land use and land cover were identified. A CN value was assigned to each LULC according to their corresponding HG. Table 2 presents the description of each category.

c) Digital elevation model (DEM). The DEM was used to calculate morphometric parameters (Table 1). The layer provides elevation and slope information with a spatial resolution of 30 m.

The CN calculation was carried out by applying the 'Generate CN Grid' tool of the HEC-GeoHMS extension for ArcGis (Fleming and Doan 2003). A vector layer of polygons was created that 'intersected' (such as the GIS tool name) the surveyed territorial information with the HG shape. Each polygon of the new layer had a unique combination of land use and land cover and hydrological group. Slope percentages were calculated with the DEM, and related to the previously created vector layer.

The 'Generate CN Grid' tool assigned a previously established CN value for each polygon (Table 2), according to Ponce (1989), Chow et al. (1994) and Gaspari et al. (2013). As a result, a new column with CN data is added to the attribute table of the polygon layer and a raster layer was generated with CN information in each cell.

The differences between the CN values for the study years were estimated with the ArcGIS raster calculator.

Table 2 CN associated with each land use land cover and hydrological group. (Sources: Chow et al. 1994; Gaspari et al. 2013; Ponce 1989)

ID	Land use and land cover	Description	CN by Hydrological Group			
			A	B	C	D
1	Brush-forbs-grass	Low and herbaceous shrubs. With coverage > 75%	30	48	65	73
2	Meadow-continuous grass	Meadows and lawns without cattle, mowed periodically.	30	58	71	78
3	Pasture, grassland	Mountain pasture	39	61	74	80
4	Crops	Cultivated land. Small grain (wheat).	63	75	83	87
5	Rock	Granitic rock with faults and slope > 3%	94	94	94	94
6	Impervious surface	Impervious surface (except streets / circulation areas)	98	98	98	98
7	Woods	Trees and grass mixture	36	60	70	76
8	Asphalt street	Streets paved with ditch (gutters)	83	89	92	93
9	Dirt street	Unpaved, dirt streets	72	82	87	89
10	Residential low density	With an impervious area of 25% approximately	54	70	80	85
11	Residential high density	With an impervious area of 65% approximately	77	85	90	92
12	Open spaces	Low grass (lawn for homes, golf courses, etc.)	49	69	79	84
13	Fallow	Land without vegetation	77	86	91	94

The methodological steps for CN calculation are shown in Fig. 4.

The average value of CN for the basin was obtained from the following equation (Gaspari et al. 2013):

$$CN = \frac{1}{A}\sum_{i=1}^{n} A_i CN_i \tag{1}$$

where CN is the basin curve number, A is the basin area (m^2), Ai is the area of each land use and land cover polygon (m^2), CNi is the curve number for each land use and land cover polygon, and n is the number of polygons calculated.

A descriptive statistical analysis of the rasters generated by the geoprocessing analysis was carried out in order to characterise the mean value of CN calculated by sub-basin and the standard deviation. The 'Band Collection Statistics' tool, from the ArcGis spatial analysis tools, was used.

In order to represent the significance of the CN values obtained, the expected runoff calculation was performed in typical rainfall events of the region. The variation in the period 2003–2020 and the significance of the changes in land use land cover was analysed.

Typical events were selected from the regional study of Collazos and Cazenave (2015) who elaborated intensity, duration, and frequency curves (IDF) with correction coefficients for the center of Buenos Aires province, where the study area is located. Based on that work, it was considered rainfall lasting 60 min with return periods (T) of 5 and 25 years, which resulted in events of 49 mm and 63.6 mm respectively.

Equations 2 and 3 were applied to estimate surface runoff for both events (USDA 1986).

$$S = 254\left(\frac{100}{CN} - 1\right) \tag{2}$$

$$Q\,(mm) = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{3}$$

where CN is the basin curve number, S is the maximum possible retention, Q is the runoff flow (mm) and P is the precipitation (mm).

Results and discussion

Basin morphometric parameters

The Lago del Fuerte basin, with an area of 19.94 km^2, corresponds to the classification of a micro-basin (Campos Aranda 1992). In relation to the basin shape, the compactness coefficient (Kc = 1.51) indicates it is oblong (Gaspari et al. 2013). However, according to the shape index (If = 0.77) and the elongation ratio (Re = 0.99) the basin resulted in a rounded shape (Table 3). The elevation of the basin ranged between 197 and 486 m above sea level, with an average slope of 5.41%. The basin presented a smooth relief according to the classification by Ortiz Vera (2004).

In terms of drainage parameters, the hypsometric curve indicated that the basin presents an advanced stage of hydrologic evolution. The basin reached a maximum stream order of 4 following the ranking method by Strahler (1964). The density of the drainage (Dd = 1.24 km.km^{-2}) was between low and moderate (Fuentes Junco 2004), with a concentration time (Ct) of 45 min and a torrential coefficient (Tc) of 0.85 (Table 3).

In the field, modifications of the drainage networks as a result of anthropic actions were identified. The increasing expansion of residential land use and the subsequent opening of streets has caused alterations in the drainage of some transitory tributaries. The streams have been modified with respect to their original channel, thus increasing the values of stream order number and drainage density.

According to shape parameters, the basin presented an intermediate dangerous situation in case of high intensity rainfall events. In addition, the high number of first-order streams in the basin (17) generated a high torrential coefficient (Tc = 0.85), which implies a high susceptibility to erosion, a shorter time to reach the peak of flood and a greater

Table 3 Lago del Fuerte basin morphometric parameters

Morphometric variables	**Area**	**Perimeter**	**Al**	**Width**	**L**	**Ln**
	(km^2)	(km)	(km)	(km)	(km)	(km)
	19.94	23.68	5.08	3.93	6.10	24.78
Shape parameters coefficient	**Kc**	**If**	**Re**	**Rc**		
	1.51	0.77	0.99	0.44		
Relief parameters	**Max Height**	**Min Height**	**Dist.**	**Slope**	**Slope**	**Ra**
	(m.a.s.l)	(m.a.s.l)	(m)	(m/m)	(%)	
	298.94	197.00	101.94	0.05	5.41	232.50
Drainage parameters	**Order**	**Dd**	**Ct**	**Tc**		
	(nº)	(km.km^{-2})	(min)			
	4	1.24	45.53	0.85		

Fig. 5 Hydrological Groups in Lago del Fuerte basin
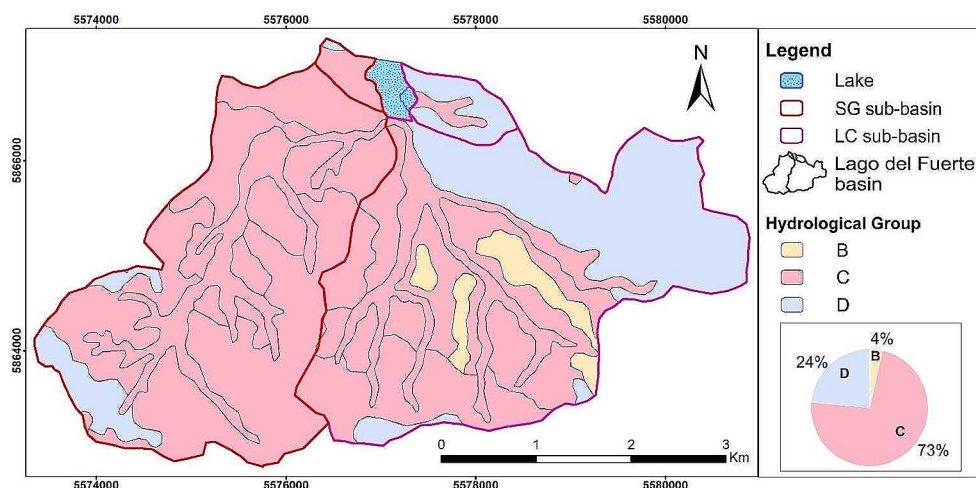
Table 4 Land uses and land cover areas for 2003 and 2020

Land use and land cover	2003	2020	Variation
	(ha)	(ha)	(%)
Residential low density	123	263	7.0%
Residential high density	1	41	2.0%
Fallow	31	4	-1.4%
Asphalt street	7	7	0.0%
Dirt street	20	26	0.3%
Impervious surface	7	7	0.0%
Crops	46	7	-2.0%
Meadow-continuous grass	28	28	0.0%
Woods	128	127	0.0%
Open space	167	99	-3.4%
Pasture, grassland	241	200	-2.0%
Brush-forbs-grass	594	585	-0.5%
Rock	600	600	0.0%

generation of torrential flows (Busnelli and Horta 2014). These conditions motivated the construction of the dam in 1962.

Hydrological groups (HG) of the basin

Three hydrological groups (HG) of soils were identified in the basin (Fig. 5): Group B (71 ha.), Group C (1454 ha.), and Group D (469 ha.). HG C had the largest area covering 73% of the basin. Four main soil series were identified in this group: Sierra de los Padres (SP6), Tandil (Ta19), Tandil (Ta7), and Tres Esquinas (TEs3). These series present, respectively, Lithic Hapludol, typical Argiudol, typical Argiudol, and vertic Argiudol as main soil taxonomy (INTA 1989).

The second largest HG was D covering 24% of the area. It is entirely composed of the Rock (R) series. HG B was the smallest group with 4%. It is formed by La Alianza (La13) soil series which present a superficial petrocalcic Paleudol as its main taxonomy (INTA 1989).

In SG predominated by far the HG C (94%) followed by the HG D (6%) and there was no presence of HG B. In the LC basin the three HG were found with 7% for B, 58% for C and 35% for D.

Changes in land uses and land covers

Table 4; Fig. 6 show the thirteen identified land uses and land cover (LULC) areas and the variations for the study period.

Figure 7 shows the covered area (%) for each use and land cover identified with respect to the total area of the basin for the years 2003 and 2020 and their temporal variation. Approximately 30% of the study area had rocky outcrops which remained unchanged during the study period. Brush-forbs-grass was the most predominant coverage in 2003 (30%), followed by grassland (12%), and open spaces (8%). However, grassland and open spaces were the most affected LULC; their areas were reduced by 2020 because of the partial replacement by growing high and low density residential uses, with 7% and 2%, respectively. The crop land use was in general low, covering around 2% for 2003 with a reduction of the surface by 2020.

These results are consistent with other works carried out on the basin. Ulberich (2007) analysed the changes in land use in the period 1973–2006 in a region which includes part of the study area and evidenced a growth of the residential land use, an increase in the concentration of buildings, and a replacement of the crops by buildings for residential and recreational use.

Rodríguez (2014) analysed the changes in land use within the LC sub-basin and found that, from 2003 to 2013, the variations were characterised especially by the increase in residential, tourist-commercial, livestock, and not-defined uses, while farming use presented the highest decrease.

Fig. 6 Land uses and land covers in Lago del Fuerte basin for 2003 and 2020
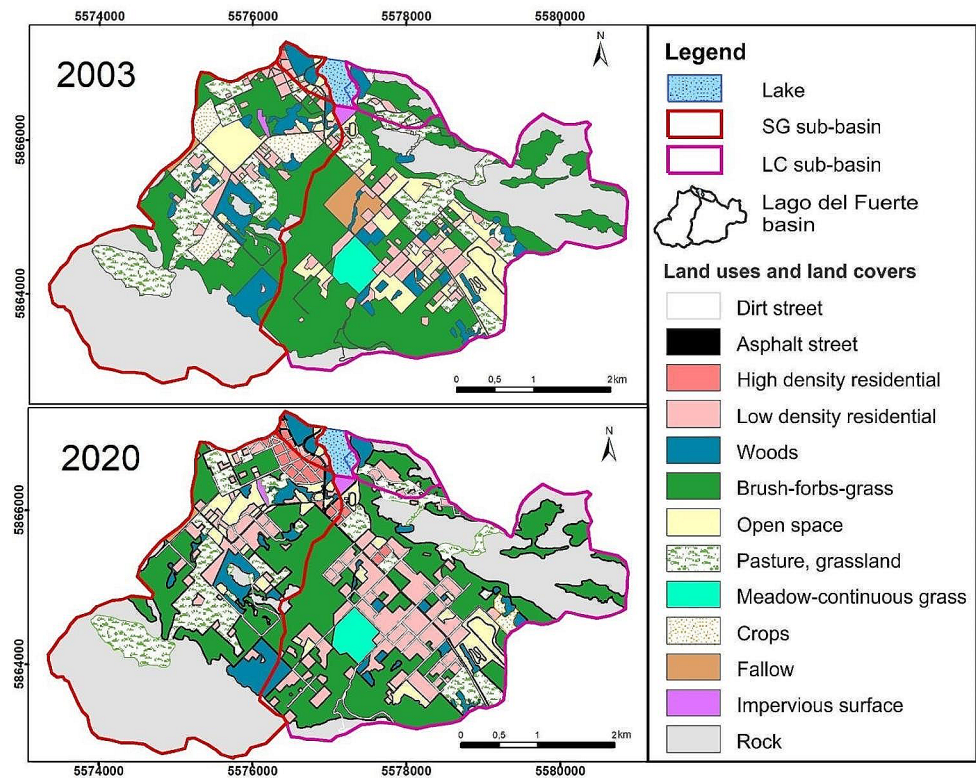
Fig. 7 Occupation and temporal variations of the land use and cover in the study area for the years 2003 and 2020
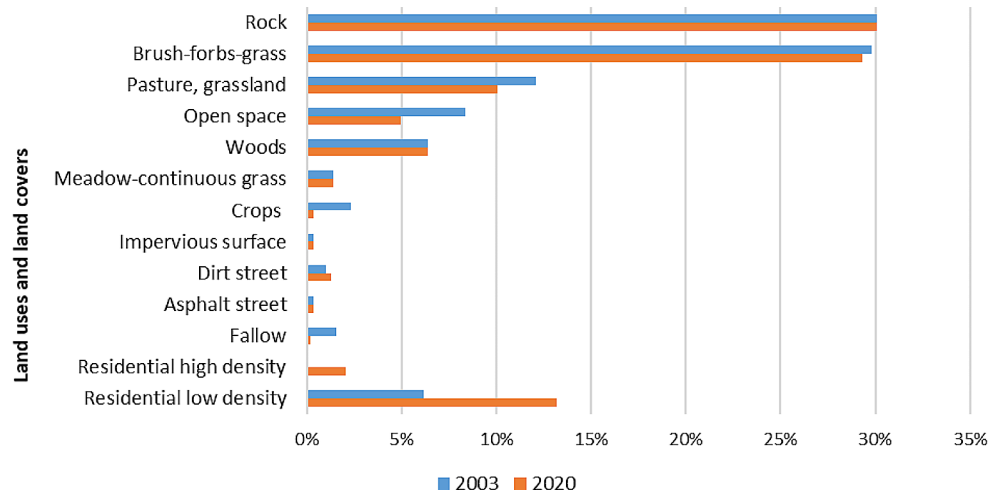

Curve number (CN) identification and analysis

Curve Number (CN) maps showed values from 48 to 98. These results were grouped into categories and showed, according to their colour, areas with similar runoff conditions (Fig. 8).

The average CN estimated for the Lago del Fuerte basin was 79 for the year 2003 and 79.2 for 2020. This estimation showed that, although there was no perceptible variation in the mean value of the CN, the general conditions of the basin tends to favour runoff processes over infiltration.

Although the temporal variation between the average CN values in each sub-basin was not considerable, the analysis of each direct runoff zone (Fig. 1) showed great diversity of results. Thus, while for the direct runoff zone of the LC sub-basin the CN ranged from 79.6 to 80.6, in the direct runoff zone of the SG sub-basin it varied from 76.5 for 2003 to 78.9 for 2020 (Table 5).

Figure 9 shows the difference of CN values in the study period. Some areas of the basin had lower CN values in the year 2020, while other areas showed higher values (Table 2). The decrease in CN values was generally associated with

Fig. 8 CN maps for Lago del Fuerte basin in 2003 and 2020
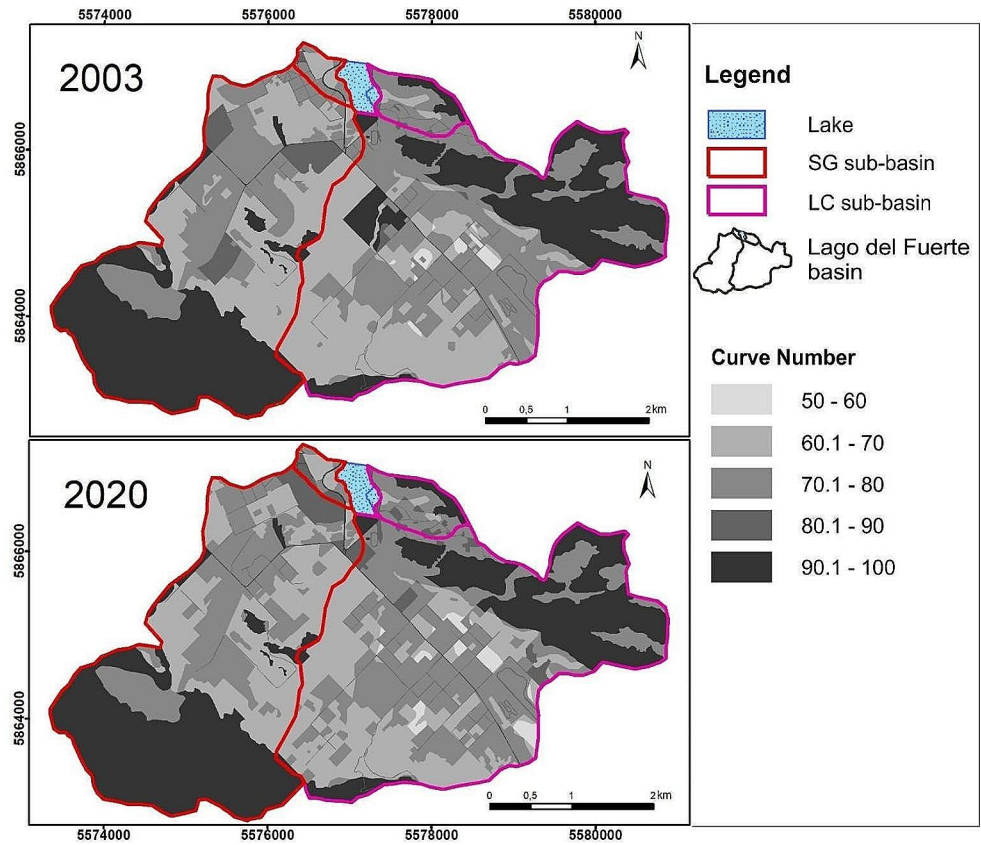
Fig. 9 CN variation in Lago del Fuerte basin between 2003 and 2020
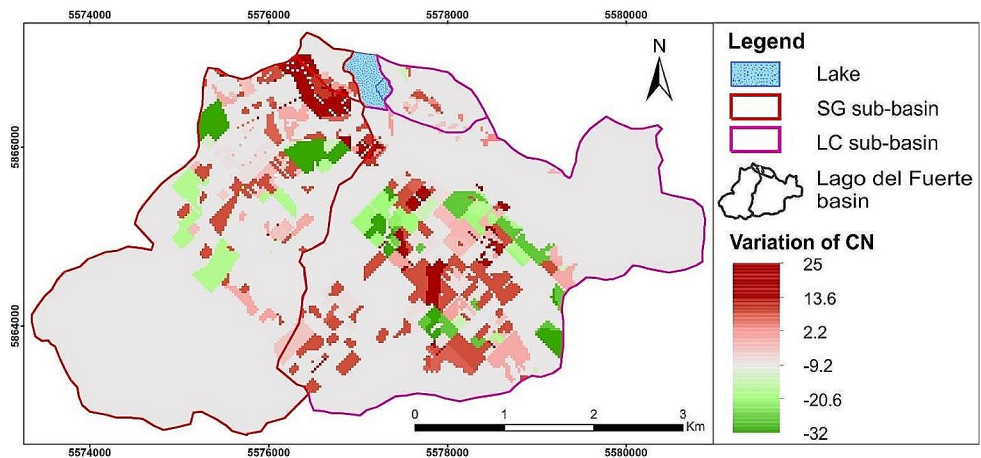
stopping a use or an activity such as crops and with the renaturalization of an area. Thus, there is a successional growth of the natural vegetation species which would allow greater infiltration. However, there was also a decrease in the CN when moving from fallow to low-density residential since the former is associated with bare soil, while in the second, an open area is always allocated with some kind of cover. Furthermore, the increase of the CN values occurred in areas where residential use was intensified, but especially when an area was transformed from scrub vegetation or grassland to urban use.

While, in general, changes in land use and land cover tend to increase CN values, there are studies in which decreases are recorded, as occurred in the present research. Havrylenko et al. (2006) identified a seasonal decrease in CN values depending on land use and land cover in the Arrecifes River basin (Buenos Aires, Argentina). The highest CN values occurred in spring where 49% of the surface had bare soils while in summer with 92% of the surface covered by crops the CN values were lower. In addition, De Antueno et al. (2020) and Bottan et al. (2023) showed a decrease in CN values due to changes in land use that applied conservation

improvements in agricultural activities, thus favouring infiltration in the upper basin of the Sauce Chico River (Buenos Aires, Argentina).

The analysis of CN values shows averages with high standard deviation values, which indicates a significant amplitude in the CN values throughout the sub-basins. These results are consistent with Gallegos Reina and Perles Roselló (2019) who worked in Malaga province, Spain. They affirmed that, although the values of the runoff threshold remained practically the same during a study period of 50 years, these moderate differences were the result of a regional compensation and masked the reality of intense changes that took place in certain areas where the differences are higher.

Main areas with notable variations in CN values were identified. In SG sub-basin these areas are coincident with a residential area that changed from low to high density. While in LC sub-basin the changes primarily occured along the route of a main street, where both residential and tourist-recreational buildings have been constructed.

However, the differences are compensated due to the areas in which agricultural activity was stopped and their subsequent renaturalization in both sub-basins.

Table 5 shows the transformation of the CN to surface runoff, according to the typical precipitation considered for the region. As a result, large variations are homogenized and offset along the sub-basins.

However, a significant variation in surface runoff can be observed in the areas of direct contribution with a smaller surface. In both events of T = 5 and T = 25 years, an increase in the range of 4.6% and 2.2% was observed in the percentage of surface runoff from San Gabriel and La Cascada basins, respectively.

The increase in the direct runoff zone could accentuate soil erosion processes and, therefore, a greater accumulation of sediments in Lago del Fuerte, thus reducing its efficiency in water regulation and increasing nutrient inputs.

These results regarding changes in land use and land cover and their connection to surface runoff constitute the first precedent in the Lago del Fuerte basin and serve as a starting point for future research.

Conclusions

This work consisted of a comprehensive hydrological characterization of Lago del Fuerte basin and its tributaries, considering the morphometry of the basin, the LULC changes and the surface runoff analysis. An intermediate dangerous situation in case of a flood event was identified.

Spatial and temporal changes in land uses and covers were identified. CN values increased mainly due to both replacement of green areas by urbanised ones and an increase in urbanisation density. Inversely, CN values decreased when a use or activity stopped and consequently the area is renaturalized.

While CN values varied widely in each sub-basin, the average CN value, and therefore the surface runoff value, did not show great variations at the total basin level, which is explained by a compensation between areas where the CN increased and those where it decreased.

It is highlighted the need to assess the progress of land use and modification as well as possible impacts. If the trend

Table 5 Estimated runoff according to CN in each sub-basin and direct runoff zones

San Gabriel sub-basin				La Cascada sub-basin			
Area (ha)		884.6		**Area (ha)**		1022.0	
Year		**2003**	**2020**	**Year**		**2003**	**2020**
CN		80.95	81.03	**CN**		77.33	77.58
S		59.78	59.45	**S**		74.48	73.42
T = 5	**runoff (mm)**	14.19	14.28	**T = 5**	**runoff (mm)**	10.73	10.95
49.0 mm	**runoff/Pp (%)**	28.9%	29.1%	49.0 mm	**runoff/Pp (%)**	21.9%	22.3%
T = 25	**runoff (mm)**	23.91	24.03	**T = 25**	**runoff (mm)**	23.91	24.03
63.6 mm	**runoff/Pp (%)**	37.6%	37.8%	63.6 mm	**runoff/Pp (%)**	37.6%	37.8%
San Gabriel direct runoff zone				La Cascada direct runoff zone			
Area (ha)		26.6		**Area (ha)**		60.7	
Year		**2003**	**2020**	**Year**		**2003**	**2020**
CN		76.45	78.85	**CN**		79.56	80.62
S		78.24	68.12	**S**		65.26	61.08
T = 5	**runoff (mm)**	9.9	12.11	**T = 5**	**runoff (mm)**	12.79	13.85
49.0 mm	**runoff/Pp (%)**	20.4%	24.7%	49.0 mm	**runoff/Pp (%)**	26.1%	28.2%
T = 25	**runoff (mm)**	18.20	21.13	**T = 25**	**runoff (mm)**	22.04	23.45
63.6 mm	**runoff/Pp (%)**	28.6%	33.2%	63.6 mm	**runoff/Pp (%)**	34.7%	36.9%

*S = Maximum possible retention

**T = Return period

of population growth and urban-touristic development in the basin continues, together with its morphometric characteristics, the surface runoff could increase and affect the functionality of the reservoir.

This work is expected to contribute to the analysis of the integrated water resource management of the basin in order to protect its environmental quality and the functionality of the reservoir. This information is essential for the monitoring, control, and management of surface and groundwater resources in the basin and particularly for the reservoir maintenance and usefulness.

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Declarations

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References

Aghsaei H, Dinan NM, Moridi A, Asadolahi Z, Delavar M, Fohrer N, Wagner PD (2020) Effects of dynamic land use/land cover change on water resources and sediment yield in the Anzali wetland catchment, Gilan, Iran. Sci Total Environ 712:136449. https://doi.org/10.1016/j.scitotenv.2019.136449

Albornoz H, González Castelain J, Cifuentes MR, Rodríguez L (2009) Estado trófico Y monitoreo de variables limnológicas en un lago artificial (Lago Del Fuerte, Tandil, Prov. De Buenos Aires). Biología Acuática 26:1–6

Barbosa JDS, Bellotto VR, da Silva DB, Lima TB (2019) Nitrogen and phosphorus budget for a deep tropical reservoir of the Brazilian Savannah. Water 11(6):1205. https://doi.org/10.3390/w11061205

Berasain G, Padín D (2014) Campaña De Relevamientos limnológicos e ictiológicos: Lago Del Fuerte, Ciudad De Tandil. Ministerio de Asuntos Agrarios, La Plata

Bertora A, Grosman F, Sanzano P (2016) La Comunidad De peces de la cuenca alta del arroyo Langueyú. I Jornadas Internacionales y III Nacionales de Ambiente. Tandil

Bogetti L (2015) Diagnóstico ambiental de la Cuenca Superior del Arroyo Langueyú. Unpublished thesis. Universidad Nacional del Centro de la Provincia de Buenos Aires

Bottan L, Delgado MI, Gaspari FJ (2023) Análisis de la respuesta hidrológica de una cuenca serrana bonaerense ante diferentes eventos pluviales y cambio de uso del suelo. In XVII Encuentro del Centro Internacional de Ciencias de la Tierra (E-ICES 17) (Mendoza, modalidad virtual, 1 al 4 de noviembre de 2022)

Busnelli J, Horta LR (2014) Morfometría De Cuencas montañas y metamorfosis fluvial, Tucumán. Revista De La Asociación Geológica Argentina. Buenos Aires: Asociación Geológica Argentina 71(1):11–20

Campos Aranda D (1992) Procesos del Ciclo Hidrológico. 2da reimpresión. UASLP-Facultad de Ingeniería, México

Chow VT, Maidment DR, Mays L (1994) Hidrología Aplicada. Ediciones McGraw-Hill, Colombia

Cifuentes MR (2012) Algas cianofitas y aptitud recreativa del Lago del Fuerte (Partido de Tandil). Unpublished thesis. Universidad Nacional del Centro de la Provincia de Buenos Aires

Cifuentes MR (2020) Estudio ecohidrológico del embalse eutrófico Lago del Fuerte (Tandil, provincia de Buenos Aires). Thesis (PhD). Universidad Nacional de La Plata

Cifuentes MR, Jacinto GP, Rodríguez CI (2022a) Problemáticas Y desafíos en la gestión del agua y del territorio en una cuenca urbana embalsada. Revista Estudios Ambientales 10(2):67–78. https://doi.org/10.47069/estudios-ambientales.v2i2.1584

Cifuentes MR, Rodríguez CI, Ruíz de Galarreta VA, Gabellone NA (2022b) Dinámica hídrica Y balance hidrológico en la cuenca del embalse Lago Del Fuerte, Tandil. Cuad Del CURIHAM 28. https://doi.org/10.35305/curiham.v28i.178

CINEA - Centro de Investigaciones y Estudios Ambientales (2009) Estudio Hidrogeológico en la zona aledaña a la Avenida Don Bosco De La Ciudad De Tandil. Convenio Municipalidad de Tandil - UNICEN. Informe final, Tandil

Collazos G, Cazenave G (2015) Curvas IDF para el centro de la Provincia de Buenos Aires. En Actas del XXV Congreso Nacional del Agua. Paraná (pp. 480–486)

Creparula HJ (2006) Relaciones entre los usos del suelo y las comunidades de algas diatomeas del arroyo San Gabriel. Unpublished thesis. Universidad Nacional del Centro de la Provincia de Buenos Aires

Davis SN, De Wiest RJM (1971) Hidrogeología. Ed. Ariel, Barcelona

De Antueno L, Gaspari FJ, Guaraca AG (2020) Análisis Del efecto del cambio en El uso del suelo sobre El escurrimiento en la cuenca alta del río sauce Chico, Argentina: use changes effect analysis on runoff in the upper basin of the Sauce Chico River, Argentina. Revista Estudios Ambientales-Environmental Stud J 8(1):20–42. https://doi.org/10.47069/estudios-ambientales.v8i1.659

De Lopez Cardenas F (1998) Restauración hidrológica forestal de cuencas y control de la erosión. Ingeniería Medioambiental, TRAGSATEC, Ministerio De Medio Ambiente. Editorial Mundi Prensa, Madrid, España

De Oliveira Serrão EA, Silva MT, Ferreira TR, de Ataide LCP, dos Santos CA, de Lima AMM, Gomes DJC (2022) Impacts of land use and land cover changes on hydrological processes and sediment yield determined using the SWAT model. Int J Sedim Res 37(1):54–69. https://doi.org/10.1016/j.ijsrc.2021.04.002

Delgado MI, Gaspari F, Senisterra G (2013) Tendencia De Cambio Espacio - temporal Del escurrimiento superficial en una cuenca serrana. Tecnociencia Chihuahua 7(2):99–109

Delgado MI, Carol E, Casco MA (2020) Land-use changes in the periurban interface: hydrologic consequences on a flatland-watershed scale. Sci Total Environ 722:137836. https://doi.org/10.1016/j.scitotenv.2020.137836

Eshleman KN (2004) Hydrological consequences of land use change: a review of the state-of-science. Geophys Monogr Ser 13–29. https://doi.org/10.1029/153gm03

Fleming JM, Doan HJ (2003) HEC Geo-HMS Geospatial Hydrologic modeling extension Versión 10.1 user Manual. US Army Corps

of Engineering Center, Hydrologic Engeneering Center (HEC), USA

Foley JA, Defries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309:570–574

Fuentes Junco JJA (2004) Análisis morfométrico de cuencas: caso de estudio del Parque Nacional Pico De Tancítaro. Dirección General De Investigación De Ordenamiento Ecológico Y Conservación De Ecosistemas. Instituto Nacional de Ecología (INE), México

Gallegos Reina A, Perles Rosello MJ (2019) Relaciones entre Los cambios en Los usos del suelo y El Incremento De Los riesgos de inundabilidad y erosión: análisis diacrónico en la provincia de Málaga (1957–2007). Boletín De La Asociación De Geógrafos Españoles 81(2740):1–38. https://doi.org/10.21138/bage.2740

Gaspari FJ, Bruno JE (2003) Diagnóstico de degradación ambiental por erosión hídrica en la cuenca del arroyo Napostá Grande. Ecología Austral 13(1):109–120

Gaspari FJ, Vagaría AMR, Senisterra GE, Denegri GA, Delgado MI, Besteiro SI (2013) Caracterización morfométrica de la cuenca alta del río Sauce Grande, Buenos Aires, Argentina. AUGMDOMUS, 4: 143–158

Grosman F (1999) Estrutura Da comunidade de peixes da represa Lago Del Fuerte, Tandil, Argentina. Acta Scientiarum 21(2):267–275 Maringá: UEM

Guerrero EM, Wagner LS, Rodríguez CI, Sosa B (2015) Acciones colectivas y recursos naturales en conflicto. Historia Ambiental De luchas urbanas por agua y sierras en Tandil. Argentina Luna Azul 41:274–295 ISSN 1909–2474

Guo Y, Zhang Y, Zhang T, Wang K, Ding J, Gao H (2019) Surface runoff. In: Li X, Vereecken H (eds) Observation and Measurement of Ecohydrological processes. Ecohydrology, vol 2. Springer, Berlin, Heidelberg, pp 241–306. https://doi.org/10.1007/978-3-662-48297-1_8

Havrylenko SB, Damiano F, Pizarro MJ (2006) Estimación Del número de curva en la cuenca del Río arrecifes (Provincia De Buenos Aires). Instituto Nacional de Tecnología Agropecuaria, pp 1–4

Hawkins RH, Ward TJ, Woodward DE, Van Mullem JA, Reston (2009) https://doi.org/10.1061/9780784410042

Henaos JE (1988) Introducción al manejo de cuencas hidrográficas. Universidad Santo Tomás, Centro de enseñanza desescolarizada, Bogotá, Colombia: 396 p

Horton RE (1945) Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Bull Geol Soc Am 56:275–370

IGN (Instituto Geográfico Nacional) (1957) Topographic Chart Nº 3760-29-2 sierras Del Tandil, scale 1: 50.000. Instituto Geográfico Nacional, Argentina

IHLLA (Instituto de Hidrología de Llanuras) (1995) Diagnóstico limnológico, sanitario, ictiológico y estado ambiental del Lago del Fuerte, ciudad de Tandil. Informe final a la Municipalidad de Tandil, marzo de 1995

IHLLA (Instituto de Hidrología de Llanuras) (2005a) Estudio de la calidad del agua del Lago del Fuerte, Tandil. Diagnóstico. Informe Nº 3 a la Municipalidad de Tandil, marzo de 2005

IHLLA (Instituto de Hidrología de Llanuras) (2005b) Monitoreo De Toxinas algales (microcistinas). Lago Del Fuerte, Tandil. Informe Final a la Municipalidad de Tandil. mayo de 2005

INTA (Instituto Nacional de Tecnología Agropecuaria) (1989) Mapa de suelos de la provincia de Buenos Aires, escala 1:500.000. INTA. 544 p. Buenos Aires

Kirpich ZP (1940) Time of concentration of small agricultural watersheds, vol 10. Civil Engineering, New York, USA, 6

La Macchia ML (2014) Modelización del drenaje urbano en la ciudad de Tandil mediante Tecnologías de la Información Geográfica. Geografía y Sistemas de Información Geográfica. (GESIG-UNLU, Luján). 6, N° 6, Sección I: 66–81

Llamas J (1993) Hidrología general: principios y aplicaciones. Servicio Editorial de la Universidad del País Vasco, Bilbao, España

Miranda del Fresno MC, Ulberich AC (2010) Problemas ambientales derivados del crecimiento urbano en el sector serrano S-SE de la ciudad de Tandil, provincia de Buenos Aires. En: Actas del VI Congreso Nacional Ambiental 2010. Trabajo Nº 04–04. En CD. San Juan

Miranda del Fresno MC, Ulberich AC (2011) Técnicas fotocartográficas, una herramienta para la detección de impactos y problemas ambientales. Revista de Teledetección 36, 84–97. Asociación Española de Teledetección. http://www.aet.org.es/revistas/revista36/Numero36_08.pdf. [Accessed 29 Feb 2024]

Nonglait TL, Tiwari BK (2016) Application of SCS-CN method for estimation of runoff in a humid microwatershed. Int J Curr Agric Sci 6(10):121–127

Ortiz Vera O (2004) Evaluación hidrológica. Hidrored, pp 1–7. 1

Patton PC (1988) Drainage basin morphometry and floods. In: Baker VR, Kochel RC, Patton PC (eds) Flood geomorphology. Wiley, New York, pp 51–65

Ponce VM (1989) Engineering hydrology: principles and practices. Prentice Hall, Englewood Cliffs, N.J

Ponce V, Hawkins R (1996) Runoff Curve Number: Has It Reached Maturity? Journal of Hydrologic Engineering, 1, 11–19. https://doi.org/10.1061/(ASCE)1084-0699(1996)1:1(11)

Rodríguez CI (2014) Evaluación ambiental del uso y gestión del agua subterránea en el partido de Tandil. Pautas para su gestión sustentable. Thesis (PhD). Universidad Nacional de La Plata

Rodríguez E, Rosa S, Salinas B (2008) Levantamiento topo-batimétrico de la zona del Lago del Fuerte (Tandil) para apoyo de obras de saneamiento. Universidad Nacional de La Plata. Facultad de Ingeniería. Departamento de Agrimensura, Trabajo final. 207 p. http://200.5.74.242/greenstone/collect/facagr/index/assoc/HASHca39.dir/doc.pdf [Accessed 9 September 2021]

Rodríguez CI, Miranda del Fresno MC, Miguel RE, Ulberich AC, Ruiz de Galarreta VA (2013) Cambios De uso del suelo e impactos sobre El agua subterránea en un barrio Al Sur De Tandil, Buenos Aires, Argentina. AUGM DOMUS 5:75–90

Romero Díaz MA, López Bermúdez F (1987) Morfometría De redes fluviales: revisión crítica De Los parámetros más utilizados y aplicación al alto Guadalquivir. Papeles De Geografía 12:47–62

Ruiz de Galarreta VA (2006) Geohidrología y balance hidrológico de la zona no saturada en la cuenca superior del arroyo Tandileofú, Provincia de Buenos Aires. Thesis (PhD). Universidad Nacional de La Plata

Ruiz de Galarreta VA, Banda Noriega R, Barranquero R, Díaz AA, Rodríguez CI, Miguel RE (2010) Análisis integral del sistema hídrico, uso y gestión. Cuenca Del Arroyo Langueyú, Tandil, Argentina. Boletín Geológico Y Minero. 121(4):343–356

Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy. Geol Soc Am Bull 67(5):597–646

Senisterra GE, Gaspari FJ, Delgado MI (2015) Zonificación de la vulnerabilidad ambiental en una cuenca serrana rural, Argentina. Revista Estudios Ambientales 3(1):38–58

Shuster WD, Bonta J, Thurston H, Warnemuende E, Smith DR (2005) Impacts of impervious surface on watershed hydrology: a review. Urban Water J 2(4):263–275. https://doi.org/10.1080/15730620500386529

Strahler AN (1964) Quantitative geomorphology of drainage basins and channel networks. Section 4-II of Handbooks of Applied Hydrology. McGraw-Hill Book Co, New York, USA

Teruggi ME, Kilmurray JO (1980) In: Turner J (ed) Sierras Septentrionales De La Provincia De Buenos Aires, vol 2. Geología Regional Argentina, Academia Nacional de Ciencias, Córdoba, pp 919–965

Ulberich AC (2007) El Crecimiento Urbano en torno a Los paseos del sur de la ciudad de Tandil, Buenos Aires – Argentina. Facultad de Ciencias Humanas, UNICEN. Multimedios Ambiente Ecológico

USDA (United States Department of Agriculture) (1986) Technical Release 55. Urban Hydrology for Small Watersheds. Engineering Division, Soil Conservation Service, US Department of Agriculture. Washington, DC. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf [Accessed 30 September 2021]

USDA (United States Department of Agriculture) (1972) Sect. 4: Hydrology. National Engineering Handbook. Soil Conservation Service, Washington, DC

USGS (United States Geological Service) (2014) Digital Elevation Model 's37 w59 SRTM1S37W059V3'. EROS Archive - Digital Elevation - Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global

Vagaría AR, Gaspari F, Senisterra G, Delgado MI, Besteiro S (2012) Evaluación Del efecto de la restauración agro-hidrológica mediante la aplicación del modelo hidrológico GeoQ. RIA Revista De Investigaciones Agropecuarias 38(2):171–181

Villaroya JP, Farias HD, Amarilla ME (2013) Estimación Del parámetro hidrológico del Número de curva NC: Automatización Del cálculo mediante S.I.G. y nuevas fuentes de información cartográfica. Caso del área urbano De Pozo Hondo. IX Jornadas de Ciencia y Tecnología de Facultades de Ingeniería del NDA. Santiago del Estero, Argentina

Woldesenbet TA, Elagib NA, Ribbe L, Heinrich J (2017) Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia. Sci Total Environ 575:724–741. https://doi.org/10.1016/j.scitotenv.2016.09.124