Alluvial Terraces and Contaminant Sources of the Santa Catarina River in the Monterrey Metropolitan Area, Mexico

G. E. Martínez-Quiroga, H. De León-Gómez, F. D. Yépez-Rincón, S. López-Saavedra, A. Cardona Benavides, and A. Cruz-López

Instituto de Ingeniería Civil, Universidad Autónoma de Nuevo León, San Nicolás de los Garza, México; Faculty of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada; Facultad de Ingeniería, Universidad Autónoma de San Luis Potosí, San Luis Potosí, México

ABSTRACT

The development of the Monterrey Metropolitan Area (MMA) and human carelessness have severely altered the Santa Catarina River (SCR). The objective of this research was to integrate fieldwork, a digital elevation model, exploratory surveys and satellite images analysis to develop a GIS-based map scale 1:40,000 and 1:5,000 of the Quaternary alluvial terraces and Cretaceous geologic formations present in the SCR. In addition, this study presents river geologic cross-sections, hydraulic conductivity estimates per terrace, a piezometric chart (dry season), and a database of contaminant sources along the river. The main results were the following: three terraces levels were identified, the distribution and hydrogeological properties of the terraces were documented, groundwater flow direction was southwest (SW) to northeast (NE), and 154 contaminant sources were georeferenced. This investigation lays down the basis for future environmental assessments and studies related to the quality and water supply for the MMA.

1. Introduction

Contamination of potable water sources is a problem that nowadays affects numerous cities around the world. Such is the case of the Monterrey Metropolitan Area (MMA) of the state of Nuevo León (Mexico). This area has a sustained annual population growth rate of ∼2% (National Institute of Statistics and Geography (INEGI), 2018a) and its economic activities represent approximately 7% of the GDP (National Institute of Statistics and Geography (INEGI), 2018b). The sustained economic and population growth has caused the potable water extraction rate to rise from ∼800,000 to ∼1,200,000 m3/day between 2000 and 2017 (National Institute of Statistics and Geography (INEGI), 2017).

With respect to the distribution, half of the potable water allocated for the MMA comes from surficial sources and the rest from underground sources (Water and Sewage Service of Monterrey (SADM), 2017). Contamination of the SCR is an issue that affects the water destined for the MMA (Monforte García et al., 2012). Throughout the section that crosses the MMA, there are contaminant sources that dump different residues to the river (Nacional Institute of Ecology (INE), 1988; Limón Rodríguez, 2000). Some of the contaminants that have been identified include heavy metals and emerging contaminants (Puente-Martínez, 2017; Ramírez-Gallegos, 2017). Moreover, contaminant agents can be transported from the SCR until the runoffs of San Juan River and subsequently flow into the El Cuchillo dam. This dam is one of the main potable water surface sources for the MMA (Water and Sewage Service of Monterrey (SADM), 2017; Flores-Laureano & Návar, 2002; Flores-Laureano, 1997; Návar Cháidez, 2011).

Due to the importance of the SCR in the MMA potable water supply chain, an aspect that should be further examined is the human-induced alterations to terraces and the river. For this purpose, an integrated analysis of the zone could shed light on many areas. For example, studying the river terraces can help better understand the media by which contaminants permeate and eventually reach the aquifer’s water. In addition, attaining a georeferenced database of the present contaminant sources around the urban section of the river could show how these are affecting the riverbed and terraces. Hence, the objective of this research has been to study the distribution and the properties of the alluvial terraces and geologic formations present in the SCR and to document contaminant sources towards the river.
2. Area of study

The study covered ~30 km of the Santa Catarina riverbed and its flanks which limits were considered to be the main avenues bordering the river (Map 1-A). The river is located in the state of Nuevo León and the area investigated comprehended the municipalities of Santa Catarina (SC), San Pedro Garza García (SPGG), Monterrey (Mty), Guadalupe (Gpe), Juárez, and Cadereyta Jiménez.

The general geology of the area of study is described by a package of alluvial sediments of the Quaternary period with varying degrees of consolidation overlying calcareous sedimentary rocks from the Upper Cretaceous. Map 1-A was adapted based on an open-access shape file (SGM, 2008). Across this area, the rock formations normally exposed are the shales of the Méndez Formation and the sequence of limestones, marls and shales of the San Felipe Formation. A stratigraphic column (Michalzik, 1987) is displayed in Figure 1.

3. Methods and results

3.1. River terraces

The area of study was analyzed by integrating data from in-person river plain field investigations of the entire area in addition to, aerial and street-view photo interpretation. A premise to develop this research was to encompass the river area most influenced by the MMA urbanization.

The fieldwork procedure involved covering the accessible areas of the river plain and river flanks (during dry season) from the SW near the La Huasteca zone advancing slightly NE ending near the Guadalupe-Reynosa highway toll. Field excursions had the purpose of generating a geological description of the sediments encountered, identifying river terraces morphology (i.e. stratigraphic and lithological compositions, thicknesses, and present residues), collecting samples from the river terraces, and documenting contaminant sources across the river.
Analysis of satellite images (WorldView, 0.5 m, 16 bits) and street-view captures was conducted on Google Earth Pro software and targeted primarily the identification of river terraces and contaminant sources when urbanization hindered in-person access.

A digital elevation model (DEM) of 1 m per pixel with an accuracy of 0.1 m in elevation covering the area of study and standard penetration test (SPT) exploratory surveys were facilitated by government agency National Water Commission (National Water Comission (CONAGUA), 2010). Likewise, they shared grain-size data from different samples of the riverbed. This information was used for grain-size analysis and the calculation details are provided afterwards.

To identify the river terraces, acquired field data was compared with a preliminary map generated through photo interpretation of satellite and street-view images. Field observations through the entire area of study helped validate interpreted results and reconcile discrepancies. Simultaneously, terraces field elevations were compared with DEM elevation profiles.

This entire complemented process was conducted in an iterative manner (Figure 2(A)) to generate an integrated geologic map (Main Map) in ArcGIS 10.7.1 software scale 1:40,000 (Map 1-B) with a segment scaled to 1:5000 (Map 1-C). The first scale was adequate to display the piezometric chart and the entire area of study; the second was used to analyze in detail a portion of the river. In addition, geologic cross-sections (Figure 3(A–D)) of the river were prepared with DEM profiles, SPT surveys and terraces field observations and subsequently, digitized in CANVAS X. Furthermore, supplementary maps for the entire area of study were created (Martinez-Quiroga, 2018).

Through the methodology described above, three river terraces were identified and are hereafter referred as T1 (Terrace 1), T2 (Terrace 2) and T3 (Terrace 3). Where the lowest terrace – and most recent – was T3 and the highest terrace – and oldest – was T1. Such river terraces are composed of alluvial sediments of the Quaternary period. Hence, surface geologic contacts between the terraces and
The T1 was found emerging only in scarce points in the municipalities of SC and SPGG. It consisted of sandy gravels low in fines with thicknesses of 2–6 m (Figure 2(B)). The T1 elevation was found at about 10 m above the riverbed (ar). Since this terrace is farther away from the riverbed, it was majorly affected by urbanization. With respect to T2, irregular settlements and avenues seem to cover it across the entire area of study. Where visible, it was composed of a gravelly-sand matrix with fines content with elevations of about 8–14 m ar (Figure 2(C)). The static levels from wells Suchiate II, Miravalle and Agustin Lara, indicated that the water table was approximately between 11 and 16 m below T2 ar (Figure 2(B and E)).

On the other hand, the natural composition of the terraces has been altered in different manners across the river. For example, a ~6 m column of metallurgical waste produced by the former steel industry was found in T2 and was also seen dumped in the riverbed in Mty district (Figure 3(C)). Another example was T3 where urban landfills were seen (Figure 2(F)). Other areas showed the absence of river terraces (Figure 3(D)) and substantial garbage accumulations (Map 1-B site D148).

With respect to the geologic contacts with Cretaceous bedrock, the Méndez Formation was exposed in contact with the three terraces and in the four municipalities investigated (e.g. Figure 2(B and E)). This rock formation was composed of shales displaying light brown, green, and gray colors, with laminar stratification and a high degree of fracturing, characterized by forming the ‘pencil structures’ or ‘almonds.’ On the other hand, the San Felipe Formation was exposed on the riverbed, with thicknesses up to 0.25 m of gray limestones and light brown shales intercalations (Figure 2(G)). Rock outcrops across the area of study were more visible upstream (Map 1-B).

### 3.2. Hydraulic conductivity

The hydraulic conductivity ($K$) values of the river terraces were estimated using grain-size analysis methods. These techniques calculate $K$ based on the samples grain-size distribution and could be an alternative when field methods are not available. In addition, in comparison with field methods, this approach reduces costs and is time effective (Hölting & Coldewey, 2019). On the other hand, $K$ can be spatially heterogeneous and vary by several orders of magnitude; however, comparing several calculation
methods has yielded acceptable ranges of estimated values for large areas of study (Biswal et al., 2018).

In this study, six grain size analyses were used to compute \( K \) (Alyamani & Sen, 1993; Barr, 2001; Slichter, 1899; Terzaghi, 1925; Zamarin, 1928; Zunker, 1930). The samples complied with each method criteria. Afterwards, with the values computed from granulometric methods, a geometric mean was calculated to attain a parameter less sensitive to extreme values. This process was repeated for each sample. Verification of each method applicability and analytical calculations were conducted through the HydrogeoSieveXL v2.0 software (Devlin, 2015).

The grain-size distributions were obtained from two database sources from deposits from \( \sim 1 \) m depth below ground level. The National Water Commission facilitated the first database (National Water Commission (CONAGUA), 2010) and 22 samples from the riverbed were examined. The second was composed by 9 samples collected in the field from T3, T2, and, T1 and were sieved and analyzed in the laboratory. In this manner, the three terraces and the riverbed were investigated. The obtained values of \( K \) were included in the geologic map (Map 1-B) in order to correlate such data with the field data. The estimated \( K \) values ranged between 2.4 and 87,200.4 m/day (Table 1) and were classified between semipervious to pervious (Bear & Cheng, 2010).

### 3.3. Hydrogeology

From a hydrogeological perspective, two hydrogeological units have been defined in the area of study (De Leon-Gomez et al., 1998). The upper unit is composed of alluvial sediments mostly formed by gravels with varying composition of fines. The underneath unit corresponds to fractured shales of the Méndez Formation. Therefore, due to their sedimentary composition and hydrogeological classification, the aquifer is composed of two media: the upper one a granular media and the underlying a fissures media. On this basis, the upper unit could be subdivided into four as per the river terraces and riverbed to in the future serve as framework to evaluate the contamination potential per terrace.

Static levels from water wells available and close to the river were collected using a Solinst acoustic probe. The data was used to create a piezometric chart (Map 1- B) corresponding to March (dry season) using the technique of inverse distance weighting (IDW) in ArcGIS 10.7.1 software. This method interpolates by using the inverse distance between samples (Isaaks & Srivastava, 1989). An advantage of analyzing dry season was that the aquifers’ flow tend to be steadier as there are less water mixtures and potentially, fewer hydrochemical variations.

The calculated piezometric heads ranged between 574.10 (SW) and 496.64 (NE) meters above sea level (masl) (Table 2). The preferential direction of groundwater flow was from SW to NE. The slope changes in hydraulic head indicated that piezometric buffer had three main hydraulic gradient (i) changes: from contour \( \sim 570 \) masl up to approximately contour 561 masl, i was \( \sim 0.38 \)%. Downstream around curve 531 masl, i was \( \sim 0.79 \)% Thereafter, it decreased to \( \sim 0.43 \)% until contour \( \sim 513 \) masl.

### 3.4. Contaminant sources

Contaminant sources were documented through fieldwork across the area. Different approaches exist to classify such sources (Zaporozec, 2002). For this study, the methodology was to organize them by origin adapting a previously proposed list (Freeze & Cherry, 1979) to local sources. On these bases, identified contaminant sources were classified according to the following four categories: clandestine garbage dumps, wastewater discharges, metallurgical waste dumps and others. In addition, a basic site description was generated based on the residues observed. Simultaneously, a georeferenced databank of contaminant sources was generated (Martinez-Quiroga, 2018). This data was incorporated to Map 1-B so that it could be correlated with the terraces. Moreover, sites D148, W75, W78d, W112 and,
O145 are locations where the presence of heavy metals (Ramirez-Gallegos 2017), emerging pollutants (Puente-Martinez, 2017) has been reported and their water chemistry has been analyzed through Piper diagrams (Ramirez-Gallegos, 2017) for two sampling periods. Consequently, photographic evidence was included in Map 1-B for these sites. The aforementioned data was compiled (Figure 4(A–D)) to preliminary investigate its relation to the river’s hydrogeologic and hydraulic conductivity characteristics.

Field investigation yielded a total of 154 river contaminant sources which were organized per municipality according to the aforementioned categories (Table 3).

Inadequate solid wastes treatment has been identified for leading to contamination of water resources (Pokhrel & Viraraghavan, 2005). In the zone, five clandestine garbage dumps were located in SC and Gpe. In general, these locations showed large volumes of residues from different origins (i.e. household, industrial and health-care waste). For example, site D148, showed severe disturbances to the area (Map 1-B). Accumulations of various types of garbage covered T2 and T3, encroached on the riverbed and reached the riverbed surface water. In addition, evidence suggested that garbage was burned openly on-site. On the other hand, previous laboratory analyses (Cruz-López et al., 2020) have indicated concentrations of emerging contaminants such as bis(2-ethylhexyl) phthalate (DEHP) and bisphenol A (BPA) around 200 and 30 μg/L, respectively (Figure 4(A)).
Deficient wastewater treatment or lack of treatment can lead to severe contamination and decrease the quality of river runoffs. In the area of study, 140 contaminant sources were classified as wastewater discharges with some sources found spilling oil residues, soaps or detergents, paints and fecal wastes. For instance, sites W75, W78d and, W112 evidenced unusual liquid and ground colorations, foul smells, and external substances (Map 1-B, Map 1-C). Discharge W75 drained through T3 reaching the riverbed and had gray-colored water accompanied by solid urban waste. Site W78d discharged water of brown colorations that have caused reddish tones in T3 sediments. Previous heavy metals analyses (Ramírez-Gallegos, 2017) have found high zinc concentrations from 3400 to 15,400 μg/L in this location (Figure 4(B)). The comparison of these values with the mean concentration found in groundwater wells in the area (Mora et al., 2017) (i.e. ∼60 μg/L sampling locations M2, M4, M7, M10 and M11) suggested that the superficial water might have higher concentration levels due to the closer contact with anthropogenic contaminant sources.

A similar case was discharge W112, where such analyses showed copper values lower than 1300 μg/L (Figure 4(B)) which compared to groundwater wells mean concentration (Mora et al., 2017) (i.e. ∼13 μg/L sampling locations M2, M4, M7, M10 and M11) indicated an anthropogenic-induced concentration at surface; displayed by the anomalous turquoise tonalities on the sediments (Map 1-B site W112).

In addition to the contamination caused by wastewater reaching the river runoffs, the accumulation of toxic substances and external compounds can lead to harmful consequences. For example, inorganic materials can adhere to sediments, react chemically with other substances and even permeate the subsoil (Guzmán-Colis et al., 2011).

Foundry waste is considered hazardous industrial waste; contamination of soil and water resources due these residues has been identified in different areas of Mexico (National Institute of Ecology and Climate Change (INECC), 2007, Queipo-García et al., 2011). Different types of foundry waste have been dumped in unquantified amounts in several areas of the MMA, including the SCR (Limón Rodríguez, 2000).

In Mty and Gpe, two locations were catalogued as metallurgical waste dumps. These were characterized by slag deposited in slopes with approximate thicknesses of 2–3 m over T2.

The contamination of surface water and shallow wells due to leaks in the sewage systems, septic tanks, and latrines in urban areas represents a significant problem since they are a prevalent source of diffuse pollution that can cause migration of bacteria and pathogen viruses (Foster et al., 1998), (Dávila Pórcel et al., 2012). Seven locations were classified as others. This category comprises septic collectors, pipe leaks flowing to the river, and overflown sewers to the river. The site O145 was a septic collector which presented a spill of gray-colored water and emitted a fecal odor (Map 1-B).

Piper diagrams (Figure 4(C)) for sites D148, W75, W78d, W112 and, O145 (Ramírez-Gallegos, 2017) showed six family types and eight hydro-geochemical facies. The presence of different family types could be related to natural factors and anthropogenic effects. Although some samples showed mixed water types suggesting no dominant ion, the samples with bicarbonate and chloride ions were predominant. Based on the hydro-geochemical facies, the type of waters that dominate for both periods are Ca-Na-Cl-HCO₃ and Ca-HCO₃ (Figure 4(D)).

### 4. Discussion

Three river terraces were identified through the complemented methodology presented here. The analysis of the integrated map (Map 1-B) showed that T3 has more continuity. Sections where T3 was discontinuous was due to urbanization. On the other hand, T2 showed less continuity; its North flank was covered by human settlements from SC up to SPGG municipality. A sparser case was T1 for which only remnants were visible. Therefore, the documented morphological characteristics of the river terraces indicated multiple alterations to their natural properties.

From a hydrogeological view, the estimated K values suggested that liquid contaminants reaching the riverbed and T3 could be more susceptible to be transported across the river and eventually filtrate to the fractured shales unit. Conversely, liquid contaminants reaching the other upper sub-units (i.e. T1 to T2) could be less susceptible to be displaced.

The ease or difficulty of water movement through porous media can be respectively indicated by the
nearness or farness between equipotential lines (Șen, 1995). River cross-sections showed variations in the aquifer’s thicknesses. Thus, these changes could be correlated to the local changes in \( i \). On the other hand, a comparison of the behavior of hydraulic gradients with local tendency changes of estimated \( K \) values were in reasonable agreement. Namely, the increase of \( i \) from the inlet part of the piezometric buffer to the middle section indicated a \( K \) reduction. Meanwhile, the gradient decrease from the middle section to the last portion of the piezometric buffer suggested an increase in \( K \).

The documentation of contaminants sources may help raise awareness about the most affected areas and be considered when a sampling campaign is undertaken.

Although Gpe had the majority of contaminant sources, the major density per kilometer was in SPGG. On the other hand, Gpe presented all the types of contaminants sources and the site D148 showed the highest concentrations of DEHP and BPA which could be attributed to plastic accumulations (Cruz-López et al., 2020).

Mty displayed a zone (Map 1-C) that might be critical as not only has antecedents of heavy metals and emerging contaminants but large volumes of metallurgical waste exist. For example, site W78d had the highest average concentration in cadmium, zinc, and nickel while W112 had the maximum average levels of arsenic, copper, chromium and mercury (Figure 4(B)). Hence, these places appeared to have the highest heavy metals concentrations, which could be related to waste of the former iron-and-steel foundry industry. In addition, the high \( K \) values of the riverbed and T3 could faster propagate these contaminants and the exposure of surface water to anomalous residues increases the contamination potential.

With respect to the dominance of certain ions in the geochemical data (Figure 4(D)), the major presence of chloride could be associated to: precipitations (Ramirez-Lara et al., 2010), a prolonged water exposure to rock in the area (Mora et al., 2017) and anthropogenic contamination (Custodio & Llamar, 1983). The preponderant presence of bicarbonate during rainy season could be associated to the water being in contact with the calcareous shales and limestones of the area of study (Mora et al., 2017).

5. Conclusions

This work provided a detailed overview of the terraces and contaminant sources across the urban section of the SCR. The results represent a step towards evaluating the anthropogenic impact on the river water.

The complemented methodology used in this study comprised fieldwork, analysis of satellite images and GIS-based cartography to effectively map the river terraces and contaminant sources. Such methodology led to identify three terrace levels (T1–T3) and map exposed Cretaceous bedrock. The terraces characteristics documented were: spatial continuity, elevation, thicknesses, distance to water table, sediments composition, \( K \) (approximated through grain-size methods) and presence of contaminant sources. In sum, this information describes the media by which water and contaminants are transported.

The riverbed was identified as the hydrogeological sub-unit with more potential to transport contaminants across the river. In addition, the piezometric chart (dry season) in conjunction with geologic cross-sections and estimated \( K \) values helped analyze the groundwater dynamics in the zone. Subsequent research should incorporate rain season piezometric data to compare with this study.

The amounts of heavy metals previously registered (Ramirez-Gallegos, 2017) in the area, although not above the Mexican standard limit (NOM-001-ECOL-1996), pose an environmental threat further accentuated by the lack of controls on the substances that are discharged to the river. The ingestion of some of these elements could be associated to human pathologies and cancer (Martin & Griswold, 2009). With respect to the emerging contaminants, regulations are not adequate and even low concentrations might be harmful for the endocrine system (Cruz-López et al., 2020).

The data presented here provides a broad picture of contaminant sources present and human-induced alterations to the investigated area. Besides sites with antecedents of heavy metals and emerging pollutants, this research provides 149 additional contaminant sources, which have not been registered or analyzed. The contaminant sources database generated in this study can be useful for future studies on hydro-geochemistry, groundwater contaminant modeling, vulnerability assessments or remediation plans.

Software

Google Earth Pro was used to generate a database and geologic maps with georeferenced discharges, hydrogeological maps and, topography maps were generated using two different GIS software: Mapa Digital de México V6.3. and ArcGIS 10.7.1.

Open Scholarship

This article has earned the Center for Open Science badge for Open Data. The data are openly accessible at https://zenodo.org/record/4563068#.YDgX_ehKgjI.
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