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THEMATIC ISSUE

Groundwater characteristics within loessic deposits: the coastal springs of Los Acantilados, Mar del Plata, Argentina

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Abstract

The urban growth of the southern neighborhoods of Mar del Plata City provoked significant changes in the groundwater balance of the loessic sequences. These regional loessic levels with a significant portion of volcanic ash layers were reported subject to fluoride and nitrate concentrations. Residential houses pump from sands located 70 m depth and withdraw the sewages to depths less than 5 m. These effects cause significant local and seasonal (summer) increments of the water table outcropping via springs at certain unconformities of the coastal cliffs. A mathematical model was applied to analyze the water level lowering at the productive levels, while there is a decrease in the quality of the upper levels subject to waste discharges. Much of this groundwater flow is concentrated in unconformities between different types of sediments. Human activities have affected the aquifer dynamics increasing the groundwater pumping rates and the return velocity of the sewages. This should be considered in the management strategies of coastal hydric resources.

Keywords Water table · Loess cliffs · Spring · Mar del Plata · Argentina

Introduction

The term loess was originally proposed by K. C. Von Leonhard, but popularized by Charles Lyell (Smalley et al. 2001). It was originally defined as unstratified yellowish or brownish fine sediments deposited by eolian activity with particular capability to preserve steep bluffs. Loess and loess-like sediments extend across different countries, including China, Central and Eastern Europe such as Germany and France, North America, South America such as Argentina, Bolivia, Brazil, Ecuador, Paraguay and Uruguay, and New Zealand. Today, loess and loess-like sediments cover about 10% of the emerged plates (Li and Qian 2018). Regarding loess origin, there has been discussion if the silt has originated exclusively by subglacial grinding or if certain loess deposits are genetically related to hot deserts (Whalley et al. 1982). In Ecuador, loess-like deposits are related to a volcanic origin in locally called *Cangahua* (Ficcarelli et al. 1992). In many of these areas, loess is related to Quaternary climatic changes that occurred in the last 2.5 million years (Kukla 1987), and in this sense interfingered to paleosols assigned to warmer phases (Flint and Brandtner 1961). This succession between loess and paleosols conditions permeability. In China, loess layers have higher porosity with infiltration rates of 0.93 mm/min, while the paleosols have lower rates (0.62 mm/min; Zhao et al. 2015). This loess–paleosol succession is also common in the Argentine Pampas and assumed to cause slope instabilities that triggered landslides in some areas (Isla et al. 2015; Chengxuan et al. 2015), and cause significant spatial and temporal differences in soil moisture (Fu et al. 2018). In this sense, irrigation practices in loessic plains can affect soil structure and crop yields (Li et al. 2013). Although several studies were oriented to the importance of loess groundwater resources, little research was devoted to springs of loessic cliffs contributing to the coastal system.

In Argentina loessoid sediments (reworked from the original loess) are more abundant than primary loess deposited only by eolian activity (Zárate 2003). Although the South

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American loess origin was related to the Andes orogeny, it became dominant at the Plio-Pleistocene plains. In regard to its composition, South American loess is not directly related to the deflation of moraine deposits. Instead, the volcaniclastic supply by Westerly winds from the Andes has a dominant role (Teruggi et al. 1957; Zárate 2003; Morrás 2003). The volcanic origin of these sediments and their origin from the Andes are confirmed by recent volcanic activity (Fig. 1). The genesis of Pampean loess deposit is similar to the loess deposits of Alaska and New Zealand (García Jiménez et al. 2012). The volcanic ash found between these deposits have been associated with high contents of F (García Jiménez et al. 2012) and As (Robles et al. 2016) in groundwater. However, the main problem in relation to water supply is the increase in nitrates from agricultural areas to aquifers of urban areas (Martínez et al. 2014).

Fluvial redeposition and pedogenesis have a dominant role in the loess-like (sandy silts) deposits. Several depositional environments have been described for the coastal cliffs south of Mar del Plata City.

Coastal springs occur dominantly in karstic areas, either emerged or submerged. They were reported in Croatia,

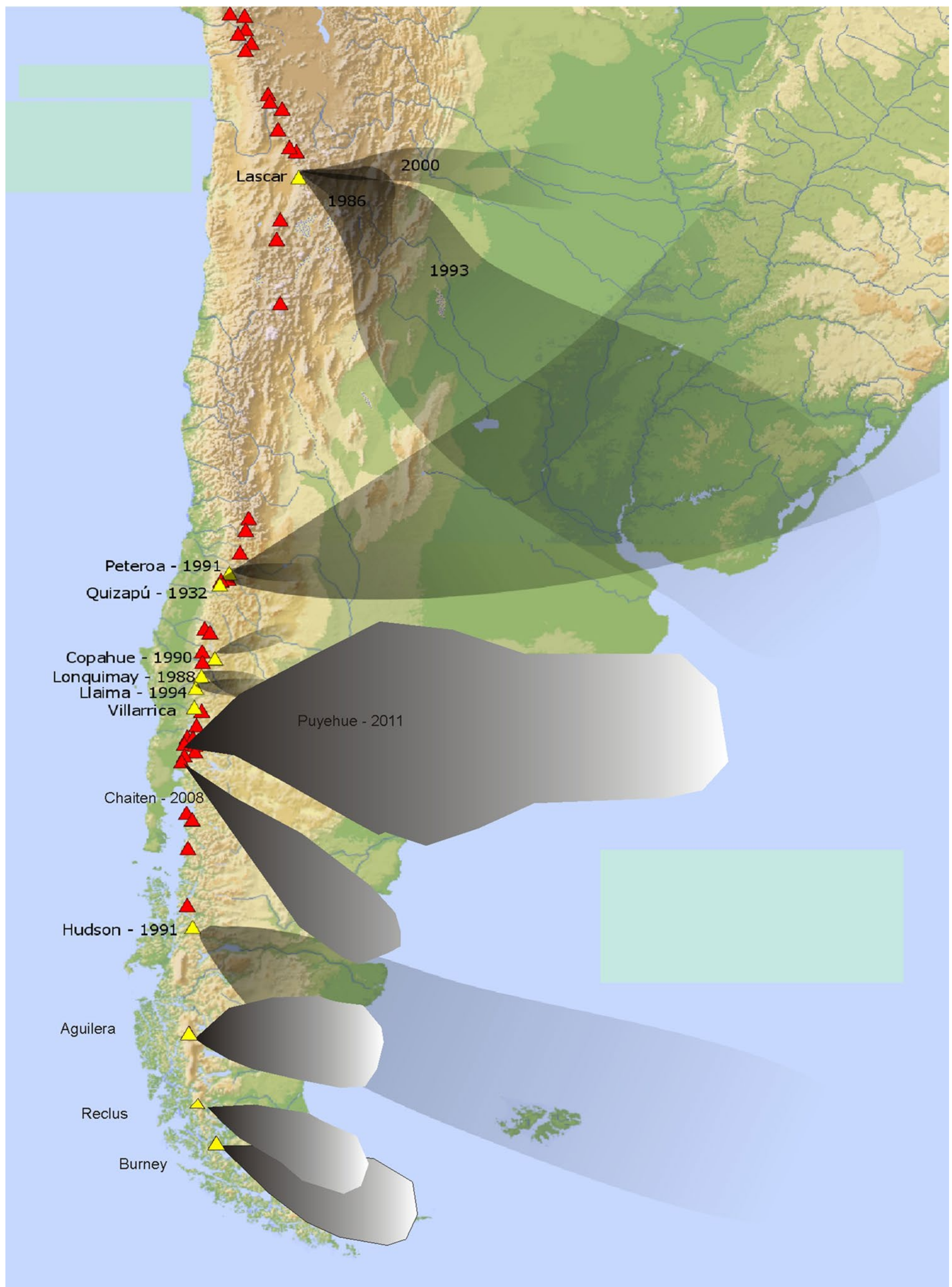

Fig. 1 Recent volcaniclastic plumes derived from active volcanoes (modified from GEVAS 2015)

Greece, Lebanon, France, China, Sardinia, Mexico, Florida and other carbonatic coasts (Fleury et al. 2007). It is not common to find springs developed in loessic plains. Loessic sequences have been considered as homogenous, slope resistant and porous material. However, significant landslides have been induced in some irrigated areas (Zeng et al. 2016).

In this manuscript, the coastal springs of Los Acantilados cliff is described and analyzed in relation to the loessic composition and the land-use changes that have caused variations of the water table, either at the residential areas or at the spring discharge at the cliffs. These changes increase during the summer season with higher demand.

Study area

Mar del Plata is located at the southeastern tip of the Tandilia Range (Fig. 2) The loessic plain between this Mar del Plata and Tres Arroyos City has a dominant slope to the south, although groundwater flows toward the SE. The area is characterized by ranges surrounded by plains with slopes below 0.05% (Quiroz Londoño et al. 2008). The spring of Los Acantilados is located south of the city, precisely at 38° 07 × 05″S; 57° 35 × 33″W. The city has a temperate and humid climate, being the winter months the less rainy. Precipitation was 933.6 mm/year and increased progressively during the twentieth century: 752 mm/year for the period 1901–1920, 777 for the interval 1921–1940, 846 for

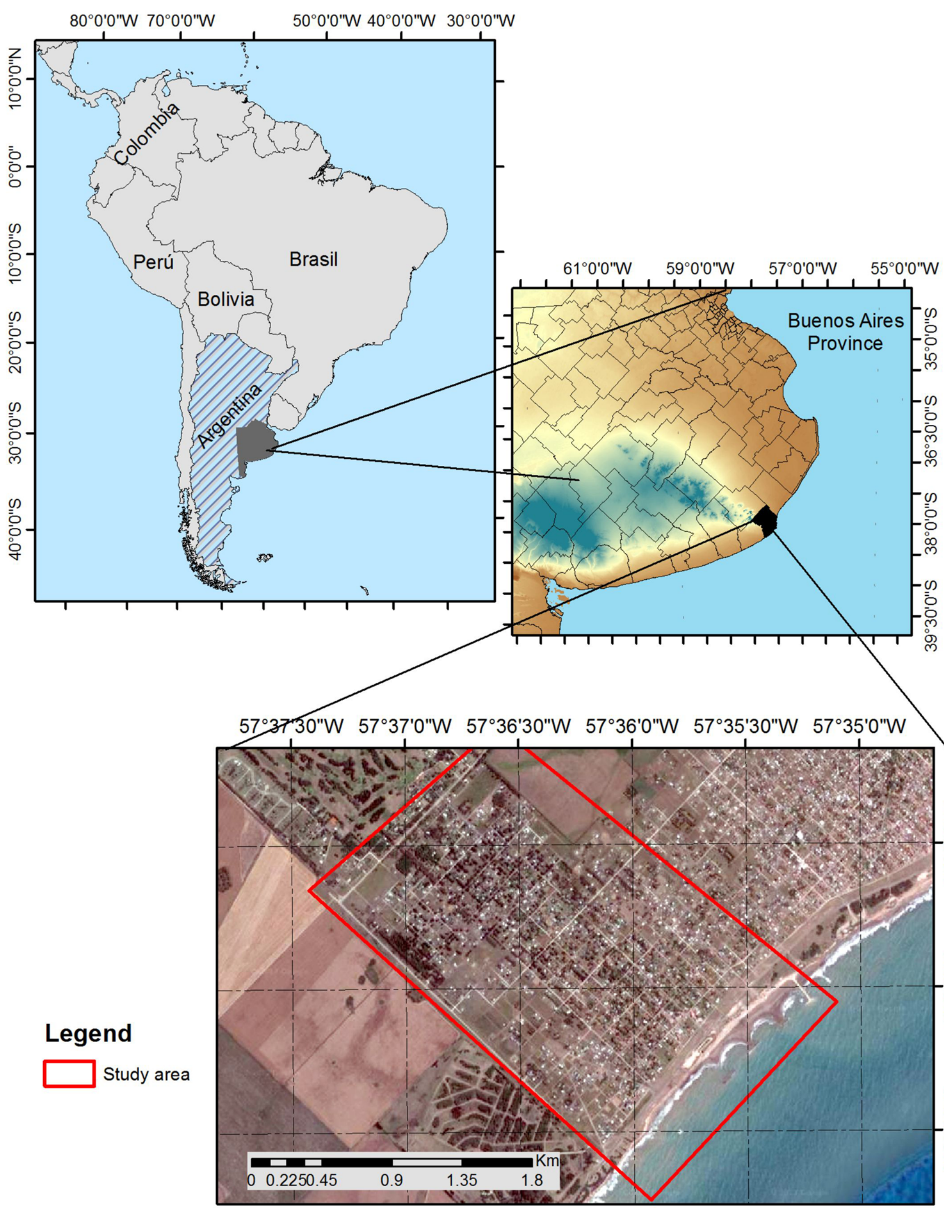

Fig. 2 Location of Mar del Plata cliffs. Topographic map of the Buenos Aires Province and aerial photograph of Los Acantilados Beach

the period 1961–1980, and 931 for the 1981–2000 interval (Cionchi and Redin 2004). An increment in precipitations has been described for the Pampas region (E of the Andes) occurring since the 1950s and 1960s. In Mar del Plata, this increase occurred between 1940 and 1950 (Minetti and Vargas 1997). During the interval 1983–2005, there was also an increasing trend; peaks in monthly rains have been increasing in recent years: 1992 (320 mm/month), 1998 (330 mm/month) and 2000 (350 mm/month). In the last few years, daily rains have been even heavier than in former years. However, there are annual differences between 700 and 1400 mm/year and between 750 and 833 mm/year for the evapotranspiration according to Thornwaite (1948) and Quiroz Londoño et al. (2008).

In regard to hydrogeology, these sediments have been categorized as a multi-layered unconfined aquifer with a thickness ranging from 30 to 100 m, in some cases with a semiconfined behavior in depth (Auge et al. 2002). Groundwater is dominated by bicarbonate and has less content in chloride ions (González Arzac and Vizcaíno 1995; Martínez et al. 2017). Two main hydrogeochemical processes dominate within the Pampeano aquifer: the chemical equilibrium between calcite and silica values, and cationic exchanges (Martínez and Osterrieth 2013). Calcite concentrations are distributed in discrete caliche levels or disseminated. Silica is also disseminated as volcanic glass shards or composed of thick tuff units (Isla et al. 2015). The selective cation adsorption follows the succession Ca > Mg > Na > K in an evolution from calcium to sodium contents. Although calcite, quartz and aluminosilicates are known to have low dissolution rates within the Pampeano aquifer, they were rapidly incorporated into water, and saturation of solution appeared, in the first minutes of dissolution experiments (Vital et al. 2016). These processes are assumed to cause in some areas changes from water dominated by Ca–HCO_3 at the recharge areas to types dominated by Na–HCO_3 at the discharge areas (Carol et al. 2012).

Loess deposits from Argentina are dominantly composed of very fine sand and coarse silt. The Pampas loess is finer and more selected than the dominant loess-like sediments (Frenguelli 1955). Median diameter from samples collected from Mar del Plata cliffs varies between 40 and 70 µm (Fig. 3; Teruggi et al. 1957). Heavy and magnetic minerals increase from the Pliocene to the Pleistocene deposits (Teruggi et al. 1957; Isla et al. 2015).

The Chapadmalal Formation is composed of light minerals (> 95%) with less than 1.3% of magnetic minerals (Teruggi et al. 1957). This light fraction is composed of plagioclase grains (usually > 20%), K-feldspar (> 11%), quartz (3–19%) and volcanic glass (1–20%). Some mineralogical variations were detected in the upper formations of the Plio-Pleistocene sequence, although the most significant was the increase in heavy minerals (Teruggi et al. 1957). Loess-like and calcrete samples collected from the headlands of these watersheds were analyzed searching for the kinetics dissolution of the most common minerals: calcite, quartz and alluminosilicates. Most of the dissolved ions (calcium, sodium and bicarbonate) achieved an equilibrium concentration during the first 2 h of reaction, while the remaining substance lasted about 6–8 h (Vital et al. 2016). According to the analysis of chlorofluorocarbon gases, the groundwater from the Quequén Grande River catchment has an age of 30–40 years (Martínez et al. 2017). The outcrops of the Chapadmalal Formation continue to depths of 87 m belowground (González Arzac and Vizcaíno 1995; Fig. 4). Below it, sandy levels grade to sandstones and quartzites related to the Balcarce Formation (Dalla Salda and Iñiguez 1978).

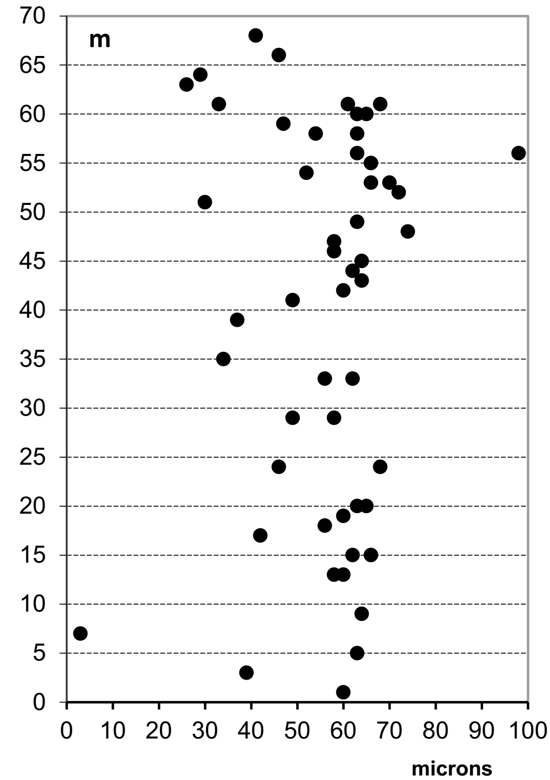

Fig. 3 Grain size along the Mar del Plata cliffs sequence. Inset corresponds to the Chapadmalal Formation (modified from Teruggi et al. 1957; Isla et al. 2015)

The study area is located in a transitional zone between a hilly area and a coastal plain, approximately 10 m above mean sea level (Auge 2001). The hydrogeologic basement is composed of quartzitic rocks of Paleozoic age, located between 80 and 100 m (Massone et al. 2008). A secondary permeability is assigned to three fault systems (NE–SW; NW–SE, and E–W); the fourth group of horizontal joints was assigned to the stratification planes (Mauriño et al. 1981) that is assumed to supply the freshwater (Bocanegra et al. 2001; Romanelli et al. 2011). This aquifer is composed of sandy silts and fine sands,

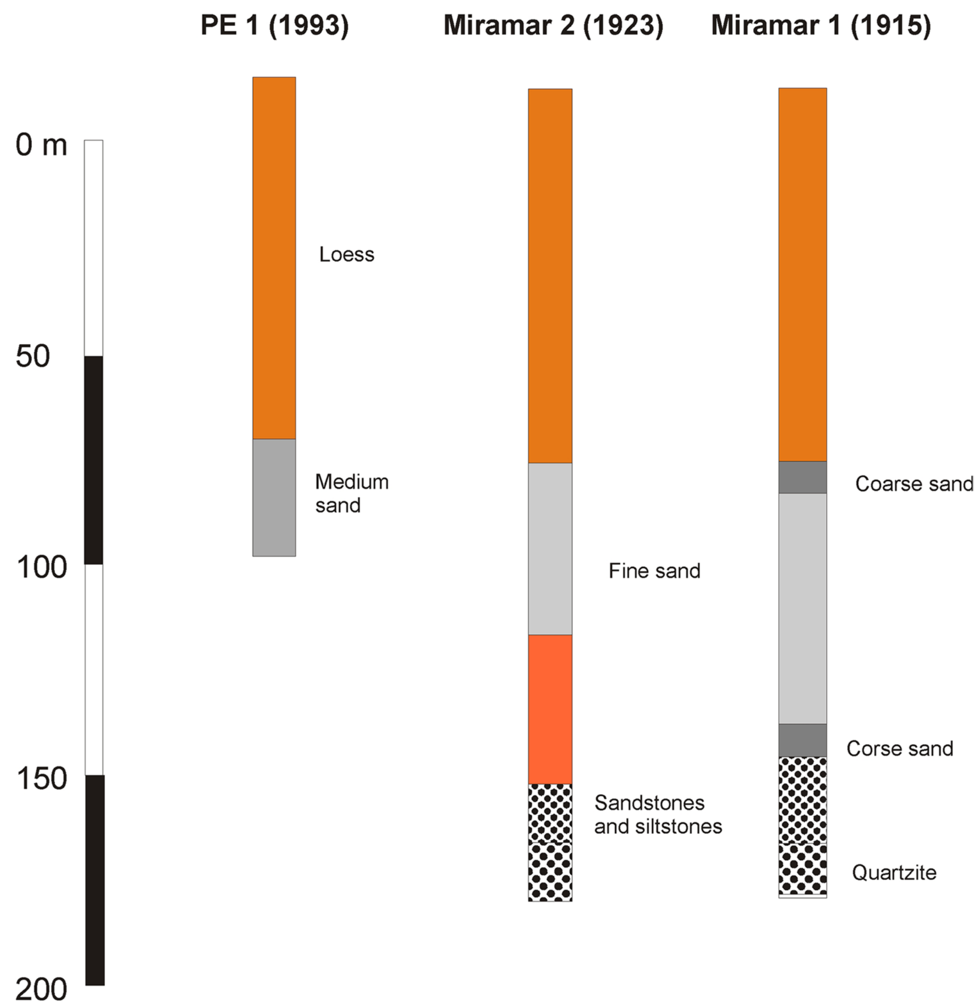

Fig. 4 Geologic descriptions of Miramar wells (modified from González Arzac and Vizcaíno 1995)

with clayey levels, the so-called Pampean and post-Pampean sediments. Permeability was estimated about 10–20 m/day, indicting an average transmissivity of 525 m^2/day (Bocanegra et al. 1993). However, maximum transmissivity values of 1400 m^2/day were reported (Cionchi et al. 2000). The porosity of similar post-Pampean sediments from La Plata was calculated in 5–10% (Auge 2001). Precipitation is the main factor of recharge. During the last 23 years, the recharge was estimated to be about 15.51% of the precipitation. Surficial runoff is about 4% of the rainfall (Massone 2003). The region was evaluated as 61% available (very high to moderate) for irrigation facilities (Romanelli et al. 2012). At the Quequén Grande watershed, the age of the groundwater is approximately 30–40 years according to isotopic monitoring (Martínez et al. 2017).

Materials and methods

Stratigraphic profiles were surveyed during several years, sampling and analyzing rocks from strategic sites and levels (Isla et al. 2015). The stratigraphic scheme was based on previous papers (Kraglievich 1952; Zárate and Fasano 1989). Land-use maps were performed based on Landsat TM images. Training sites were discriminated on a composite image applying the Idrisi program of the Clak University (Eastman 1999). The minimun distance option was selected to obtain a land-use map.

Groundwater flow of the Pampean aquifer was simulated using a steady (since 1963) and transient (1964–2016) state numerical model. MODFLOW (McDonald and

Harbaugh 1988) was the 3-D finite model, with the ModelMuse graphic interface (Winston 2009). The area analyzed was 4.82 km^2 with two layers: aquifer and hydrogeologic basement. The grid was 42×36, about 2236 cells per layer, with a spatial resolution of 80×80 m for each cell. The model analyzed regional flow from northwest to southeast; the Atlantic Ocean in the southeast is a groundwater regional discharge zone and was considered as a constant head boundary. The lateral boundaries of the model are parallel to the general direction of groundwater flow inferred from piezometric maps, so they were assigned the Neumann no-flow boundary condition. Natural recharge occurs directly as infiltration from precipitation. Evapotranspiration was considered to be 1 m^3/year with a depth of roots of 0.3 m. The permeability of the Pampean aquifer was estimated in 6.22 e^{-5} m/seg (Bocanegra et al. 2001) with a storage coefficient of 0.1. The quartzitic basement has a permeability of 1 e^{-7} m/seg.

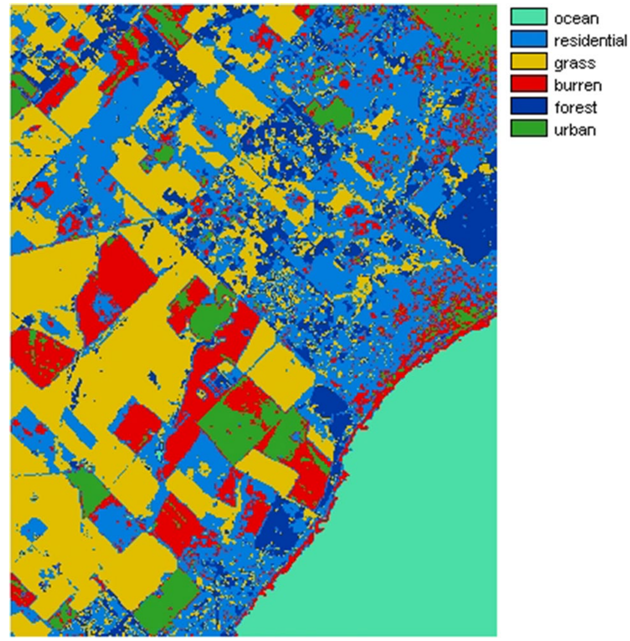

Fig. 6 Land-use map of the Los Acantilados residential site

Results

The spring level

The coastal cliffs south of Mar del Plata are known specifically by their paleontological importance (Cione and Tonni 1996). In the last few years, new Geologic concepts were introduced in relation to paleosols, caliche levels, impact events and large biogenic structures (Zárate and Fasano 1989; Zárate et al. 1998; Schultz et al. 1998; Isla et al. 2015). The groundwater seeping level of the Los Acantilados beach originated by a disconformity located at the contact between the Chapadmalal and Barranca de Los Lobos formations (Fig. 5). The underlying formation (Chapdmalal) has a higher content of mud and therefore is more cohesive.

Urban growth

The coastal plain south of Mar del Plata was progressively urbanized in relation to a progressive demand of touristic beaches located at the foot of coastal cliffs (Juárez et al. 2001). The construction of second residential houses increased during the end of the 1970s due to a seasonal demand during the summer months (January

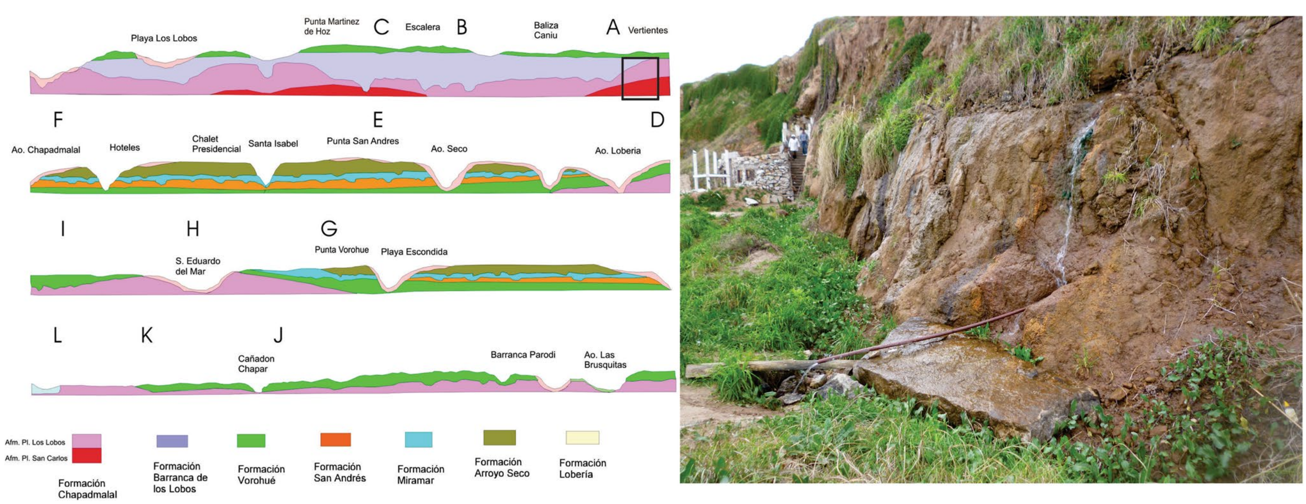

Fig. 5 **a** Stratigraphic loess-like units outcropping at the coastal cliffs between Mar del Plata and Miramar (modified after Kraglievich 1952; Isla et al. 2015; with an inset of the level of springs. **b** Natural springs at the cliffs of Los Acantilados beach)

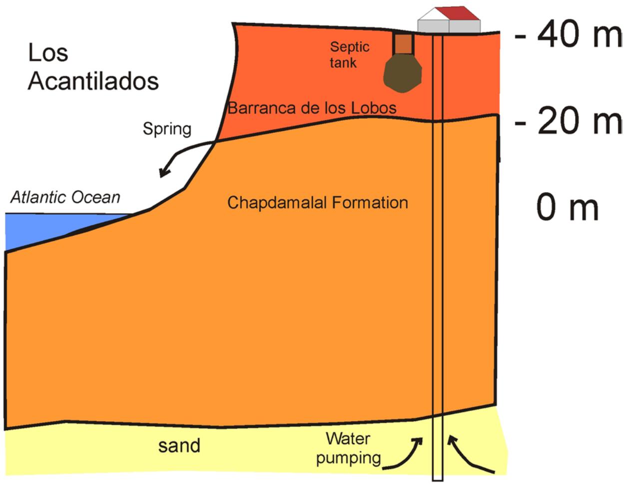

Fig. 7 Schematic profile of the coastal spring of Los Acantilados

and February); those closer to the city had higher rates of occupation (Fig. 6). As at this area residential areas have no municipal distribution of water, the urban growth required domestic wells drilled to depths lower than 70 m. As there is no sewage network, septic tanks collect the sewages from each house increasing the recharge of the water table. At the suburban areas of Mar del Plata, the aquifers are affected by nitrate increments caused by agricultural activity at the upstream areas and sewage contributions at the urban areas. The reduction of the leakage of the city sewage network was assigned as a priority (Martínez et al. 2014). This situation is different from other loess plains where the nitrate pollution is related to agricultural activities (Zhang et al. 2018).

Drainage

The spring of Los Acantilados has been reported since the beginning of the twentieth century. It is located between Chadadmalal and Barranca de Los Lobos formations (Fig. 7). The discharge of the spring has significant variation. During the heavy rains of September 13, 2016, the discharge was 0.001 m^3/s. A week later (20/9/2016), the spring was discharging 0.0001 m^3/s.

Groundwater simulations

To test the model, the levels of 2016 were analyzed based on 24 piezometric measurements. The best fit was yielded, considering the hydraulic conductivity to values of 7×10^{-6} m/seg, in concordance with previous assumptions of similar lithology (Custodio and Llamas 1976; Escuder et al. 2009).

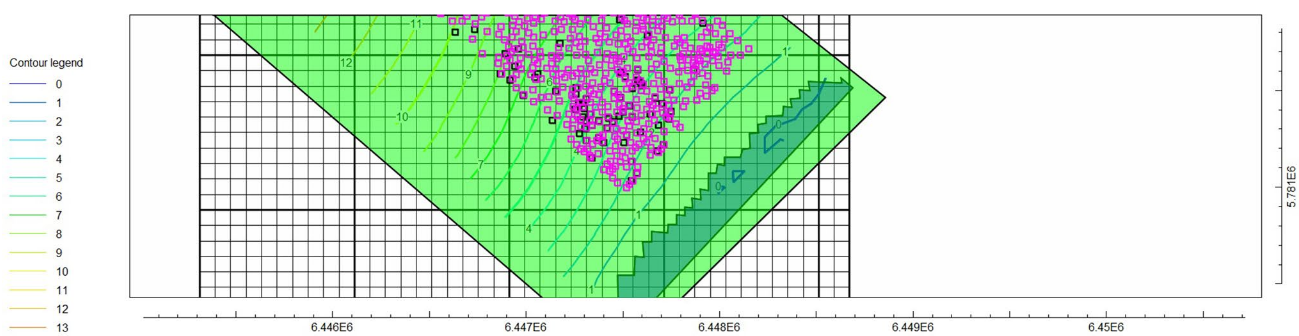

Fig. 8 **a** Deviations between estimated and measured phreatic values. Red dots are higher than estimated values and blue dots lower. **b** Fitting of the model used

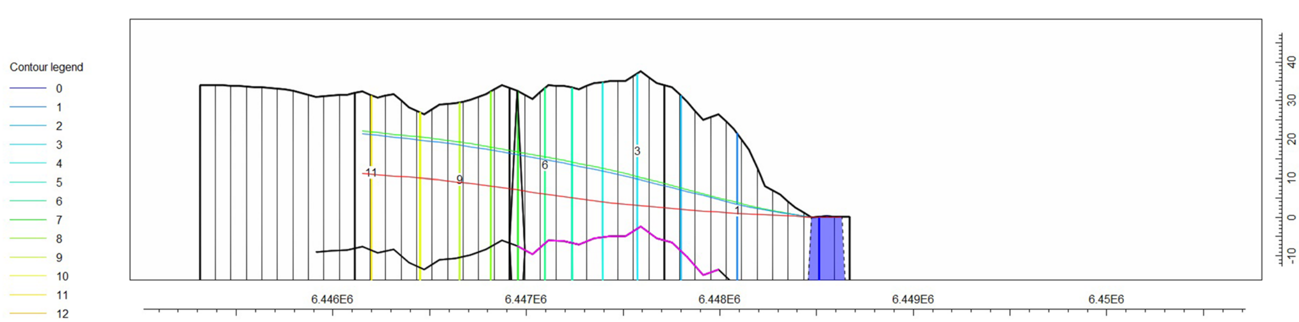

Fig. 9 Phreatic variations estimated between 1964 and 2016

There was a good fitting between the estimated and measured values (Fig. 8).

The water table varies from a few meters at the cliffs to 25 m at the northwestern limit of the analyzed area (Fig. 9). Despite these estimations, the population increase was analyzed based on remote-sensing techniques considering the seasonal touristic effect. Inventories of 81 buildings in 1964 increased to 664 in 2016. As the neighborhood does not have a municipal water supply, each owner should dig wells for their own supply. Assuming average house consumptions of about 1 m^3/day, and a water return to the aquifer of 70–80% due to irrigation activities and septic tanks, daily extraction was estimated to be 0.2–0.3 m^3.

Discussion

As submarine groundwater discharge to the ocean is difficult to evaluate (Burnett et al. 2004), coastal springs are easier for monitoring although there are not many references about them. The Blaz Spring from Northern Croatia is located at a submerged karstic region where brackish areas were subject for research in relation to the applicability of the Ghyben–Herzberg relationship at non-homogeneous coastal aquifers (Bonacci and Roje-Bonacci 2009). The Coastal Springs Ground-Water Basin (Florida, USA) was analyzed to detect trends of discharge toward the Gulf of Mexico. In this sense, the perched coastal spring of Los Acantilados is an ideal site to monitor variations of the groundwater discharge at the coast.

In regard to the sediment composition, Mar del Plata loess has significant grain-size variations in relation to fluvial facies. Considering a dominant volcanic origin for this loess, there is a significant increase in heavy and magnetic minerals toward the Pleistocene levels (Isla et al. 2015). These contents in volcanic glass shards are responsible for the fluoride concentrations in the groundwater (García Jiménez et al. 2012). However, in other areas of Buenos Aires, there are significant spatial variations in these loessic Pleistocene levels assigned to different origins (Morrás 2003). These temporal and spatial variations of the Argentine loess contrast to other loess deposits such as the Chinese that are more spatially uniform (Eden et al. 1994).

To analyze climate change effects on different loessic plains, precipitation trends should be considered. Pampas plains behave opposite to the Chinese Plateau, a region assumed to have the most severe erosion worldwide (Zuo et al. 2016). While the Chinese Plateau receives less precipitations (Sui et al. 2009; Liu et al. 2013; Zhang et al. 2015), at the Mar del Plata's plain there is a constant increase in annual rains from 752 to 931 mm/year (Cionchi and Redin 2004); however, this bias could be assigned to modern strong ENSOs recurrence (1982–1983, 1997–1998 and 2015–2016). In sum, while a drying trend is expected for the Chinese Plateau (Sun et al. 2016), positive jumps in precipitations were indicated for Argentina plains (Minetti and Vargas 1997).

The loess contribution to the Western Atlantic Ocean is thought to be significant (Gili 2014), mostly in regard to the importance of Fe content (Simonella 2013). Offshore Buenos Aires, the Mar del Plata canyon has a dominant deposition of selected coarse silt (10–63 µm size) with a sedimentation rate estimated around 160 cm/kyr during the Holocene (Voigt et al. 2013). Considering the selection of this coarse silt fraction, it can be assumed that the erosion of loess deposits could be a significant contributor to these canyons.

In Argentina, crop choice may influence water table levels during the growing season, but has only a subtle effect on year to year fluctuations (Mercau et al. 2016), mostly induced by El Niño years. In the case of the Los Acantilados village, the land-use change (urbanization) introduced a significant bias by the vegetation changes, but mostly by groundwater pumping.

Conclusions

The loessic deposits of Argentina have significant contents of volcanic ash supplied from the Andes Cordillera. Regarding their groundwater composition, flouride concentrations are therefore assigned to this inherited volcanic origin. On the other hand, nitrates have been increasing due to land-use alterations. Precipitations have increased in the region from 752 to 931 mm/year; the groundwater age of these small watersheds is 30–40 years.

At the coastal cliffs of Los Acantilados (Mar del Plata, Argentina), natural springs operate within a loessic sequence and, in response to the groundwater balances conditioned to the neighbourhood demand, are mostly biased to the seasonal consumption.

Much of this groundwater flow is concentrated in unconformities between different types of sediments. Pumping and withdrawals at these touristic neighbourhoods are increasing the velocity of the hydrological cycle.

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