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Water resource quality as related to economic activity and health patterns in Sonora, Mexico

Calidad de los recursos hídricos en el contexto de la actividad económica y patrones de salud en Sonora, México

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ABSTRACT The aim of this work is to analyze the spatial distribution of potential pollution pathways of water resources given the economic activity in the Mexican border state of Sonora and propose a regional distribution in relation to cancer mortality rates across the state. The methodology is based in an exploratory and inferential data analysis using two sources of primary data: wastewater discharge concessions registered in the Public Registry on Water Rights [*Registro Público de Derechos de Agua*] (REPDA) and the records generated by the National Health Information System [*Sistema Nacional de Información en Salud*] (SINAIS) in the period 1998-2011 based on the International Classification of Disease (ICD-10). The spatial concentration analysis allows for the identification of specific cancer mortality causes at the regional level. Results indicate that the projected adjustments to the regulation NOM-250-SSA1-2014, which controls a subset of pollutants common in mining activity surroundings, is a matter of regional concern.

KEY WORDS Neoplasms; Water Resources, Mexico.

RESUMEN El objetivo del presente trabajo es analizar la distribución espacial de fuentes potenciales de contaminación de los recursos hídricos en el contexto de la actividad económica, y proponer una regionalización en relación con la ocurrencia de defunciones por cáncer en el estado fronterizo de Sonora, México. La metodología se basa en análisis exploratorio e inferencial de datos, en el que se utilizan dos fuentes de datos primarias: los aprovechamientos por descargas de agua residuales inscritos en el Registro Público de Derechos de Agua (REPDA) y los registros generados por el Sistema Nacional de Información en Salud (SINAIS) en el periodo 1998-2011 basado en la Clasificación Internacional de Enfermedades (CIE-10). El análisis de concentración espacial propuesto permite identificar causas específicas de defunción por cáncer a nivel regional. Los resultados indican que es de interés para la región el ajuste de los parámetros de calidad proyectados por la Norma Oficial Mexicana NOM-250-SSA1-2014 que consigna un subconjunto de contaminantes comunes en sitios con actividad minera.

PALABRAS CLAVES Neoplasias; Recursos Hídricos; México.

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INTRODUCTION

The Mexican state of Sonora on the US border has historically recorded an intense mining activity,[1,2,3,4,5] a productive vocation that extends across the border[6] and that has developed human relationships in the binational region between Arizona and Sonora.[7,8,9,10,11]

As regards environment and economy, the Sonora and Arizona border region is an important place for mining activity as it is the main area of copper extraction in Mexico. Due to this fact, 58 companies that produce this mineral have been established in this region and also the two largest mining complexes in the country: Buenavista del Cobre and La Caridad, located in the municipal districts of Cananea and Nacozari respectively.

In the context of the bibliography that addresses the relationship between externalities[a] derived from the economic activity and health effects, a relevant factor for its correlation is long term exposure to common pollutants in places of frequent mining activity. This research establishes that understanding the social factors that affect health is a matter of global priority.[12]

In economic activities such as mining and in particular the extraction of copper, the process known as acid drainage, among others, becomes the focus of attention. This process involves the filtration of residues and the absorption into the sediment of heavy metals, such as cadmium (Cd), chromium (Cr), lead (Pb), iron (Fe) and metalloids, such as arsenic (As), among other chemical elements.[13,14]

Among these elements, arsenic is very important[15,16] because it can be released as a result of anthropogenic activities, such as in open-pit mining typical of copper extraction, although it is an element of natural occurrence, common in arid and semi-arid regions as, for instance, the border region between Sonora and Arizona.[17]

Since the 1980s, several studies have shown that chronic exposure to high doses of arsenic in its organic form is associated with the incidence of cancer and other adverse health effects, including skin conditions[18,19,20] and that drinking water is one of the main pathways of human exposure to this element.[21]

Similarly, in the last decade in this border region, the incidence of diseases such as cancer has shown an increase of 44%, going from 1,594 cases in 1998 to 2,299 cases in 2011, showing an annual growth rate of 3%, which is higher than the annual growth of mortality rate which was 1.1%.

While it has been recognized that the mechanism of pollution of water resources is complex and involves multiple factors,[22] studies have shown that certain anthropogenic activities, such as mining, may increase the risk of exposure of supply sources by way of subsurface contamination or contamination of shallow sources of water supply in population centers, such as rivers.[23]

Moreover, it has been recognized that exposure to chemical wastes resulting from these production processes is a potential risk to health due to its persistence in the environment.[24] When residues deposited in surrounding areas of frequent mining activity reach the surface of water currents, they become a mechanism of transmission that exposes the population to these elements.

In this context, the quality of water resources is an issue that attracts attention when certain events occur, such as the spill of 40,000 m^3 of a solution of copper sulphate (CuSO4) in the surrounding areas of the Bacanuchi River, a tributary of the Sonora River, in August 2014,[25] a contingency that, initially, resulted in the highest economic sanction in history ever imposed by the environmental legislation in Mexico.[26]

As documented, the solution spilt contained the following metal concentration: Iron 1080 mg/l, aluminum 461 mg/l, copper 141 mg/l, manganese 98.1 mg/l, zinc 51 mg/l, arsenic 42.7 mg/l, nickel 11 mg/l, cadmium 7.76 mg/l, lead 2.5 mg/l, chromium 1.54 mg/l; all of them being chemical elements whose adverse impact on health is acknowledged after prolonged exposures and, which has been included in the Official Mexican Standard NOM-127-SSA1-1994 of

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environmental health[28]. Figure 1 shows the location of the area studied in this research.

In spite of the relationship between factors of environmental exposure from a public health perspective, in Northern Mexico, the study of the relationship between anthropogenic-related environmental factors of exposure and geographically disaggregated health indicators is still limited. However, the existence of geographically referenced microdata, provided by the National Health Information System (SINAIS) is a valuable source of information to evaluate this relationship in the Sonora-Arizona border region.

The aim of this study is to analyze the spatial distribution of potential pollution sources of water resources, to propose a regional distribution based on the hydrological characteristics of the State and to conduct an exploratory and inferential analysis of data in relation to the cancer-related deaths in the state of Sonora.

This analysis aims to contribute to the creation of a frame of reference for further studies conducted after the environmental contingency that occurred in Sonora, Mexico in 2014, which presents a challenge due to the complexity of the factors involved. According to regulatory agencies in charge of the protection against health risks, it is advisable to conduct a long-term epidemiological follow-up[25].

The initial conceptual framework of this research is based on the study of social determinants affecting the health conditions of the population from a geospatial conception. This analysis framework helps to connect the development of specific economic activities at the local level with the distribution of health events.

The approach adopted in this investigation is based on two theoretical pillars: the first one is the concept of environmental health defined by the World Health Organization as "those aspects of human health, including quality of life, which are determined by chemical, physical, biological, social and psychosocial factors in the environment."[29 p.23] The second conceptual pillar of this theoretical framework is the paradigm of social epidemiology. As Krieger points out,[30] one of the critiques to the contemporary classical epidemiology canon represented by the multiple causation model is its dependence on medical individualism. This paradigm gives epidemiological methods a predominant position on causation theories of disease, but an alternative approach proposes to complement the classical paradigm with a view on "the social production of disease"[30 p.894] that is not focused only on a biological sphere.[31]

The application of this theoretical approach has been particularly accepted at a global level in order to understand the relationship between health and economic activities such as mining, an area in which a poor understanding still prevails despite the growing social interest in investigating this relationship. The growing importance of the research in this area suggests that the incorporation of geographic aspects contributes to understanding the mechanisms of exposure and incidence[24,32,33] as well as the design of long-term evaluation schemes in the event

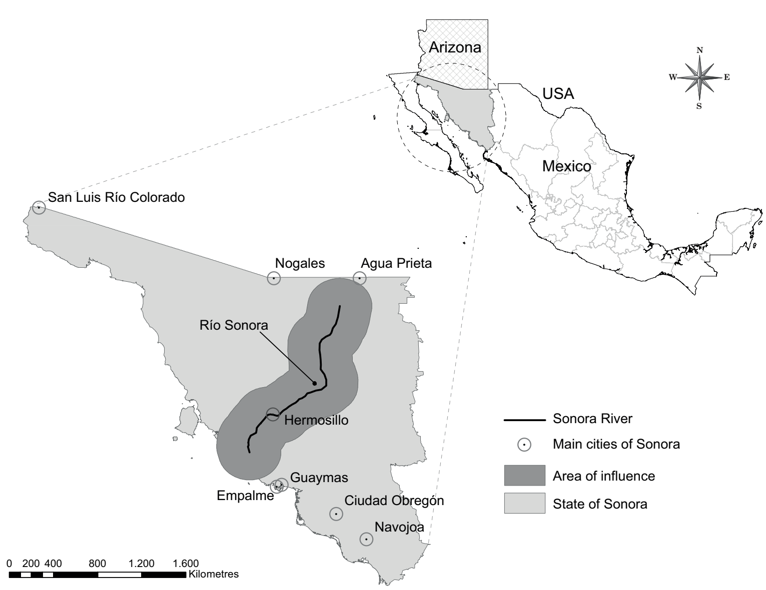

Figure 1. Location of the area under study. State of Sonora, Mexico.

Source: Own elaboration based on information provided by the National Institute of Statistics and Geography (INEGI) and the National Commission for the Knowledge and Use of Biodiversity (CONABIO).

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of hazardous occurrences. For this reason, it is considered that applying this conceptual framework could provide elements about social determinants in the context of the economic activity in the border state of Sonora in the north of Mexico.

METHODS

The study is based on an exploratory and inferential data analysis. The analysis is divided into two phases: the first one applies spatial analysis techniques to determine the relationship of economic activity and the uses registered in the Public Registry on Water Rights (REPDA) under the category of wastewater discharges.

This level of analysis is relevant due to the social implications related to the quality of the surface water resources of the state. A delimitation by watersheds has been adopted as the unit of analysis. In this line of research, geostatistical tools using the Kriging-based probabilistic method(34) have been applied, which adopt the principle of ordinary least squares regression in the geographic context(35) to build a surface that shows the spatial density of the concessions by discharges of wastewater, enabling the identification of important areas based on discharge clusters.

For this purpose, a geostatistical Kriging probability model was constructed, which uses applications such as those proposed by Waller and Gotway,(36) which determines the probability of exceeding the average volume under concession in the state, considering the geographical distribution of the concessions from a spatial correlation function, and helps to build a surface that shows the concentration.

The model is based on the following functional formula:

$$I(s) = I(Z(s) > ct) = \mu 1 + \varepsilon 1(s),\ Z(s) = \mu 2 + \varepsilon 2(s)$$

Where: I(s) is a binary variable that takes the value 1 if the average volume under concession is exceeded, otherwise it takes 0; IZ(s) > ct) is the reference threshold; Z(s) is the volume of the concession authorized in the area s; $\mu 1$ and $\mu 2$ are the constants and $\varepsilon 1$, $\varepsilon 2$ are stochastic errors.

The data source in this first stage of the research has been compiled from the Public Registry on Water Rights created by the National Water Commission (NWC),(37) which provides georeferenced information on the concessions for wastewater discharges in the state. The Public Registry on Water Rights reports that there are 642 concessions with variables, such as the volume granted and the type of discharge, which associates the impact with specific economic activities throughout the 72 municipal districts covered by the registry. The objective of the first section is to propose a regional distribution from which health indicators in the second stage of the research may be explored.

In the second stage, an exploratory and inferential analysis of data was conducted by using the records provided by the National Health Information System (NHIS) in the time period 1998-2011. This information makes it possible to study the spatial patterns of deaths by cancer in the state of Sonora. The database is based on international standards as the information has been compiled from the International Classification of Diseases (ICD-10), which makes it possible to create indicators to be compared at an international level.

A total of 14,752 records were included for the year 2011 and, within those records, the deaths classified under the C00-C97X code regarding neoplasias, were identified.(38) Density curves were constructed to study the age structure of deaths by cancer and other causes. Based on this structure, age-adjusted mortality rates were estimated every 100,000 inhabitants at a municipal level and per region, which made it possible to obtain a standard comparison measurement.

In addition, in this second part of the research in order to detect specific causes of cancer mortality in each region of the state, the relative spatial concentration measurement has been estimated, here referred

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to as *local index of deaths* (ILD) for each year in the period 1998-2012, which also makes it possible to observe the historical trajectory of the indicator. This is a measurement that takes up the principle of location indicators[b] of economic activity, developed in the context of the bibliography on regional analysis.(39) However, given its potential to detect patterns of spatial behavior, it is a measurement that has been taken into account in the field of biostatistics and empirical studies of an epidemiological nature, as documented by the contributions made by Beyene and Moineddin,(40) Moineddin *Et al*.(41) or Wright.(42)

In this context, the measurement is applied by taking into account the geographic reference of the available microdata on cancer in Mexico. The local index of deaths is represented as follows:

$$IDL = \left(\frac{c}{T}\right)_r \Big/ \left(\frac{c}{T}\right)_s$$

Where c represents deaths for a particular cause within the C00-C97x range; T represents the total number of deaths within the C00-C97x range. Subindexes r and s refer to the regional and state geographic areas respectively. This indicator reflects the proportional incidence in a geographic area and calculates the size of its population in terms of the incidence observed in a base geographic area. This research focuses on each of the five regions of the state of Sonora. Two thresholds of the index are taken as reference: IDL > 1 indicates a higher incidence of the disease under study in relation to the level observed in the state for the i-th region. Similarly, IDL < 1 indicates a lower incidence in that region with respect to the state. This indicator will make it possible to distinguish the specific causes with greater incidence in each region of the state, which may be useful in terms of specific economic activities.

From the information obtained in the exploratory data analysis, an inferential statistical model was proposed which applies logistic regression to evaluate the relative significance of each region considering additional demographic characteristics, such as sex and age group. The formula of this model is the following:

$$Y = \frac{1}{1 + e^{-\left(\alpha + \beta_1 + \beta_2 + \beta_3 + \beta_4\right)}}$$

The dependent binary variable Y takes the value of 1 if the death was caused by cancer – classified under the C00-C97x code of the International Classification of Disease – otherwise it takes 0.

The dependent variables of the model are: β_1 age group: 1 (0-14 years), 2 (15-64 years), 3 (65-74 years), 4 (75 and more); β_2 sex: 1 (male), 2 (female); β_3 region: 1 (South), 2 (Yaqui River), 3 (Empalme), 4 (Sonora River), 5 (North). The regionalization was based on the hydrological criteria and the location of the mining activity in the state.

The dichotomous cluster variable (β_4) takes the value of 1 if the individual resides in one of the municipal districts included in the zones of relative concentration by discharges of wastewater established in the geostatistical model; otherwise it takes 0.

RESULTS

Quality of water resources

As documented, a relevant analysis on the consequences of health conditions is the one that refers to those activities that affect the quality of water resources, as the latter constitute a mechanism of transmission that exposes people to pollutants.

In order to analyze the externalities of the economic activity on water resources, the state of Sonora was classified into five regions by taking into account their relationship between their proximity to areas of mining activity and the hydrological division of the state by watersheds. The regions were divided as follows:

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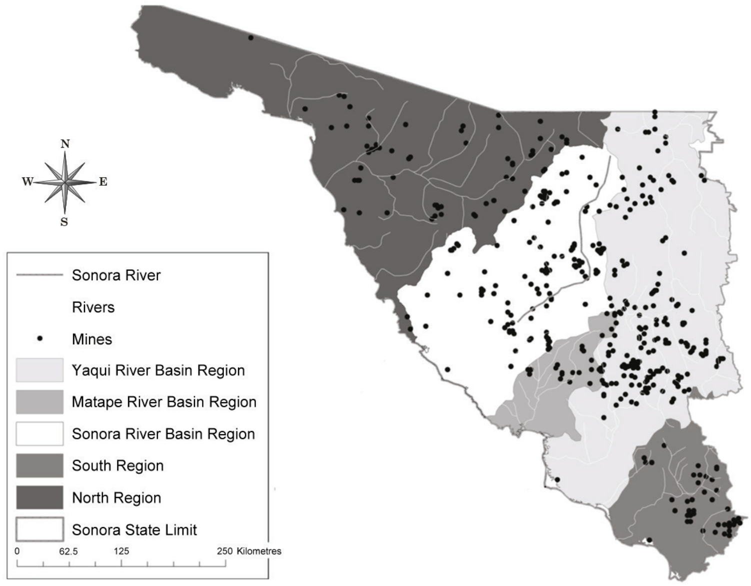

Figure 2. Regional distribution to measure the negative externalities of economic activity. State of Sonora, Mexico, 2015.

Source: Own elaboration based on data from the National Institute of Statistics and Geography (INEGI) and the National Commission for the Knowledge and Use of Biodiversity (CONABIO).

- Region 1 (South): formed by the basins of the rivers Mayo, Fuerte and Estero de Bacorehuis, which comprises 43 mines.
- Region 2 (Yaqui River): formed by the basin of the Yaqui River which comprises 173 mines.
- Region 3 (Empalme): formed by the basin of the Matapé River, which comprises 27 mines.
- Region 4 (Sonora River): formed by the basins of Sonora River and Bacoachi River, which comprises 121 mines.
- Region 5 (North): formed by the basins of Bacanora-Mejorada, Colorado River, Altar-Río Bamorí Dessert, Concepción-Arroyo Cocaspera River, San Ignacio, which comprises 64 mines.

Figure 2 shows the suggested regional distribution, based on the hydrological criteria and the location where mining activity takes place in the state and Figure 3 shows the Sonora River basin and its area of influence within the municipal demarcation. In Sonora there are a total of 428 mines, 138 of which are gold mines, 97 are silver mines, 58 are copper mines and 8 are coal mines.

Figure 4 shows the spatial distribution of the concessions registered in the Public Registry on Water Rights under the category of discharges, exploitations that impact on the quality of water resources at the local level and are of special importance for their implications in contamination from the perspective of environmental health. For more information, two radiuses of influence with a circumference of 70 km are included, taking as criterion for their delimitation the density of concessions around the two main cities of the state: Hermosillo and Obregón in the south.

Figure 5 shows the result of the geostatistical model for the density of concessions due to wastewater discharges, making it possible to detect which are the areas of relative concentration in the state.

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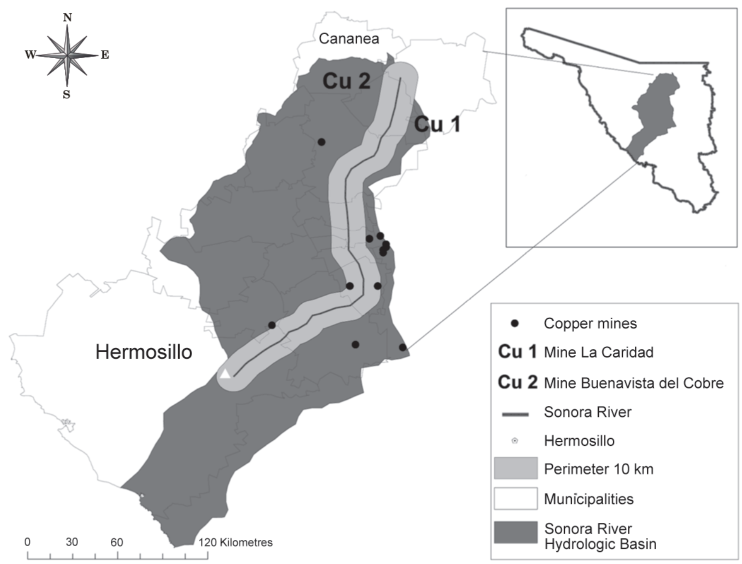

Figure 3. Regional distribution to measure the negative externalities of economic activity. Sonora River Basin, Mexico, 2015.

Source: Own elaboration based on data from the National Institute of Statistics and Geography (INEGI) and the National Commission for the Knowledge and Use of Biodiversity (CONABIO).

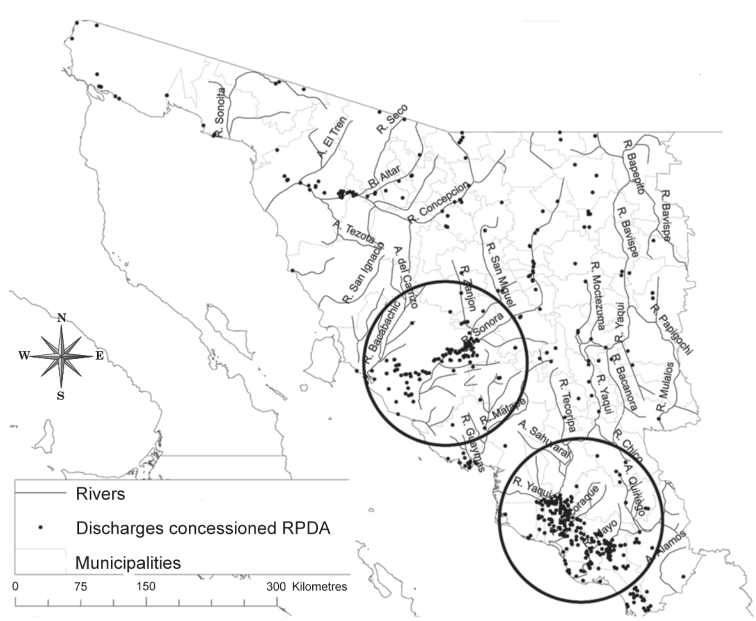

Figure 4. Spatial distribution of exploitations of wastewater discharges. State of Sonora, Mexico, 2015.

Source: Own elaboration based on data from the National Water Commission (CONAGUA)

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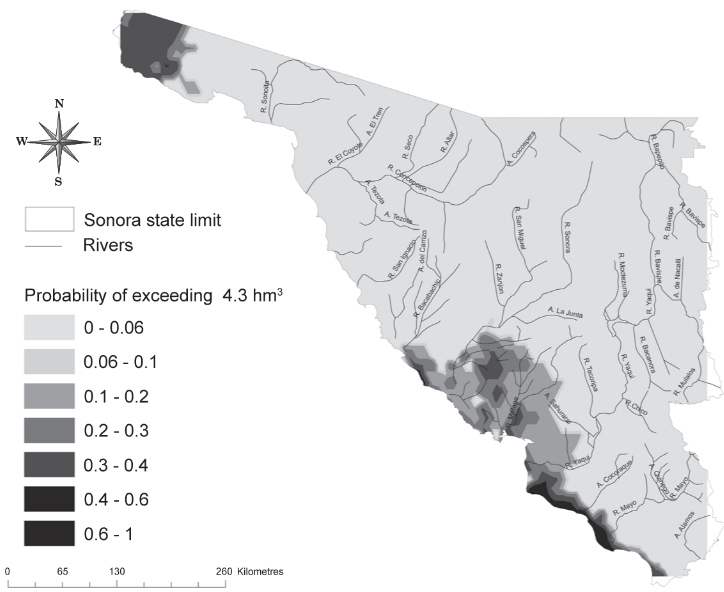

Figure 5. Spatial distribution of exploitations of wastewater discharges. State of Sonora, Mexico, 2015.

Source: Own elaboration based on data from the National Water Commission (CONAGUA).

The categorization of discharges registered by type makes it possible to determine that aquaculture and industrial use are the main contamination emitters in the state, which account for 54.7% and 41.1% of the total volume of concessioned discharges respectively, while the types urban, livestock, services and agriculture emitters together account for the remaining 4.2%. This classification of concessions enables to emphasize the importance of the industrial activity in which mining, as discussed, plays a central role. In turn, the results indicate the impact of a dynamic aquaculture activity that takes place in the municipal districts along the Gulf of California, among which Guaymas is the main municipality because of its concessioned volume for conducting wastewater discharges.

In addition, the geostatistical model confirms the existence of a cluster of residual discharges that includes the municipalities of Hermosillo, Guaymas and Huatabampo on the Pacific coast. This distribution is important as it points out that the location of the concessions per discharges exerts pressure on three surface currents adjacent to urban concentrations: the Sonora River, the Yaqui River in the vicinity of Obregon, an important industrial center of the state, and the Mayo River in the borders of the city of Navojoa.

Cancer-related deaths in the state of Sonora

This section focuses on the study of spatial distribution of cancer-related deaths in the state of Sonora. As previously mentioned, the effects of specific economic activities, such as mining, affect the quality of water resources in the vicinity of important urban centers of the state. One of the social implications of these effects is manifested in the health conditions of the population. In this context, an interesting relationship was found between the incidence of cancer-related deaths as a consequence of long term exposure to pollutants in

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areas of mining activity.[20,43] This relationship is still poorly understood, although it is recognized that there is no direct causality due to the multiple risk factors involved.

Figure 6 shows the historical evolution of cancer-related deaths in the last decade, whereas figure 7 shows the age structure of cancer-related deaths in the state of Sonora in 2014.

The density curves relating to the distribution of the ages of deaths in Sonora reveal that cancer is a disease that shows a greater incidence in individuals between the ages of 37 and 78 and reaches its highest level around the age of 74, on average. As it is observed, cancer is a cause of death that clearly affects the individual's productive stage. This distinction is also notorious due to the gap existing after the age of 78, in which the remaining causes of death ("Other causes" category) occur more frequently. It is interesting to note that, for the child population, the incidence of other causes prevail.

In order to control the gap found in age distribution, age-adjusted mortality rates in each of the proposed five regions of the state were estimated by using the direct method[44] as well as the age standardization of the state as the standard population (Figure 8). Regarding the results of the estimate of the local death index, the age-adjusted mortality rate for the C00-C97X categories corresponding to cancer-related deaths for the state of Sonora is 87 persons per every 100,000 inhabitants, which is higher than the figure estimated for the national level in the same time period: 69 individuals for every 100,000 inhabitants according to the World Health Organization[45]; and which is lower than the figure estimated in the nearby state of Arizona: 156 individuals per every 100,000 inhabitants in the period 2007-20011.[46]

On the one hand, the estimate makes it possible to notice a clear difference in this phenomenon across the state, in which region 3 (Empalme) has the highest mortality rates. On the other hand, the estimate of the local index of deaths provides the means to identify in each region the specific causes of death that occur in a higher relative

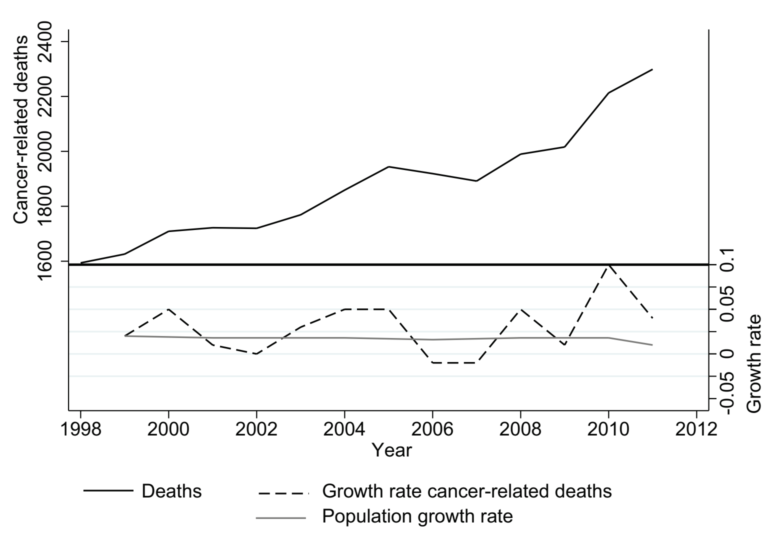

Figure 6. Cancer-related deaths. State of Sonora, Mexico, 1998-2011.

Source: Own elaboration based on data from the National Health Information System (SINAIS) and from the National Institute of Statistics and Geography (INEGI).

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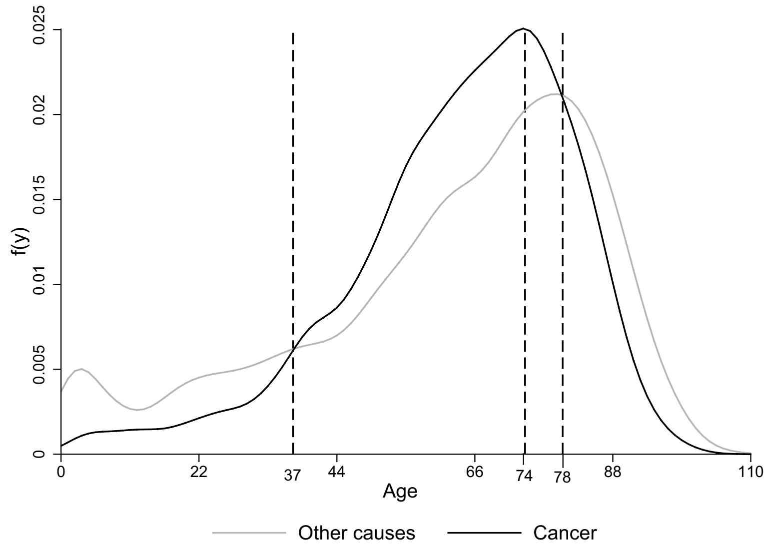

Figure 7. Distribution of cancer-related mortality and other death causes, by age. State of Sonora, Mexico, 2011.

Source: Own elaboration based on data from the National Health Information System (SINAIS) and population data from the National Institute of Statistics and Geography (INEGI).

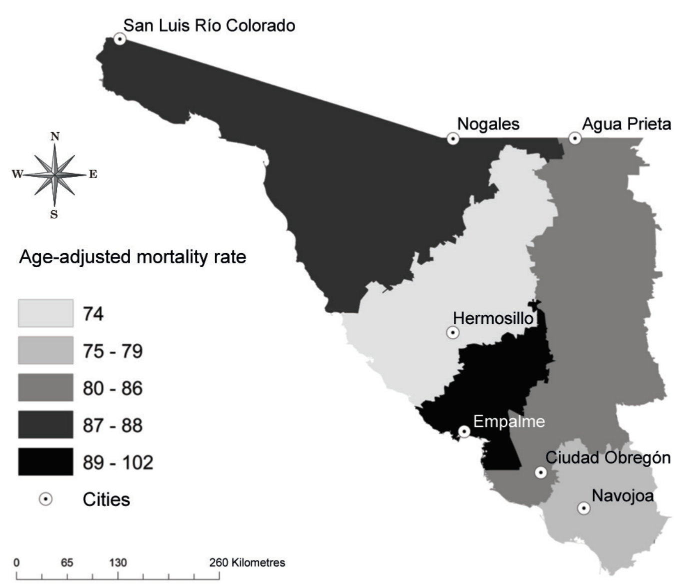

Figure 8. Age-adjusted mortality rates per region. State of Sonora, Mexico, 2011.

Source: Own elaboration based on data from the National Health Information System (SINAIS).

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proportion in comparison to the level observed in the state. The following causes of death have been identified per region:

- Region 1 (South): C32 (larynx malignant neoplasm of the larynx); C76 (malignant neoplasm of other parts of the body or wrongly identified body parts); and C90 (multiple myeloma and malignant neoplasm of the plasma cells).
- Region 2 (Yaqui River): D38 (middle ear malignant neoplasm of unknown or uncertain behavior and of respiratory and intrathoracic organs); C53 (malignant neoplasm of the cervix); C61 (malignant neoplasm of the prostate)
- Region 3 (Empalme): C45 (mesothelioma); C71 (malignant neoplasm of the encephalon); C23 (gall bladder malignant neoplasm of the gall bladder).
- Region 4 (Sonora River): C34 (malignant neoplasm of bronchus and lung); C16 (malignant neoplasm of stomach); C18 (malignant neoplasm of colon)
- Region 5 (North): C25 (malignant neoplasm of pancreas); C64 (malignant neoplasm of kidney); C15 (malignant neoplasm of esophagus).

Table 1. Logistic regression model for cancer-related deaths. State of Sonora, Mexico, 2014.

Variables	OR	*p*-value	95% CI
Sex			
Male[1]	-	-	-
Female	1.20	0.00	1.14; 1.37
Age group			
0-14[1]	-	-	-
15-64	3.83	0.00	2.79; 5.25
65-74	4.51	0.00	3.27; 6.22
+75	2.67	0.00	1.94, 3.67
Region			
South Region[1]	-	-	-
Yaqui River Region	1.12	0.14	0.96; 1.31
Empalme Region	1.08	0.48	0.88; 1.32
Sonora River Region	1.27	0.00	1.09; 1.48
North Region	1.15	0.11	0.97; 1.36
Cluster			
Outside[1]	-	-	-
Inside	1.17	0.02	1.02; 1.33

Source: Own elaboration based on data from the National Health Information System (SINAIS).
[1]Value of reference.
OR= Odds ratio; 95% CI= 95% Confidence interval.
Note: The selection of the model specification was based on the Hosmer-Lemershow goodness of fit test. Furthermore, standard tests were applied to rule out problems of multicollinearity and specification errors in the link function between the dependent variable and the regressors.

Although the exploratory phase of data has revealed important evidence to study this relation, inferential methods should be applied in order to examine the differences among each region of the state and their interaction with the characteristics of the population, such as age and sex.

Table 1 shows the results of the inferential analysis in which cancer-related deaths in the state are considered the dependent variable.

In the case of the "sex" variable, it was found that the probability of a cancer-related event shows a statistically significant increase for females in comparison to males (OR=1.2; 95%CI [1.14; 1.37]). With regard to the "age group" variable, it was observed that the group that has a higher probability of suffering a cancer-related event is under category 3 (65-74 years old) (OR=4.51; 95%CI [3.27; 6.22]), which confirms the exploratory analysis carried out in the previous section. It was also found that the increase observed in category 4 (75 years old or more) is lower than the increase in the previous category, which means that in this age group the prevailing causes of death are different from those in the age group 65-74 years old.

In the case of the "cluster" variable that groups the municipal districts by the wastewater discharge activity, an odds ratio of 1.17 (95%CI [1.02; 1.33]) was observed, therefore living in the municipal districts that make up the cluster is associated with an increase in the probability of dying of cancer.

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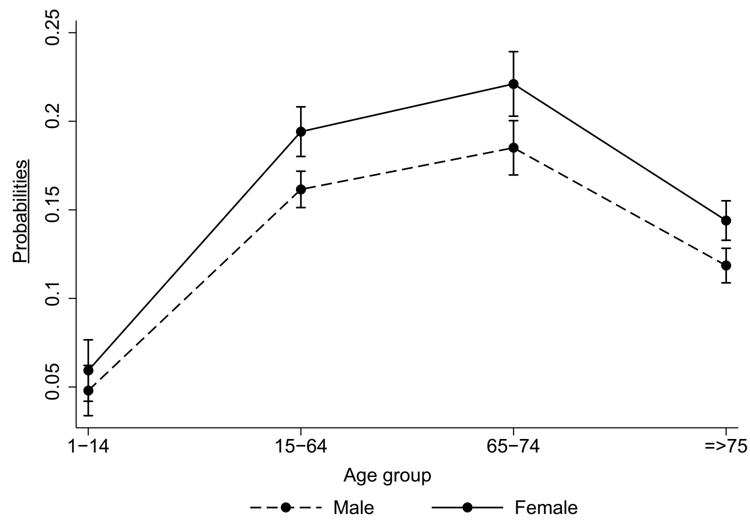

Figure 9. Estimated probabilities for cancer-related mortality depending on sex. State of Sonora, Mexico, 2014.

Source: Own elaboration based on data from the National Health Information System (SINAIS)

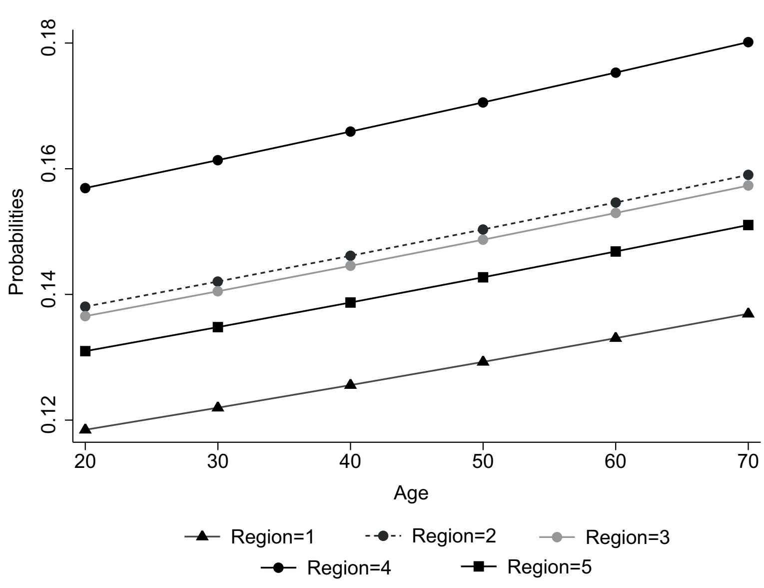

Figure 10. Estimated probabilities for cancer-related mortality by region. State of Sonora, Mexico, 2014.

Source: Own elaboration based on data from the National Health Information System (SINAIS).

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The "region" variable highlights two important findings: the first one is that, apparently, the difference among the odds ratios for regions 1, 2, 3 and 5 is not statistically significant; the second finding shows that the probability of incidence of a cancer-related event among region 1 (South), the category of reference and region 4 (Sonora River) increases remarkably (OR = 1.27; 95%CI [1.09; 1.48]). In order to have a graphical view of these findings, the evolution of probabilities is estimated by the marginal effects with the interaction among the "age group", "sex" and "region" variables (Figure 9 and Figure 10).

The results show the highest probability of cancer in females and its evolution as their age increases, reaching the highest level in the 64-74 age group. However, the probabilities differ for each region, ranging from 12% to 18% and reaching the highest level in region 4 (Sonora River). In accordance with the international estimates of the National Cancer Institute,[47] the probability of dying of cancer in the period 2009-2011 was 17.7% for the Hispanic population in the US.

RESULTS, DISCUSSION AND CONCLUSIONS

In the relation between the economic activity and environment, the spatial distribution of the mining activity and wastewater discharge concessions was examined as these activities have an impact on the quality of water resources and constitute a transmission mechanism that exposes the population to pollutants.

The debate was developed under the theoretical paradigm that holds that the incidence of health conditions is the result of social production[48] in which the economic activity is the immediate trigger owing to the fact that it creates negative externalities that are susceptible to affect the population's health condition.

This research agrees with previous studies carried out by authors such as Bundschuh, *et al.*,[23] who, within the context of public health for Latin America, affirm that anthropogenic activities, such as mining, cause problems that impact on public health, as they facilitate the mobilization of natural pollutants.[23] In addition, in spite of the fact that authors such as Ebenstein[49] have previously documented the relationship between the increase in cancer of the digestive organs and water quality deterioration, his proposal differs from this approach, among other causes, because he considers the process of economic development as a triggering factor and takes into account, for his empirical validation, the case of countries having a fast growth rate of the economic activity in the last decade, for example, China. One of the challenges of this approach is the control of possible effects arising from the exposure to risk behaviors and traditional social determinants, such as diet, tobacco and the exposure to air pollutants, which have an impact on the incidence of diseases, such as cancer. Moreover, the results of this study might be complemented with additional research efforts that provide evidence regarding the suggested causality relationship.

As it has been documented in this study, the regional variations at the levels of health indicators observed here provide the means to identify different degrees of population vulnerability and these data represent an asset for the design of preventive strategies that is not restricted to manufacturing or traditional extractive industries, such as mining. However, this study's examination of the mining field becomes pertinent for the need of having a better understanding of the impact of contingencies at the local level in the long term.

The complementary elements proposed by Colborn[50] within the context of public health reveal the potential of a multidisciplinary approach suggested in this study. The author investigates emerging activities such as the extraction of unconventional sources of natural gas (shale gas) by using a technique called *hydraulic fracturing*, which is a powerful technique in the use of water resources and which, according to Myers,[51] poses potential pollution risks of water supply sources for human consumption.

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This is an area of interest that reveals the usefulness of applying the paradigm suggested in this study for several Latin American countries, such as Venezuela, Brazil, Mexico or Argentina; the latter having the most significant potential amount of unconventional sources of natural gas reserves in the American continent, mainly around the basin of Neuquén.[52] Therefore, addressing the local implications may be of interest under a broad conception of the factors that determine the health conditions of the population, and the analytical framework applied in this research provides an alternative for its approach.

While some proposals, for instance, the analysis carried out by Mactaggart,[53] also highlight the distinction in the degree of population vulnerability in terms of the rural or urban nature of the area of analysis, in this research this aspect is not addressed in an explicit manner, beyond the regional delimitation based on hydrologic criteria, thus, this aspect is perceived as a research opportunity for future research studies.

In this study, the proposed regionalization based on the distribution determined by the hydrographic basins enabled to establish the means to detect differences among the age-adjusted cancer-related mortality rates in region 3 (Empalme), which includes the municipal districts of Empalme, Guaymas, La Colorada, Mazatán and Villa Pesqueira and has the highest rates in the state: 102 cancer-related deaths for every 100,000 inhabitants. This figure is higher than the estimate made at a national level in the same period of time: 69 cases for every 100,000 inhabitants, according to the WHO,[45] but it is lower than the figure of the nearby state of Arizona: 156 cases for every 100,000 inhabitants in the period 2007-2011.[46]

Additionally, the proposed analysis of spatial distribution helped to examine the behavior of identified cancer-related mortality inside the region. In fact, in region 3 (Empalme) a particularly high incidence of cases was found under category C45 for mesothelioma, a type of cancer whose relationship with productive activities had been documented[54]; which indicates areas of possible intervention in the design of monitoring strategies in the economy-health relation in the state.

The model designed with inferential techniques makes it possible to determine that the 8 municipal districts that make up the wastewater discharge cluster show a higher probability of causing cancer-related deaths in comparison to the districts in the state outside this area. Moreover, it was found that the probabilities regarding cancer-related mortality in the state of Sonora differ for each region in a range of 12% to 18%, reaching their highest level in region 4 (Sonora River), a result that is comparable to the estimates for the Hispanic population in US, which registers a 17.7% probability of dying of cancer, in the period 2009-2011.[39]

In region 4 (Sonora River), a relative concentration of the occurrence of cancer-related deaths was observed in the following events: malignant neoplasm of bronchus and lung, malignant neoplasm of stomach and malignant neoplasm of colon. Although in the first event mentioned a relationship with the exposure to pollutants, such as arsenic, has been proven,[20] establishing a causality relationship with specific exposure levels requires further research studies, given the multiple risk factors involved.

Nevertheless, considering the chemical elements, such as arsenic, found in the area of influence of the mining contingency that occurred in Cananea in 2014, located in region 4 (Sonora River) as described in this study, with a level of 42.7 mg/l[27], which exceeds the permissible limit in human consumption water that is of 0.05 mg/l in accordance with the Official Mexican Standard NOM-127-SSA1-1994, it is concluded that the proposal of adjustment of the parameters of such regulation is of interest for the region as provided in the NOM-250-SSA1-2014, which includes a subset of common pollutants in mining activity sites.

Additionally, the analyzed relationship between the supply sources of water resources for human consumption and the intense mining activity in the state suggests the

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need for a specialized regulatory agency that monitors the environmental issues of mining activity, an entity that is taken into account in other fields having a high probability of causing negative environmental externalities; for example, hydrocarbon extraction is supervised by the recently created Agency for Security, Energy and Environment (ASEA) that offers a framework for analysis regarding the occurrence of contingencies in a field that, certainly, poses risks of emission of wastes that are potentially harmful to health.

Within the context of the mining activity, the proposed agency could create favorable conditions in order to have a better understanding of the impacts of this economic activity and its interrelation with the transmission mechanisms found in potable water supply sources.

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FINAL NOTES

[a] In the social field, this concept refers to the existence of impacts (positive or negative) on third-parties, commonly associated with the performance of economic activities. Its origin may be traced in the pioneering study carried out by Professor Ronald Coase, Economy Nobel Prize 1991. In this research study, this concept is used to refer to the adverse impacts on the population's health conditions, which results in social costs;

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thus, it is assumed that these impacts are negative externalities. The concept is not restricted only to the connotation of negative externalities. Within the context of public health, a classic positive externality is the benefit for the community derived from vaccination campaigns, due to the fact that vaccination and its effects of preventing the transmission of a disease to the community produce indirect benefits or positive externalities.

[b] Within the context of regional analysis literature, a contrastive measurement to gauge the relative concentration of economic activities is the so-called location quotient (LQ). This technique has been recently applied in the field of biostatistics and has been taken up in this research study using the geographic reference of the studied microdata.

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