Use of Geographic Information Systems for the Determination of Potentially Polluting Routes in Toluca, Mexico

L. J. Osornio-Berthet*, J. Meléndez-Estrada, M. García-Martínez, and O. Cruz-Castro

Postgraduate Studies and Research Section, Zacatenco Campus, National Polytechnic Institute, Mexico City, Mexico
Email: osornioberthet@hotmail.com (L.J.O.-B.); jmelendeze@ipn.mx (J.M.-E.); maggiegarciamartinez5@gmail.com (M.G.-M.); ocruz@ipn.mx (O.C.-C.)
*Corresponding author
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***Abstract*—Currently, the Lerma River, one of the most important rivers in the country, is going through one of the worst stages of its history due to the excessive amount of toxic waste dumped by some tributary rivers and canals built. The present work shows an innovative methodology for the detection of potentially contaminated sites through an analysis by various criteria that has been analyzed in terms of pollution by industrial discharges, starting from the premise that they are transported by the sewerage network and in the so-called contaminated routes that are the rivers streams and tributary channels to the Lerma River. The main tool used is Geographic Information Systems (GIS) for the analysis and identification of potentially polluting industries. The main objective of this work is to identify the Economic Units in the study basin and filter those whose turn is considered polluting, then classify them according to their economic turn, also analyze the possible impact on the polluting routes. Then calculate the exposed population in the area by means of the population density and the exposed area. The results show that approximately 2.5% of the population is exposed to pollutants derived from the industrial processes established in the 21 polluting routes in the 3 municipalities located in the study sub-basin.**

***Keywords*—pollutants, Geographic Information Systems (GIS), clandestine discharges, waste water**

I. Introduction

Currently, there are different computational tools that allow to contribute significantly to the development of studies that have applicability to guarantee solutions to solve different problems. In addition, they analyze the spatial and temporal variability of different data that make up the information necessary to carry out studies of this nature [1].

It is important to mention that there are different analysis methodologies depending on the risk or situation to be identified. One of these tools is the well-known Geographic Information System (GIS) [2]. which is defined as software designed to capture, store, update, manipulate, analyze and visualize geographically georeferenced data and which allows users to create interactive queries, integrate, analyze and efficiently represent any type of referenced geographic information associated with a territory, connecting maps with databases as well as being able to integrate various types of data layers that use spatial location [3, 4].

Most information has a geographic component and includes images, attributes, and basemaps linked to spreadsheets and tables. GIS emerged at the end of the 60s and work under two premises, on the one hand, from the simulation and modeling systems of disciplines such as ecology or territorial and urban planning, and on the other, from the large statistical and geographic information systems [5, 6].

However, their knowledge did not spread, nor did their use become widespread, until the mass introduction of computers in the 1990s. The progressive evolution of GIS is linked to technological progress, being fundamentally marked by the advances that are being introduced in the field of computers and microprocessors [7].

Researchers and experts such as Marcano Montilla and Cartaya Ríos [8] affirm that the use of GIS is relevant, crucial and necessary in the analysis of disaster risk, so they must be applied to generate greater benefits in territorial planning, prevention and mitigation of the occurrence of risk.

For the purposes of this study, a wide consultation was made to different government portals to detect potential industries and routes of transport of pollutants through the GIS, basemaps were built and information on transport routes of pollutants was condensed. In the Valley of Mexico Basin, much of the wastewater generated by Mexico City and surrounding municipalities is used for irrigation both in the Chiconautla Irrigation District and in irrigation units located on the banks of the Grand Drainage Canal. Downstream of the State of Mexico, wastewater produced in the Valley of Mexico is also used in the irrigation districts of the State of Hidalgo. In the Lerma-Chapala region, part of the wastewater from the Toluca Valley Metropolitan Area is treated and discharged into the Lerma River. Treated wastewater from the region, as well as untreated wastewater, is mixed at the Antonio Álzate dam and subsequently used in irrigation units and irrigation district 33, which are located downstream of this dam. The volumes of wastewater produced in the other basins are smaller and are generally used for agricultural irrigation [9].

The importance of this study lay not only in the selection of one of the most polluted bodies of water in Mexico, but in the conjunction of all the existing information and the delimitation of the area of the Toluca-Temoaya micro-basin to the discharge zone of the José Antonio Álzate dam, State of Mexico, Mexico; where the economic activities that in turn result in the generation of pollutants of industrial origin were selected, as well as the routes by which they are transported before being discharged into the Lerma River. Its important to note to note that although the José Antonio Álzate dam has been extensively studied, due to its high degree of contamination [10], it is used as a water reserve for irrigation during the months of November to April and as an empty tank for flood control during the months of May to October [11]. It handles a flow that fluctuates between 2 m^3/s in dry season and 40 m^3/ s in rainy season. From the point of view of water quality during the months of May and August, due to the reservoir volumes, dilution decreases significantly and, therefore, solids concentrations increase, causing greater activity of anaerobic processes (methanogenesis and sulfide formation), with the consequent decrease in the quality of water bodies [12]. This work shows an innovative methodology to detect potentially polluting sites, through the analysis of the existing economic units in the basin of influence to the Lerma River and the José Antonio Álzate Dam, consists of filtering the industries according to their economic turn selecting as contaminants those whose final product is wastewater that potentially contains some toxic substance, then identify the polluting routes or bodies of water in which these wastes are discharged and follow their trajectory to the reservoir of the Dam downstream. Identifying this area as polluting, subsequently an approximate calculation of the number of people living in the vicinity where these phenomena occur considering 50 m as the area of influence, this work aims to represent through thematic maps the topography of the site, drainage arrangement, polluting routes, type of turn of the industry and exposed population, the number of polluting industries, the polluting routes, the population exposed.

II. Materials and Methods

The sub-basin that has direct influence on the Lerma River was delimited in the vicinity of the city of Toluca, which is called Toluca-Temoaya, which concentrates 50% of the entire urban population of Toluca, with about 123,798 inhabitants, its discharge area is the José Antonio Álzate dam, which is considered one of the most important in the country, fed by the Lerma River, as well as by several rivers in the area, it is considered one of the most polluted in the country. The following methodology was used for data collection [13] (Fig. 1).

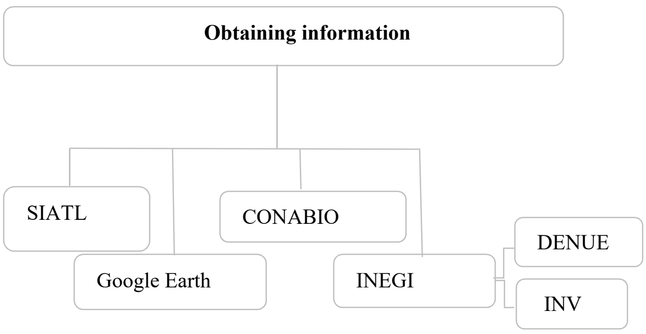

Fig. 1. Geoportals to obtain information. SIATL: Watershed Water Flow Simulator; CONABIO: National Commission for the Knowledge and Use of Biodiversity; INEGI: National Institute of Statistic and Geography; DENUE: National Statistical Directory of Economic Units; INV: National Housing Inventory.

The information collected from government portals was classified into: (a) sociodemographic information: the disposition of urban settlements was analyzed qualitatively and quantitatively using the portal of INV. In addition, the availability of services (sewers, drinking water, electricity, among others) and the existing inhabitants in the area were verified; (b) Organization of economic activities: information was collected on economic activity, geographical location and the number of people working. For this activity, the information collected in DENUE was analyzed; (c) Geomorphological information of the micro-basin: the delimitation by basins of the area of influence and its characteristics was obtained, using SIATL; (d) Natural land levels, characteristics and land-use classification; data that were necessary to determine the runoff coefficient of the endorheic microbasin. This information was obtained from CONABIO [13].

A. Information Processing with GIS

Several parameters were analyzed by industry through the use of GIS, for which it was necessary to establish some basic considerations: (1) An industry whose production of products results in industrial pollutants is a pollutant, (2) A contaminated pathway is one in which potentially polluting waste is discharged, (3) An area close to a polluting pathway, with a radius of influence of at least 50 m, is a pollutant, (4) A potentially affected population is one that is located in a potentially contaminated area.

B. Delimitation of the Basin

The Toluca-Temoaya micro-basin is part of the Lerma River basin. The study area was delimited due to natural runoff in the area of influence of the Lerma River, considering the basin whose influence corresponds directly to the José Antonio Álzate dam. For the purposes of this study, micro-watersheds upstream of the delimited area were not considered. However, important factors such as the topography of the site and the concentration of existing and neighboring industries in the area were considered (Fig. 2).

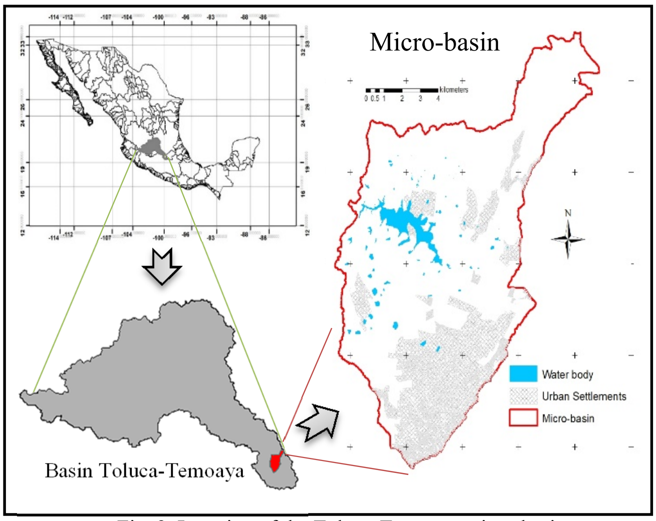

Fig. 2. Location of the Toluca-Temoaya micro-basin.

In addition to the GIS data, a walking tour was conducted to visualize terrain features, tributaries, existing infrastructure, and changing terrain features. Obstacles, infrastructure, turbulent zones (slopes), dead zones (areas of greater accumulation of sediments) along the river were identified and the so-called clandestine discharges were inventoried.

C. Determination of Contaminant Routes

After tracking the possible discharges that directly impact the rivers and ravines tributary to the Lerma River, the contaminants were obtained. For this, the strata of the influences of the industries on the natural runoff (rivers and tributary streams of the Lerma River) were obtained starting from the premise of a radius of influence of 50 m per discharge. It was also considered: a) the proximity of urban settlements to the body of water b) the type of tributary, whether river, stream or canal built, including a closed pipe. It should be noted that the routes established in this work are not all pollutants but those that are most likely to be so, also taking into account the parameter of reviewing the history of contamination of the site through the inventories of CONAGUA that are prepared every two years. It was also determined that several of the critical pollutant routes pass through crop fields. The elements that were necessary to identify the transport routes of polluting industries are the following:

1) Pollution by settlement: physical characteristics of active pollution source and the number of people living there.
2) Affected physical environment: for this study, only surface water bodies (rivers, streams, lagoons, etc.) were considered. These could be affected by various mechanisms, including: convection, advection, dispersion and/or diffusion.
3) Receptor population: populations that are exposed to the pollutants. Also referred to as exposed population.
4) Classification of routes. The choice of exposure routes important for assessment of exposure to critical pollutants was made with the following classification:

Complete route of exposure: route of exposure that has all its elements and that was taken into account for its evaluation within the risk study.

Not complete route of exposure or potential route: route that lacks some of its elements, its consideration as an important route of exposure was left to the discretion of the assessor.

D. Synthesis of Information

From the thematic maps generated for: a) polluting routes and b) classification of industries, the necessary information is obtained for the calculation of contaminated areas and affected population, which will be visualized in: Map of Affected Population (Mpa). This allows a quantitative analysis of the problem and an overview to act and contribute to society.

The first step is to obtain the Population Density, which is calculated with Eq. (1).

$$D = \frac{\text{population}}{\text{AM}} \tag{1}$$

where:

D = population density

population = people number in each municipality that shares territory with the sub-basin

AM = Total area in km^2 of each municipality that shares territory with the sub-basin

Depending on Population Density and the area affected calculated in Mpa, the exposed population is obtained, using Eq. (2).

$$P_E = D \cdot A \tag{2}$$

where:

P_E = exposed population

D = population density

A = affected area on a polluting route

This methodology for detecting potentially polluting sites can be applied in future studies, especially in countries with a high percentage of clandestine dumping, since it allows to know a list of the industries that are potentially polluting for review in future studies.

IV. Results and Discussions

A. Obtaining Information

The geomorphological characteristics of the basin are: an area of 345.35 km^2, with a slope of almost 1% and perimeter of 1,431.38 km, in addition, the order of the basin was verified, which was 5, indicating a large amount of runoff existing in the area. The study area was determined by natural runoff and springs into the micro-basin influenced by the José Antonio Álzate dam. In Table 1, we can see the geomorphological characteristics of the micro-basin [13]:

Table 1. Geomorphological properties of the sub-basin

Property	Value	Unit
Drained area	345.35	km^2
Perimeter	141.38	km
Maximum elevation (in riverbed)	2812	m
Minimum elevation (on riverbed)	2568	m
Slope	0.97	%
Runoff coefficient	10–20	%
Basin order	5	s
Concentration time	283.01	min

In the results obtained on the natural elevation of the land, there is a great slope in the sub-basin behaving as an endorheic basin, mainly the contributions of the south side stand out, whose origin is generated in the city of Toluca, because it highlights a greater number of bodies of water in the form of small lagoons and the direction of flow of the main stream goes from east to west (Lerma River). In rugged terrain like this, with great difference in elevations, there are multiple springs and groundwater streams (Fig. 3).

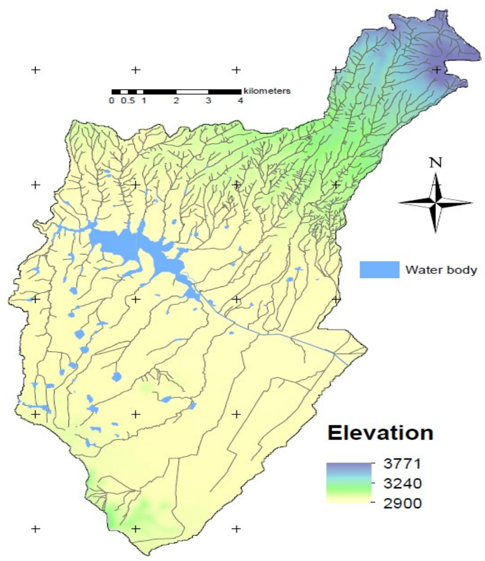

Fig. 3. Elevation map of micro-basin Toluca-Temoaya.

According to SIATL, the following information is available regarding the provision of services: more than 90% of the population has drainage, drinking water and electricity supply, essential factors for urban development and population growth in peri-urban areas (Fig. 4).

On the other hand, the National Housing Inventory considers as AGEB communities with more than 2,500 inhabitants that have more than 75% of essential services covered, communities with a high probability of growth in contiguous areas [13]. According to the INV censuses in 2018, in the regions with growth of the productive sector and industrial development, there is an increase in the number of clusters (set or conglomerate of companies of the same branch interconnected within the framework of a territory). As a result, we are facing localities with a high number of inhabitants and a high probability of growth, which is reflected in an area with a high industrial concentration, thus increasing the probability of contamination of the rivers tributaries to the Lerma River and the use of land in nearby areas.

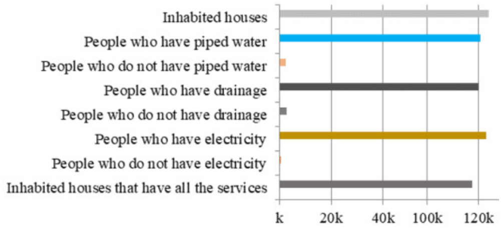

Fig. 4. Services in micro basin Toluca-Temoaya.

Fig. 5 analyzes the drainage disposition in the sub-basin, it can be seen that most localities have a disposition greater than 75%, which discharge their waste into the streams and rivers that run through them; Which is an essential part of the problem we are experiencing: clandestine.

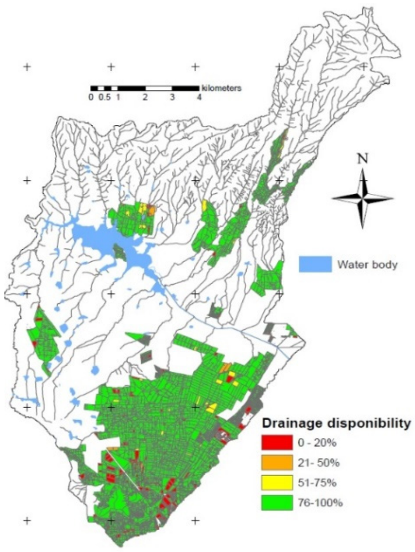

Fig. 5. Drainage disponibility in micro-basin Toluca-Temoaya.

Both municipal and industrial discharges. According to the CONAGUA 2021 report of the 215.4 m^3/s of wastewater collected, only 145 m^3 are treated and what is more important. As the second most densely populated state in Mexico, it is evident that at least three-quarters of the industries dump their waste into the drain without any type of treatment, and subsequently end up reaching the rivers and streams that cross the communities.

This problem can be appreciated only with the evaluation of the water quality of these rivers and their mouth into the Lerma River [13].

In the study area there are various plant communities: forests, bushes, shrub vegetation, induced grasslands, oak pine forests, etc. The dominant vegetation is annual moisture agriculture and annual irrigated agriculture [14] (Fig. 6). The existing vegetation at 2,990 m above sea level corresponds to secondary vegetation and to a large extent there is the presence of human settlements. At altitudes from 2,990 to 3,240 m above sea level, annual irrigated agriculture and annual rainfed agriculture predominate. Finally, from 3240 m above sea level to the hydrographic basin of the study area, pine forests predominate. Industry and agriculture are the main economic activities of this area, since the irrigation district has a large area and is fed by a network of canals and drains that distribute water from José Antonio Alzate.

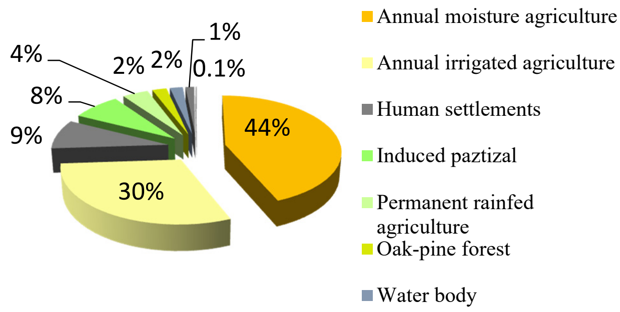

Fig. 6. Land use and vegetation.

It is important to consider that the toxic waste generated is transported through the drainage system, which largely runs through communities in the form of rivers, canals or open ducts, exposing emissions, which can affect the health of people living nearby. The water and sediments of the dam and the bed of the Lerma River are considered a highly contaminated site, according to the report made by CONAGUA and the Water Quality Index that considers various physicochemical and biological parameters [15], [16].

B. *Polluting Routes*

In Fig. 7, you can see the polluting routes that mean the route that the wastewater follows, leading it through channels and tributary rivers to the main cause of the Lerma River and downstream to the Álzate dam.

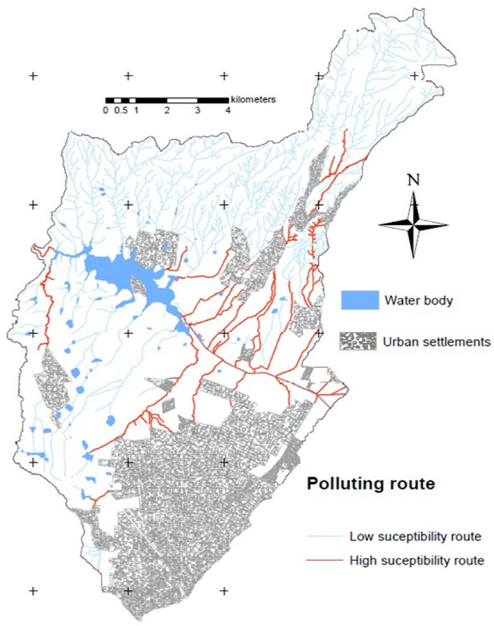

Fig. 7. Polluting route.

In Fig. 8, you can see the distribution of tributaries that are considered polluting routes, among them are some rivers that are contaminated with wastewater that in its path are discharged without any treatment, it is important to note that there are many other clandestine discharges that do not appear in sketches, and that also represent a health and ecological risk.

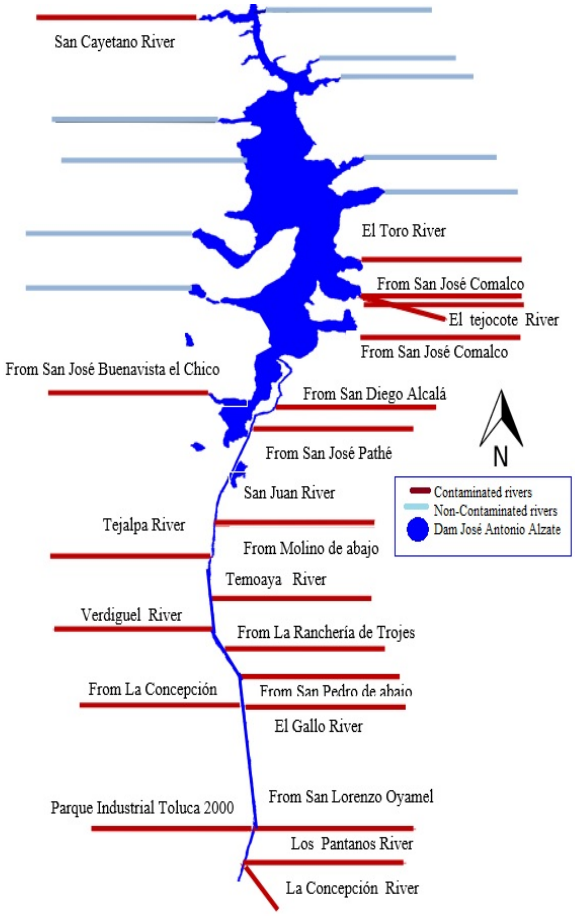

Fig. 8. Polluting tributaries discharging into the Lerma River.

C. Synthesis of Information

Finally, Fig. 9 shows the areas of urban settlements within a radius of influence of 50 m that were directly affected by roads that are mostly open channels and ducts with direct exposure to pollutants, thus representing a vulnerable area causing gastrointestinal and respiratory diseases, etc. This area represents approximately 2.5% of the surface of the 3 municipalities that are currently in the region of the Toluca-Temoaya sub-basin, which are: Toluca, Temoaya and Otzolotepec. They are among the 3 most important municipalities in the State of Mexico. It highlights the presence of toxic pollutants, which are mostly discharged by industries of various types that are located in the vicinity of the city of Toluca and operate based on current regulations. The Official Mexican Standard NOM-001-SEMARNAT-2021 [17], which establishes the maximum permissible limits of pollutants in wastewater discharges to the receiving bodies of the nation, this refers to the establishment of a limit for the physical, chemical and biological parameters in water discharges from various human activities, in such a way that there is no affectation in the receiving bodies, like rivers and seas [18].

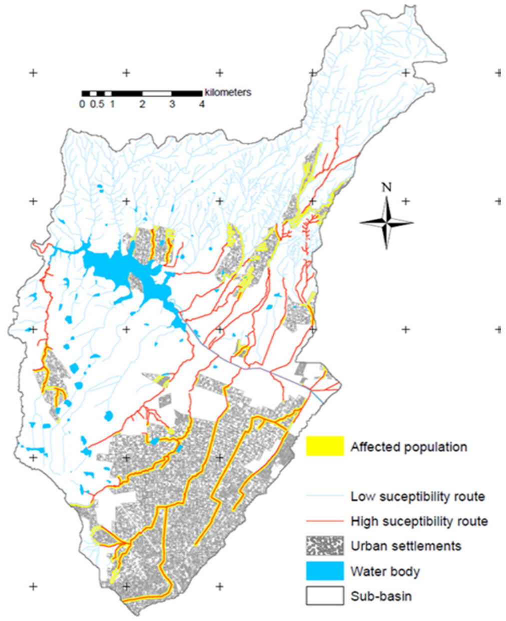

Fig. 9. Affected population.

Based on the information collected in the National Housing Inventory and the calculation of population density by municipality [19], the following information is available (Table 2) for the three municipalities that share territory with the designated sub-basin.

Table 2. Population Density calculation by municipality

Municipality	Total population (population))	Total area (km^2)	Density (population/km^2)
Toluca	90,608	452.37	201
Temoaya	105,766	190.34	556
Otzolotepec	88,783	116.67	761

Based on the areas of influence of the contaminated routes calculated by GIS, the population directly affected within the urban settlement is deduced, it is worth mentioning that this information only expresses the influence of the polluting routes and not the influence of the pollutant discharge (Table 3).

Table 3. Exposed Population calculation by municipality

Municipality	Density (hab/km^2)	Contaminated Area (km^2)	Affected Population (hab)
Toluca	201	11.20	2243
Temoaya	556	4.13	2297
Otzolotepec	761	0.53	402

The water and sediments of the dam and channel of the Lerma River are considered highly contaminated, with respect to the Water Quality Index of CONAGUA. According to previous studies, concentrations of heavy metals that exceed the maximum permissible limits of current regulations for the metals Fe, Mn, Zn, Pb Cr, Cu, and Ni, among others, were also detected, ordered from highest to lowest according to their concentration and bioavailability. This indicates that during the years of operation of the industries studied, the pollutants produced have affected the soil and water of the area for a long time [20].

The above makes evident the implementation of current regulations, a contribution of this work and the application of the methodology is that the identification of the polluting source will be relatively simple because it has the geographical coordinates, as well as the intervention to delimit the risk areas for toxic emissions.

V. Conclusions

The Toluca-Temoaya sub-basin is currently compromised by human activities, mainly wastewater discharges that do not comply with current regulations. Attempts to recover this waterbody have been insufficient, since the volume of water to be treated has been considered extremely high and therefore the amount of pollutants, which leads to the investment of large amounts of economic resources in the case of conventional treatments.

Based on the results obtained where it is observed that based on the detailed geophysical analysis, the elevation of runoff, urban settlements, the availability of services in the 3 municipalities that share territory with the sub-basin and the localities that are located in the area, are possibly responsible for the toxic waste that is dumped in the 14 polluting routes that discharge into the Lerma River, of which there is an exposed population of approximately 2.5% per municipality. It is necessary to implement new mechanisms for detecting pollutant sources and enforcing current environmental regulations to mitigate the spread of pollutants.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

OBLJ and MEJ proposed and coordinated the general methodology of the article, as well as collected field data related to walking routes in the area of the José Antonio Álzate dam. MGM oversaw the development of the thematic maps. CCO contributed to the search of the industries and their economic turns, MGM and OBLJ supervised the general methodology and contributed to the development of the references. All authors read and approved the final manuscript.

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