Using a GIS to Overcome Data Adversity: Industrial Air Pollution Risk Modeling in Tijuana, Mexico

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Abstract

Dramatic population growth and urban expansion, rapid industrialization, and inadequate infrastructure in Mexican border cities have resulted in a myriad of environmental problems, including increased air pollution. Despite their importance, data are not extensively gathered on air quality or pollutants being measured from industrial sources. The primary goals of this research are to explore the distribution of Tijuana's industrial air pollutant generation, to examine how the city's morphology affects the types of residential areas which are most susceptible to air pollution from industrial sources, and to demonstrate the possibilities of spatially disaggregating these effects within urban environments. These goals were accomplished through the use of an industrial air pollution risk model (IAPRM) that integrated spatial data on industrial location, estimated air pollution, and housing quality within a GIS environment. It was found that a small percentage of Tijuana's industries produce the majority of air pollutants and this disproportionately puts middle-class residents at risk.

Introduction

Dramatic population growth and urban expansion, rapid industrialization, and inadequate infrastructure in Mexican border cities have resulted in a myriad of environmental problems, including increased air pollution. Despite their importance, data are not extensively gathered on air quality or pollutants being emitted from maquiladoras[1] and other industries. The nature of these emissions and the amounts produced have not been measured sufficiently, if at all. Furthermore, the geographic distribution of these industrial air pollutant emissions and the relationships between industrial and residential areas have not been examined. The large scale at which this study is conducted and the paucity of essential data eliminate the use of traditional air quality models which require substantial meteorological, topographic, and air quality data. This study models the patterns of industrial air pollutant emissions and their relationship to the location of different types of residential areas that reflect social-economic characteristics in Tijuana, Baja California, Mexico within a geographic information system (GIS) environment. Tijuana is located along the United States-Mexico border just south of San Diego, California (see Figure 1). The primary goals of this research are to explore the distribution of Tijuana's industrial air pollutant generation, to examine how the city's morphology affects the types of residential areas which are most susceptible to air pollution from industrial sources, and to demonstrate the possibilities of spatially disaggregating these effects within urban environments. These goals are accomplished through the use of an industrial air pollution risk model (IAPRM) that employs a GIS to integrate spatial data on housing quality, industrial location, and estimated air pollution (see Figure 2).

Urban environmental degradation resulting from industrial pollution is a concern for developing countries throughout the world. Industrial growth fueled by foreign interests affects places as widely distributed as Mexico, the Philippines, Thailand, Indonesia, and the Caribbean (Brandon and Ramankutty, 1993; World Bank, 1994). Local environmental problems, however, can highlight international relations and this is particularly true in transborder communities. The maquiladora industry in Mexico generates significant amounts of pollution that represent a critical environmental situation (Bowen *et al.*, 1995). The growth of maquiladoras in the border region began nearly three decades before the 1994 ratification of the North American Free Trade Agreement (NAFTA) and expansion is expected to continue (Pick and Stephenson-Glade, 1994).

The environmental impacts of international trade have been more carefully scrutinized in recent years because of the acceleration of detrimental environmental effects related to international trade agreements, such as NAFTA, and differential economic levels between nations, such as those between the United States and Mexico (Lee and Roland-Holst, 1993). A particular concern is exposure to health-threatening levels of air pollution along the United States-Mexico border. Increased industrialization, both from maquiladoras and national industries, contributes significantly to point-source air pollution and mobile-source air pollution due to the service and commercial activity that accompanies industrial activity (EPA, 1996; Ganster, 1996). Lack of air quality monitoring and environmental analysis has prompted the Secretaría de Medio Ambiente, Recursos Naturales y Pesca (SEMARNAP) and the U.S. Environmental Protection Agency (EPA) to target the U.S.-Mexico border region, especially Tijuana which has the second largest concentration of maquiladoras in Mexico (Arikkath 1994). Our research, therefore, is both timely and appropriate.

[1] Maquiladora refers to the foreign-owned primarily assembly oriented industrial facilities along the northern U.S./Mexico border.

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Photogrammetric Engineering & Remote Sensing, Vol. 64, No. 11, November 1998, pp. 1089–1096.

0099-1112/98/6411–1089$3.00/0

Figure 1. Location diagram.

Primary Research Questions

This research was question rather than data driven. Our first concerns centered on improving our understanding of the types of air pollutants emitted by Tijuana's industrial sector, which led us to try to estimate the quantities of sulfur dioxide, nitrogen dioxide, carbon monoxide, volatile organic compounds, and fine particulates emitted by industrial facilities in Tijuana. Next, we sought to determine the locations and nature of industrial facilities in the urban area. Thus, we focused on the spatial arrangement of industrial facilities and production types, the air pollutants emitted, and the distribution of employees in the industrial sector. Finally, we sought to understand Tijuana's urban structure, particularly the relationship between housing quality (used as a surrogate for socioeconomic class structure), industrial location, and air pollution emissions.

Because Tijuana and other border cities (as well as most cities in developing countries) represent "data poor" environments generally lacking accurate data on population characteristics, socioeconomic variables, and environmental and other measures, we utilized a variety of indirect measurements to generate much of the information needed for this study. These data were obtained from high resolution aerial photography, satellite imagery, and other more traditional sources including census information and field observations, all of which were manipulated within a GIS context.

Methodology and Data

The IPPS Model

In order to estimate industrial air pollution in Tijuana, we needed a model which could be based on data that were obtainable and reliable as well as one which had been utilized elsewhere in analogous environments. Therefore, we selected the Industrial Pollution Projection System (IPPS) model developed by the World Bank (Hettige *et al.*, 1994). It was designed primarily for use in the developing world where industrial pollution data are not available, but industrial survey information is collected. This model was developed in response to the need for a method of industrial air pollution estimation in areas where data on industrial emissions are scarce (Hettige *et al.*, 1994). The IPPS model is based on the premise that industrial pollution is heavily affected by the scale of activity as represented by the number of employees, the technological processes used, and the type of industry. The model was initially created by merging the United States Census of Manufacturer's data with United States Environmental Protection Agency's Toxic Chemical Release Inventory, the Facility Subsystem of the Aerometric Information Retrieval System, the Longitudinal Research Database, and the Permit Compliance System of the National Pollutant Discharge Elimination System databases (Hettige *et al.*, 1994). According to the creators of the model, it is undoubtedly the most comprehensive system of its kind in the world "since it was developed from a database of unprecedented size and depth" (Hettige *et al.*, 1994). They determined that air pollution intensity based on industry type is exponentially distributed: that is, a few industries produce the majority of the pollutants.

The IPPS can be used to generate estimates of pollution of various media, such as air and water, and can make use of different inputs, such as employment, value added, or total value of output. The particular component of the IPPS used in this research estimates air pollution intensities with respect to employment and lower bound intensity values given in pounds per 1000 employees. The lower bound estimate was used because it was the only complete component that estimated air pollutants based on employment. Therefore, it can be assumed that the values produced for Tijuana are underestimates. Underestimation may also arise from the fact that "U.S. pollution intensities are likely to be lower than in less-regulated settings" (Hettige *et al.*, 1994).

Recently, "Mexico specific" air pollution intensities were produced by the World Bank (1997) and are produced for small (less than 20 employees), medium (between 21 and 100 employees), and large (over 100 employees) facilities by utilizing 2- and 3-digit International Standard Industrial Classification (ISIC) codes. The database used to create this model was the Sistema Nacional de Información de Fuentes Fijas provided by Mexico's Instituto Nacional de Ecologia. We found that the Mexico-specific model produced lower overall levels of estimated air pollution than the IPPS model used in our study. We feel that because the Mexico-specific model utilizes 2- and 3-digit ISIC codes, instead of the more specific 4-digit ISIC codes used by the IPPS model, the Mexico-specific model underestimates overall emissions through the higher levels of aggregation it entails.

The estimations from the IPPS model are for one calendar year which is comprised of 300 working days. The model is used to provide estimations for emissions of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), volatile organic compounds (VOC), and particulates less than 10 μm in diameter (PM10). Estimates are given in pounds for each

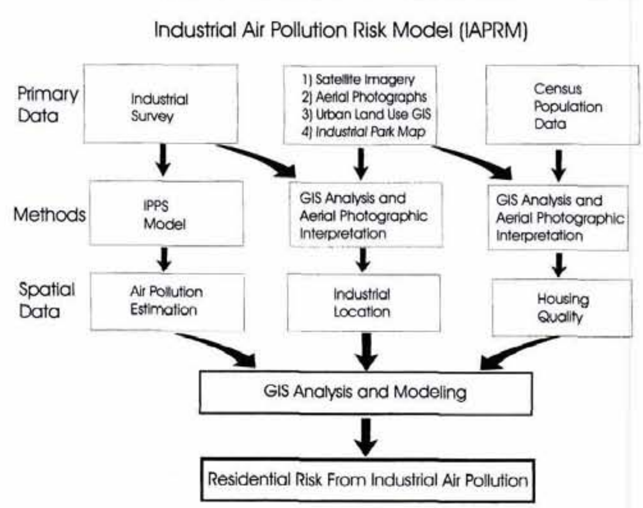

Figure 2. Industrial Air Pollution Risk Model (IAPRM).

4-digit ISIC code. These air pollutants are recognized as the most important air pollutants in the EPA-administered Clean Air Act (World Bank, 1994).

The use of ISIC codes allows for the disaggregation of industry into process and assembly oriented sectors which, in turn, permits the spatial disaggregation of the results. Our model for Tijuana was created by forming a database of the city's industrial facilities and assigning each facility an ISIC code based on the product manufactured. Only facilities employing more than ten workers were included because the integrity of the IPPS model degenerates when there are less than ten employees used to formulate estimates. We also used this database to isolate 20 separate groups of processing industries, identified previously by the World Bank (1994), which produce significantly different pollution amounts. The IPPS model was then used to generate more specific emission estimates from processing industries for each of the industrial areas within Tijuana.

Industrial Survey Data

In order to operationalize the model, it was necessary to determine the location and employment total for each industrial facility within Tijuana as well as assigning 4-digit ISIC designations to them. Three reliable industrial surveys were available for the urban area, two of which offered information only on maquiladoras while the third included data on all of the city's industrial activities. The larger listing of facilities (Directorio Industrial Canacintia, '93) was used because it provided a more robust assessment of industrial activity, including the names, addresses, neighborhood designation, census tract number (Area Geo-Estadistica Basica or AGEB), products produced, and employment figures for virtually all of the industrial facilities, including maquiladoras, within the metropolitan area of Tijuana. With these data, ISIC codes were assigned to each entity.

Industrial Locations

The ISIC codes and employment information were manipulated by the IPPS model to estimate the geographical distribution of air pollutant emissions for Tijuana. To our knowledge, in all of its previous applications, the IPPS model was used to describe pollutant characteristics for a given urbanized area, region, or country and, in this study, we analyzed the metropolitan area of Tijuana. More importantly, a unique contribution of this research was to examine the spatially discontinuous industrial areas of the city. The estimations of the emissions data was achieved by locating each facility by street location within census tract (AGEB) and neighborhood (colonia), and then applying the IPPS model to each industrial area within the urban area. The locations of industrial areas were verified through the use of a highly detailed GIS land-use coverage of Tijuana developed as a part of the Tijuana River Watershed GIS Project (Wright *et al.*, 1996). The land-use coverage was draped over merged 1995 SPOT panchromatic (10-metre) satellite imagery and multispectral (20-metre) satellite imagery using an RGB to HSI transformation. The industrial areas were then mapped based on the interpretation of multi-color 1:12,000- and 1:48,000-scale aerial photographs flown in 1994, the merged SPOT panchromatic and multispectral imagery, other mapped information, and field verification. The identification of the processing industries was accomplished through a similar process.

Housing Quality

The relationship between industrial air pollutant emissions and residential areas was determined within the GIS database through the merging of the industrial emissions and location information previously derived and a 1994 residential land-use map of Tijuana (Wright *et al.*, 1996). As can be seen from Table 1, the residential areas of Tijuana were classified into six housing quality classes ranging from elite housing (Class 1) to recently developed squatter settlements (Class 6). This was accomplished by interpreting areas of similar housing type on 1:12,000-scale true color contact prints and field checking the interpreted images for accuracy. The housing quality polygons that were interpreted were digitized as an ARC/INFO coverage, with a SPOT panchromatic 10-metre satellite image being used as the backdrop for digitizing, registration, and all subsequent editing and processing.

TABLE 1. RESIDENTIAL HOUSING CLASSES IN TIJUANA

Class 1.	Elite Residential—architecturally designed, expansive luxury homes with the full compliment of infrastructure and services. Standard, fabricated construction materials used.
Class 2.	Upper Middle-Income Residential—less elaborate than class one in terms of size and materials, but with the complete array of infrastructure and services.
Class 3.	Middle-Income Residential—while homes in this class typically have access to all services, all roads in these areas are not paved. Government housing is included.
Class 4.	Lower-Middle-Income Residential—these homes are rapidly accreting. A wide range of materials are employed in improving the structures. Paved streets, electricity, water and sewage systems are evident, but irregular.
Class 5.	Low-Income Residential—homes in this class are in the process of being transformed into more stable structures, commonly represented by the replacement of wood with cement block. Dirt roads, pirated electricity, trucked water and an absence of sewage infrastructure are common to this class.
Class 6.	Squatter Settlements—located on the periphery, these structures are built with scrap materials such as metal, wood, cardboard and plastic. These recently settled areas lack formal services and infrastructure and represent the most impoverished housing quality.

Residential Risk from Industrial Air Pollution

To measure populations potentially at highest risk from industrially generated air pollution, a 500-metre buffer was created to represent the areas in closest proximity to industrial areas. A buffer method and 500-metre distance were chosen because of several factors. Because an extremely high percentage of Tijuana's air pollution is generated through one- or two-story building height ventilation systems or other building openings, plume studies were not appropriate for Tijuana. Relevant meteorological data are not available for plume modeling, and the complex topography of the urban area makes generalizing patterns over distances greater than 500 metres very suspect. Furthermore, experimentation with 250- and 1,000-metre buffers demonstrated that they were too small or too large to be meaningful within Tijuana's complex urban environment.

The results generated were analyzed in order to determine how much area of each residential class was within 500 metres of an industrial park or processing facility. Population data for 1994 were estimated using the GIS database which was derived from the 1990 Mexican national census (Instituto Nacional de Estadistica Geografia e Informatica, 1991), up-dated housing counts, and areal density measures. The estimated 1994 population figures were then used to make inferences about the numbers of people living within the 500-metre buffers. Density information for each housing class and other socioeconomic and demographic data provided additional information about the residential areas (Wright *et al.*, 1996).

Results and Discussion

Air Pollutant Estimates for the City

The IPPS model generated industrial emissions for Tijuana for five of the EPA criteria air pollutants. In the aggregate estimate, it was estimated that the 69,641 industrial employees in Tijuana produced the following pollutant levels in tons for the 1993 calendar year:

SO_2	NO_2	CO	VOC	PM10
11,950.8	6,286.3	4,044.5	5,182.1	5,248.2

On a percentage basis, the composition of Tijuana's industrial air pollutant emissions is as follows:

SO_2	NO_2	CO	VOC	PM10
36.5%	19.2%	12.4%	15.8%	16.0%

These figures represent the estimated amount in tons of each of the air pollutants generated for the 1993 calendar year. The estimates are based on the number of employees and the composition of the industrial activity. In order to gain insight into the relative magnitude of the emissions data, we compared the Tijuana totals to a prior study which produced estimates of industrial air pollutants for Mexico City (U.N. Environment Programme [UNEP] and World Health Organization [WHO], 1992). It is obvious that reliable overall comparisons of air quality cannot be made between Tijuana and Mexico City due to a multitude of differences (e.g., topography, meteorological conditions, principal pollutant sources, size). Nonetheless, we thought it would be instructive to examine Mexico City's industrial emissions in order to gain a gross idea of Tijuana's relative level of industrial air pollution. Figure 3 shows that per capita estimated emissions of sulfur dioxide, nitrogen dioxide, and carbon monoxide for Tijuana are larger than those for Mexico City. Tijuana's per capita estimated emissions of sulfur dioxide are seven times higher, nitrogen dioxide are over four times higher, and carbon monoxide are 12 times higher than those of Mexico City. Although it is probable that, because of differences in methodologies and other factors, these relationships are overstated, the estimated levels of industrial emissions reflect the large scale of industrial activity in Tijuana and the probability of significant air pollution problems. The relatively high proportion of industrial activity in Tijuana suggests that this border city has a much higher level of industrially derived air pollution than would be anticipated, given the size of its population.

It is important to note that the IPPS model is not based directly on field measurements and, as a result, the accuracy of the absolute values produced by the model cannot be validated. The accuracy of these estimates depends on the similarity between the process technologies utilized in the United States and those employed in Tijuana because pollution factors are based on U.S. data. According to Brandon and Ramankutty (1993), air pollution generation will be higher in areas with less regulation, such as is the case in Tijuana. However, Tijuana's large industrial facilities tend to be newer, more modern, and possibly cleaner (at least in some instances) than facilities in the United States. These same authors contend that, because these and other facts cannot be reconciled, IPPS estimates are best used as relative measures of air pollution: in other words, IPPS estimates are valuable for making inferences about differences in air pollution intensities. Similar estimates produced in Asia have been found to be significantly underestimated. In fact, it has been suggested that all of the air pollutant estimates be increased by 300 percent, except particulate emissions where a 600 percent increase has been advised (Brandon and Ramankutty, 1993). More research on the accuracy of the IPPS model is needed, but this can only happen after monitoring results have become available. Six monitoring stations are currently functioning in Tijuana, but most have been operational for less than two years and the data are still in the validation stages (Fuentes, personal communication, 1998).

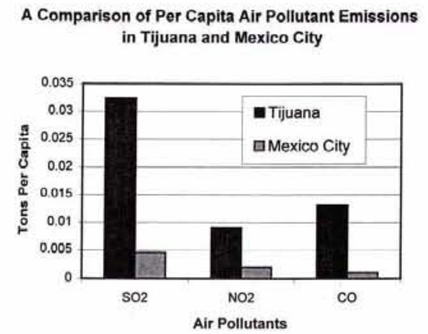

Figure 3. A comparison of per-capita air pollutant emissions in Tijuana and Mexico City.

Air Pollutant Estimates for Industrial Areas

The research focused on the spatial distribution of industrial facilities, the air pollutants emitted, and the number of employees in the industrial sector. Figure 4 identifies Tijuana's industrial areas, 20 of which encompass 83 percent of all industrial employment in the urban area. Many of these corresponded to Tijuana's formal industrial parks while the other are mixed commercial/industrial which contain significant industrial as well as commercial activity. The industrial areas vary greatly in the numbers of employees and the amounts of pollutants generated. The amount and composition of the air pollutant emissions of the industrial areas are directly related to the manufacturing process and the number of employees located in each. The industrial and mixed industrial/commercial areas shown on the map in Figure 4 correspond to the industrial areas and related data presented in Table 2. The estimates by industrial area were also analyzed by the type of air pollutant. The generation of sulfur dioxide is dominated by Ciudad Industrial de Tijuana, Parque Pacifico, La Mesa Corridor, Insurgentes Corridor, and Planetario de Tijuana, and these are also the areas with the highest estimated nitrogen dioxide and fine particulates emissions, with the exception of the Insurgentes Corridor.

This distribution for the primary pollutant generation areas for fine particulates is similar to those of sulfur dioxide and nitrogen dioxide except for the exclusion of the Insurgentes Corridor. By contrast, Fundadores, El Aguila, Presidentes, El Lago, and La Mesa were the areas that generated the lowest levels of air pollutants in all categories of emissions. Overall, the patterns for high and low air pollutant generation are consistent for the different air pollutants. Further study of ambient emissions and air quality should be focused in these areas of high air pollutant generation.

Some Industries Are More Polluting Than Others

The employment figures presented in Table 2 are an integral part of the IPPS model, yet employment alone is not sufficient for making inferences about pollutant generation. For example, Tijuana Industrial Park (TIP) and Mayacan/Centro Industrial B.C. had approximately the same number of employees, 1,522 and 1,509, respectively, yet the amount of estimated pollutants emitted varied substantially. Sulfur dioxide emis-

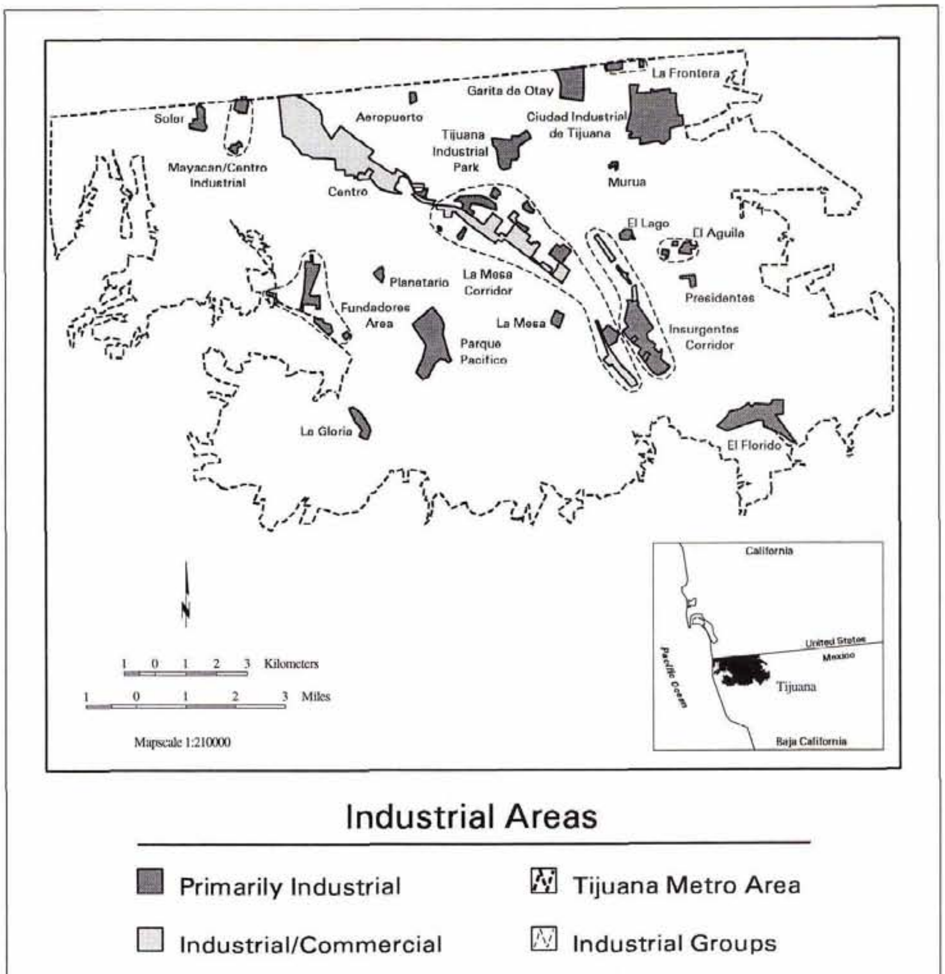

Figure 4. Industrial areas in Tijuana. Cartography by Harry Johnson.

sions were over 3.5 times greater and PM10 emissions were nearly 60 times greater in Mayacan/Centro Industrial B.C. than in TIP. In the Tijuana Industrial Park the main manufactures are radio, television, and communication equipment, all of which are relatively low pollutant emitting industries (World Bank, 1994). In Tijuana, these industries account for 21,318 employees, or 31 percent of total employment, yet only produce 0.66 percent of total sulfur dioxide and 0.59 percent of PM10 emissions. In contrast, 62.6 percent of sulfur dioxide and 94.4 percent of PM10 emissions were produced by two types of industries, non-ferrous metal production and concrete production, which had only 1,743 employees or 2.5 percent of total employment. Additional activity in these types of industrial processes obviously would greatly increase total industrial air pollutant emissions.

The utility of the IPPS model is that it allows for the comparison of air pollutant emissions by industrial sectors which ultimately allows for the spatial disaggregation of emissions. As a result, we were able to identify a number of industrial regions within Tijuana which are primary areas of industrial pollution. As noted above, the industrial regions within Tijuana which contribute the largest percentage industrial air pollutant emissions are Ciudad Industrial de Tijuana, Parque Pacifico, La Mesa Corridor, Insurgentes Corridor, and Planetario, with employment levels ranging from 399 in Planetario to 15,927 in Ciudad Industrial de Tijuana. Among the 20 most significant industrial regions in the city, Planetario has the third smallest number of employees, but the third highest emissions of PM10. Virtually 100 percent of the Planetario industrial park's emissions of PM10 are related to just one ISIC sector: non-metallic mineral products. This is a processing-oriented activity and alone it generates over 90 percent of Tijuana's industrial emissions of PM10. The dominance of a small number of industrial sectors in generating total emissions is not unusual. A World Bank study in Indonesia found that seven or eight industrial activities accounted for 50 to 90 percent of the country's industrial air pollutant emissions (World Bank, 1994).

Maquiladoras: Assembly or Processing Activity

The metropolitan area of Tijuana is dominated by assembly industries with 87 percent of all industrial employment classified as assembly oriented activities. This was expected because maquiladoras are traditionally assembly facilities. However, the 13 percent of industrial employees involved in processing-oriented activities produced the overwhelming majority of all but one of the industrial air pollutants:

SO_2	NO_2	CO	VOC	PM10
92%	93%	87%	34%	99%

Obviously, those activities that involve the processing of primary materials are much more polluting than assembly activities, and being able to identify them permits a more robust assessment of industrial pollution. The industrial sectors heavily affecting the total load of most pollutants in

Table 2. Industrial Employment and Estimated Emissions for Industrial Areas in Tijuana

Industrial Areas	Employees	Estimated 1993 Emissions in Tons SO_2	NO_2	CO	VOC	PM10
Soler	1101	27.8	24.5	36.4	89.6	5
Mayacan/Centro Industrial B.C.	1509	246.5	106.5	16.8	63.9	113.6
Centro	5051	389	255.6	264.8	244.7	97.8
Aeropuerto	1908	45.1	75.3	28.4	124.9	5.7
TIP	1522	70.1	34.8	14.8	38.8	1.9
Garita de Otay	1289	149.1	89.7	141.8	135.5	4.5
La Frontera	3064	220.8	154.1	119.6	264.4	19.5
Ciudad Industrial de Tijuana	15927	4292.1	1901.7	1452.4	1317.4	1721.5
Murua	171	67.9	4.6	12.8	13.2	51.2
El Lago	2007	7.5	3.9	1.2	45.6	0.3
La Gloria	326	97.7	52.9	12.4	15.8	71.5
Fundadores	2346	31.3	9.9	2.3	40.8	0.8
Planetario	399	498.4	277.9	40.1	6.6	416
Parque Pacifico	2675	1551.2	871.4	150.3	137.4	1286.3
La Mesa	1054	24.5	14.1	2.1	11.5	0.3
Insurgentes Corridor	4227	671.9	375.9	336.4	316.3	26.7
El Aguila	842	2.6	1.4	0.3	17.1	0.1
Presidentes	299	1.2	0.8	1	18	0.4
La Mesa Corridor	9896	1080.2	547	448.6	647.3	288.4
El Florido	2280	80.9	52.8	61.8	517.6	7.5
Total for Industrial Areas	57893	9555.8	4854.8	3144.3	4066.4	4119
% of all Tijuana Industry	83.1	80.0	77.2	77.4	78.5	78.5

Tijuana are Industrial Chemicals, Non-Metals Products, Iron and Steel production, Non-Ferrous Metals processing, and Other Electrical Machinery operations. These heavily polluting industrial activities also influence the emissions-mix in the industrial regions.

Residential Risk Modeling

The study of industrial air pollutant emissions alone reveals nothing about its potential risk to the residents of Tijuana. The industrial regions produce varying amounts of air pollutants with a small fraction of the areas generating the majority of pollutants. It can be expected that the residential areas surrounding these locations would be the most severely affected by air pollutants from industrial sources. In fact, at Parque Pacifico, a relatively new industrial park with large facilities employing hundreds of people, there are people living within a few hundred feet of some of the industrial facilities. This type of mixed land use is common in most of Tijuana, as it is in most Latin American cities. Risk levels of living near industrial regions cannot be ascertained conclusively through our research, but it is estimated that 1,551 tons of sulfur dioxide and 1,286 tons of PM10, along with 1,009 tons of smog contributors (VOC and NO_2), were emitted from the Parque Pacifico industrial park in 1993. It is not unreasonable to assume that the quality of air breathed by the people living near this park is worse than for people living further away because air pollutants are not released through high stacks, making them susceptible to wind-directed spatial dispersion. Employing this basic assumption, we attempted to ascertain the relationship of housing quality and proximity to sources of industrial air pollution emissions. Furthermore, the spatial relationships between industrial and residential areas are interesting from both urban structure and social perspectives.

The residential risk from industrial air pollution is shown in Figure 5, which depicts Tijuana's industrial regions, its residential areas, and the "pollution buffers" affecting housing quality types. As demonstrated in Table 3, a disproportionate amount of Tijuana's middle class residential areas are within the 500-metre pollution buffers of the city's industrial areas. A normalized ratio (where 1.0 = random, <1 = less than expected, and >1 = more than expected) was used to account for the great differences in the total amounts of land occupied by each of the six classes. The middle-class group, specifically Housing Class 3, represents the majority of residential land in proximity to industrial areas. The proportion of middle and upper-middle class housing in proximity to mixed industrial/commercial land uses is even greater. The mixed industrial/commercial areas tend to have the more polluting processing industries and are located along the main transportation corridor, or spine, of the city. These areas also have greater amenities in terms of location and infrastructure and are, therefore, occupied by the higher land-use categories, including better housing areas. Lowest quality housing in Tijuana (and most other large Latin American cities) has low levels of infrastructural improvement, such as sewerage, water connections, and paved roads. The infrastructural requirements of industry, or better stated the absence of infrastructure in peripheral or marginal areas within Tijuana, in effect "protects" the lowest housing quality classes and their residents from living near industrial regions and their attendant pollution. For example, there are no areas of Class 6 Housing, the lowest quality category, in proximity to mixed commercial/industrial areas. Tijuana's industrial parks, which are generally located on the periphery of the city and have infrastructure provided as part of an incentive to locate there, represent a different dynamic from the traditional industrial locations of the city because they are planned with infrastructure provided. While most of the industrial employment in Tijuana is located in formal industrial parks, the overall relationships are skewed. However, it is worth noting that municipal authorities, in combination with the landowners, frequently use official or unofficial means to restrict marginalized residential construction in juxtaposition to newly developed industrial parks.

Number of People at Risk

In this study we use housing quality classes as surrogates for socioeconomic class. Within our housing quality classification system, Class 1 and Class 2 areas represent upper and upper-middle income populations, classes 3 and 4 represent the middle and lower-middle socioeconomic sectors, while Class 5 and Class 6 housing corresponds overwhelmingly to people who occupy the lowest rungs on the city's socioeconomic ladder. The majority of the urbanized area dedicated to residential uses in Tijuana is composed of residential housing quality classes 4 through 6.

Nearly 20 percent of Tijuana's residents live within 500 metres of an industrial area. As can be seen in Table 3, housing classes 3 and 4 had the greatest amounts of area within 500 metres of industrial areas as well as the highest population densities. In combination, these two factors result in the fact that the overwhelming majority of Tijuana's population at risk from industrial air pollution reside in housing classes 3 and 4. The highest housing quality classes (1 and 2) represent a nearly random statistical relationship *vis-a-vis* their proximity to the highly polluting processing industries while the middle classes (3 and 4) are disproportionately over-represented and the lowest housing quality classes (5 and 6) are disproportionately under-represented. These results, particularly for the middle and lower classes, are similar to the more general relationship noted for housing qualities and industrial areas. Table 3 depicts the relationships between residential housing quality areas and industrial areas and processing facilities. The middle classes, 3 and 4, are most

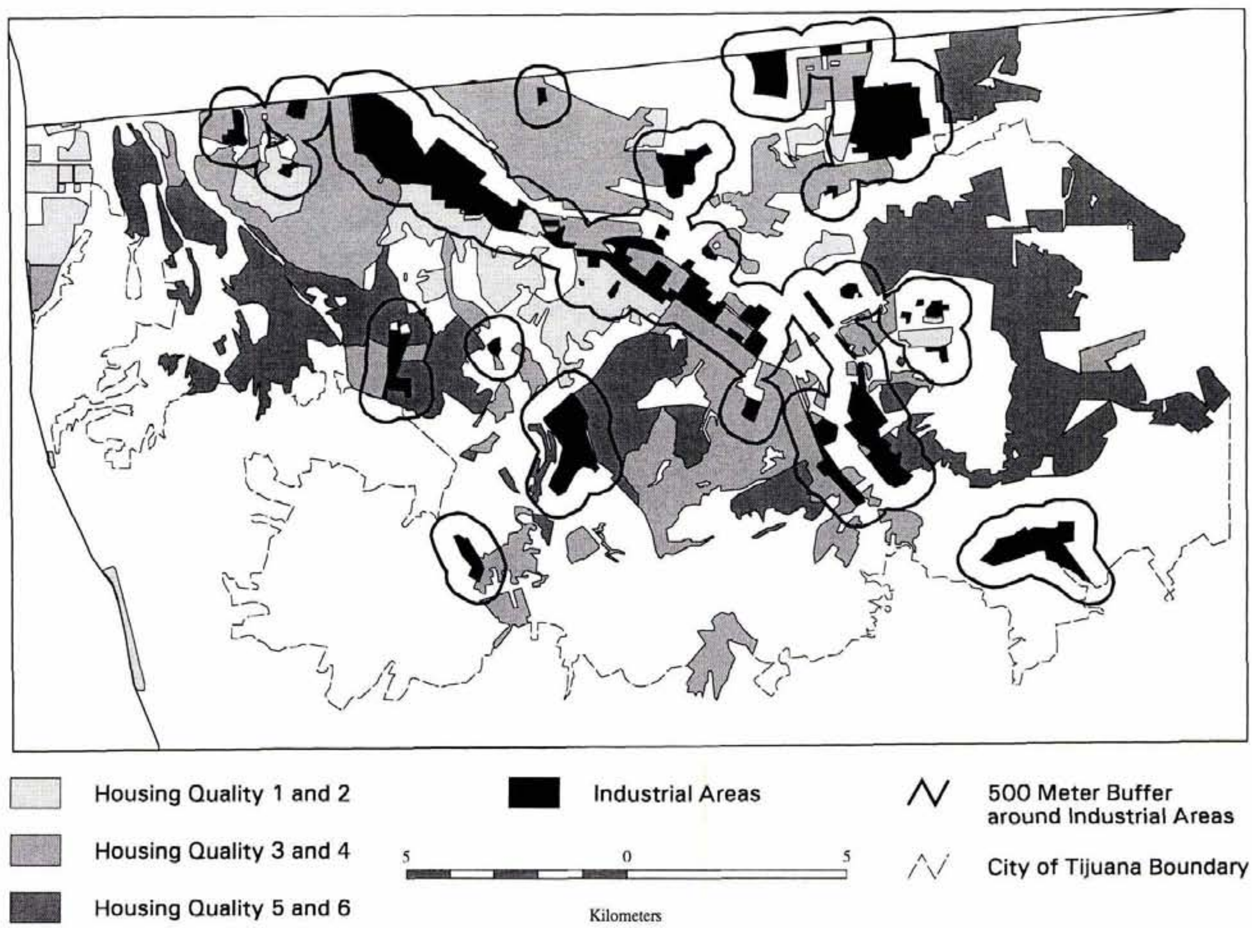

Figure 5. Residential risk from industrial air pollution in Tijuana.

over-represented in terms of proximity to industry, which supports the previous results for all industrial areas.

Processing industries, however, differ from the formal industrial parks in that they are located in traditional areas of the city along the main transportation arterials. This location places the elite and upper-middle-class residential areas in closer proximity to processing industries than the lowest socioeconomic classes and is contrary to the popular notion that lower socioeconomic classes are most adversely affected by polluting industries.

Summary and Conclusion

The proliferation of industrial facilities, particularly foreign-owned entities, which contribute to environmental degrada-

Table 3. Residential Risk from Industrial Air Pollution

Residential Risk from Industrial Air Pollution	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
All Industrial Areas						
Area within 500 meters (square Km)	0.39	4.69	11.36	6.83	0.356	1.1
Ratio:area within 500 meters/proportion of total area	0.54	1.5	1.8	1.1	0.6	0.2
Population within 500 meters	1522	14738	53194	58222	2394	6975
Industrial Parks						
Area within 500 meters (square Km)	0.07	2.5	6.19	4.5	0.166	1.1
Ratio:area within 500 meters/proportion of total area	0.5	1.3	1.7	1.1	0.7	0.2
Population within 500 meters	265	7858	28985	38326	1148	6975
Mixed Industrial/Commercial Areas						
Area within 500 meters (square Km)	0.32	2.19	5.17	2.33	0.19	0
Ratio:area within 500 meters/proportion of total area	1.2	1.9	2.2	1.1	0.09	
Population within 500 meters	1257	6880	24209	19896	1246	0
Processing Industries						
Area within 500 meters (square Km)	0.6	2.02	8.58	6.52	0.5	0.63
Ratio:area within 500 meters/proportion of total area	1.23	0.96	2	1.62	0.12	0.16
Population within 500 meters	2356	6349	40149	55655	3327	3966

tion in Tijuana, provides a case study for studying similar problems in other developing countries where data are scarce but information is urgently needed. The methodology employed in this research could be used in other cities along the U.S.-Mexico border or perhaps in cities in other developing countries to better assess the geographic distribution of air pollutant emissions within metropolitan areas. Despite its limitations, the utility of the IPPS model for examining the spatial distribution of industrial pollutant emissions has been demonstrated. The estimated emissions generated in this study provide useful relative information for metropolitan Tijuana as well as for specific geographic areas within the urban area. Analysis of individual industrial regions within Tijuana generated information about specific areas while the dominant areas of air pollutant generation within the metropolitan area of Tijuana were identified. These areas deserve the most attention in terms of air quality monitoring and assessments of the environmental and human health risks of industrialization. The spatially specific data generated within the GIS allows for making inferences about the potential risk to surrounding residential areas. The IPPS model has been previously employed to make city and regional level estimations, but linking the IPPS model to the GIS database at the sub-city level is a significant contribution of this research. The benefits of the IPPS model for data-scarce places are increased when combined with a GIS for examining sub-regional variations in air quality estimates and those segments of the population potentially at greatest risk.

The bottom line is that some industries are more polluting than others and they are not randomly distributed over space. This is apparent through the wide ranges in the level of air pollutants generated between industrial regions. The processing-oriented activities are by far the most polluting, both for the metropolitan area of Tijuana and for all of the individual industrial regions within the city. Although the industrial mix in Tijuana contains only 13 percent processing-oriented activities, those industries generate approximately 90 percent of all air pollutants (except volatile organic compounds). The majority of Tijuana's industry, therefore, contributes a relatively small proportion of pollutants. Policy and monitoring of industrial air pollution, therefore, should not target industries with the greatest numbers of employees or the largest facilities, but, instead, should focus on those industries that, due to the process technologies, are the most polluting. If possible, policies related to locating future processing-oriented activities should take air pollution generation into consideration.

The examination of industrial air pollution and urban structural characteristics that place people near industrial areas is as applicable in other cities throughout the developing world as it is in Tijuana. In most cities that are experiencing both rapid population and industrial growth, information is urgently needed that can aid monitoring efforts and policy formation. The IPPS model used in combined with a well-developed GIS database is useful for making a first approximation of air quality monitoring where data and other resources, including financial resources, are limited.

It is hoped that the results of this research motivate further study of air quality, population dynamics, and urban structure in Tijuana and other border cities. Inadequate and incomplete data are significant challenges to research in developing countries around the world, and data scarcity was a primary obstacle to answering the questions posed in this study. The use of models and surrogates is a first step to mitigating these data limitations. At some point, however, extensive efforts must be made to collect and make reliable data available. In the area of air quality analysis, further research could make use of the data from new monitoring sites as they become available. Testing the accuracy of the IPPS model and the addition of corrections that would make it specific to Tijuana or other border environments would also be important contributions to air quality analysis. Managing Tijuana's growth in the years to come would also be aided by incorporating detailed street information as well as data on other infrastructural components including sewage, water, and electricity into GIS analysis.

Data limitations are significant challenges to doing research in the developing world, but it is our belief that studies such as this one provide a first step that can be the catalyst for further study and analysis.

Acknowledgments

Funding for this research was provided by the Southwest Center for Environmental Research and Policy, and the Environmental Protection Agency. Cartographic assistance was provided by Mr. Harry Johnson.

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