MODELING PRODUCTION EXTERNALITIES IN THE MAQUILA INDUSTRY

by

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ABSTRACT: In the past decade, the maquiladora export industry surpassed both tourism and petroleum products to become the number one source of earned foreign exchange for Mexico. The continued growth and spatial concentration of the maquila industry suggest that there may be significant production spillovers into the local environments. Dynamic modeling, using STELLA, provides a framework for considering the *maquila* industry from a joint economic and environmental perspective, underscoring the importance of understanding linkages between economic growth and environmental impacts when considering infrastructural planning, linkages that have not been featured in research on this region. An economic-ecologic model is developed for two urban communities, Nogales and Mexicali. In the former case, the analysis revealed the inadequacy of the capacity planning for the treatment of effluent; in the latter case, conservative projections reveal that the system upgrades should be able to handle demands through 2020.

Introduction

Research on the maquiladora industry has been widespread, and has often focused on labor issues, including productivity, employment, housing, and the related health care, women's issues and worker's rights. Furthermore, production externalities, environmental laws, infrastructure, trade agreements, tax revenues, resources, intermediate goods, and migration are all topics of international debate and scholarship. While all these topics have been studied extensively in isolation since the industry's inception in 1965, a large gap in the literature remains in the likely nexus between economic and environmental factors in such a highly spatially concentrated

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industry. As noted in public discourse recently (*The Economist*, 2002), environmentalists and economists often have a hard time communicating. This lack of communication is apparent in the *maquila* research to date, as well.

This paper provides such a joint economic/environmental dynamic modeling framework to understand the critical localized links between the two realms. The focal question of interest is the relationship between population growth and infrastructure, with particular attention to water treatment, in the rapidly expanding Mexican border towns. As a whole, over 10 million people reside along the northern Mexican border, with 90% in urban areas. According to the US Environmental Protection Agency (1997), 88% and 69% of this population has access to safe drinking water and sewage collection, respectively. However, the agency estimates that the capacity of water treatment is only 34% of the total currently needed.

First, the efficacy of sewage treatment facilities is considered. Specifically, two *maquila* sites are examined: Mexicali, Baja California and Nogales, Sonora, which can be found in figure 1. Each city experienced the rapid population growth that accompanied the industry in the last decade. Furthermore, before the introduction of the *maquila* industry, these border towns were distinctly unpopulated, undeveloped, and non-industrialized; very little infrastructure existed. In fact, Mexicali did not have a functioning wastewater treatment facility until 1990.

<<insert figure 1 here>>

The approach taken here provides an alternative to methods used in prior studies by connecting economic drivers with environmental impacts. The paper opens with a brief review of Mexican internal migration, which especially in the case of the border regions is largely driven by economic opportunity. Structuring these population dynamics helps define the focal environmental concern associated with the border *maquiladoras*, the production of wastewater. Basic demographic variables, including birth, death and emigration rates, are augmented with a calculated monthly immigration factor, based upon *maquila* employment in Nogales, Sonora, as well as an estimated per capita effluent factor. The population model created for Nogales is first duplicated for a second border *maquila* site, Mexicali. It is then combined with a hydrologic model of the New River, into which Mexicali's partially treated and untreated sewage is dumped.

In this way, the basic model is extended from one of economic demography to an ecological model, predicting levels of coliform bacteria present in the local waterway due to the increased population. The question is not simply how much effluent enters the river system, but rather how much will enter the system in the upcoming months and years, especially if the border *maquila* industry continues to attract potential laborers at a rapid pace.

Mexican Internal Migration

Early migration research, such as Fernandez-Kelly (1983), Fernadez-Kelly and Portez (1992), Wilson (1993), Harner (1995), Chau (1997) and Reyes (1997), demonstrated that areas with the heaviest *maquila* activity draw in-migrants, particularly females, from other states. Figure 2 shows net migration in each of Mexico's 32 states, including the Federal District, from 1992 to 1995. The darker shaded regions, namely from west to east and north to south: Baja California, Sonora, Chihuahua, Mexico (the state, not to be confused with the Federal District nor the city), Morelos, Yucatan, and Quintana Roo, experienced net in-migration during this period. These states had a net gain of at least fifty thousand people. The two other border states, Nuevo Leon and Tamaulipas, also gained in terms of net migrants.

<<insert figure 2 here>>

Of the six border states, only one, Coahuila, lost people during this time period. It had a net out-migration of just over 10,000 (INEGI, 1995). The Central Intelligence Agency (CIA) estimated that Mexico's net migration rate was -2.97 per thousand population for 1996. Considering the overwhelming national trend of out-migration, or emigration, the fact that five of the border states were net gainers is significant. In addition, it supports the hypothesis that the presence of the *maquila* industry along the border has been a major attractor of internal migration, as there are few other major employment opportunities in the area (Weiler and Zerlentes, 2003). The out-migration witnessed in Coahuila does not dispute this analysis: the only large city within the state is Piedras Negras, which has a relatively small population, 98,000 (Hansen, 1994), and is not one of the major *maquila* centers. Nuevo Laredo, located to the south in the state of Tamaulipas, has a very large concentration of *maquiladoras* respective to its population size, however.

Table 1 displays the rapid growth that occurred during the 1980s in the top border *maquila* sites. Given that the border region is 90% urban, this rapid growth from 1980 to 1990 would seem to imply that the border states' in-migrants were drawn to such industrial centers. The most populous three cities, Juárez, Tijuana and Mexicali, are also the top three in terms of *maquiladora* production and employment. According to Fernandez-Portes (1992) and Wilson (1993), the *maquila* industry is responsible for a large share of the in-migration to border states shown during this time period.

<<insert table 1 here>>

The population figures Hansen (1994) included are from the official Mexican bureau. According to the 2000 census, there are 680,000 people living in Mexicali, up from the 602,000 registered in the 1990 census. However, many researchers (see EPA, 1997 *et al*) estimated that the city surpassed 1,000,000 in population as far back as 1996. Similarly, the Mexican national census for 2000 shows 96 million residents. Yet for that year, the US Central Intelligence Agency listed 99 million as its Mexican population estimate; the figure is over 100 million now, noted in Appendix D. Obtaining accurate population measurements are crucial to the infrastructure enhancements under consideration.

Methodology

A primary goal of this paper is the creation of a realistic demographic model for border towns that accurately incorporates growth in the *maquila* industry, given the likelihood of continued expansion based on the embedded agglomeration economies of existing plants. Population models for two sites, *ambos*[1] Nogales and Mexicali, were created using STELLA™, a versatile dynamic modeling system. On the whole, many advantages to dynamic modeling exist. Short and long-term outcomes of proposed actions can be predicted before they are taken. Furthermore, complex, dynamic systems can be modeled with relative ease. Once the initial model is built, the parameters can be readily modified, allowing the model to be utilized by local policy makers, among others, on site. There are key components in dynamic modeling, and similar to the focus on key sectors in economic modeling, Hannon (1995) has found that not every factor in a system needs to be modeled. Furthermore, after the key factors have been accounted for, the marginal benefit of adding other operators declines sharply, similar to

Ockham's notion that irrelevant details should be cut from maps (Ruth and Hannon, 1997). To this end, three important questions were considered in building the basic population model. First, are the variables included both necessary and sufficient? Secondly, are their interactions adequately represented and, third, are the data accurate? With the possible exception of the latter question, as mentioned previously, the answers are all affirmative. However, the questions are important to keep in mind, given the inherent flexibility of dynamic modeling.

A crucial component in dynamic modeling is, of course, the time scale. As often noted in mathematical modeling research, too much data, or calculating too many iterations, simply bogs down the system, and does not always relate to a significant increase in prediction abilities. The month was the chosen time unit for these models, even though daily data existed for some of the hydrologic data, such as water flow.

Ambos Nogales Population Model[2]

In 1967, when the first *maquiladora* opened in Nogales, Sonora, less than 50,000 people lived in the twin (US and Mexico) cities of Nogales (Kopinak, 1996). By April of 2001, the joint population was over 200,000 (INEGI, 2001). Nogales' population was modeled from 1967 until 2001 to establish a functional base model (Hannon, 1995). The national birth, death, emigration and immigration rates were utilized, as no literature was found indicating that any of the aforementioned rates could be proven to be higher or lower for Nogales specifically. This excludes in-migration, of course, which is higher in this region, as noted in the first section.

There is argument, however, to propose that the US border population demographics vary greatly from the US at large, yet it is doubtful any of the rates is as high as those for their counter-parts across the border. The immigration variable incorporates these considerations by assuming an annual 3% growth rate, which is greater than the national immigration rate, reflecting the *maquila* attraction, but which moderates the over-estimation of the birth, death and emigration rates on the US side. The functional forms underlying the model are outlined in table 2 and diagramed in figure 3.

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[1] *Ambos* means "both" in Spanish. Colloquially, the twin cities of Nogales, Sonora and Nogales, Arizona are referred to as *ambos* Nogales.

[2] The lead author wanted to thank Dr. Bruce Newbold for suggesting this population-driven ecological model.

<<insert table2 and figure 3 here>>

As table 2 indicates, effluent is a function of both population and income level; the higher the income level, the greater the amount of effluent produced. Specifically, with a higher average household income per capita, the US city creates several times more effluent than her Mexican twin. Note in figure 3, however, that in this first model, effluent is simply calculated based upon population size.

The stock labeled *Population*, represented by the topmost rectangle, is increased by the variable named *Pop Growth* and reduced by *Pop Decline*. Population decline is a function of the death and emigration rates. Population growth, similarly, depends upon the birth rate and in-migration. The latter variable is tied to growth within the Nogales' *maquila* industry. According to a border study conducted by the EPA (1999), the average annual birth rate from 1994 to 1997 was 18.1 per thousand, the death rate 5.05 per thousand. Mexico's current rate of emigration is lower, at 2.84 per thousand (CIA, 2001). The in-migration rate, considered separately from emigration, is uniquely attributed to the city's *maquila* industry. Analyzing the data from 1967 to 2001, the constant .115656 for every new person employed in a *maquiladora* was calculated using Ordinary Least Squares analysis. That is, the population in *ambos* Nogales had an additional growth factor of .115656 times the previous time period's employment level during these years that cannot be accounted for with the normal demographic variables.

Application

The North American Development Bank (NADB) is currently involved in over thirty border infrastructure projects. Part of the $969 million reserved for water and/or wastewater treatment projects includes an NADB-financed loan of $46 million to upgrade the Nogales' International Wastewater Treatment Plant (NIWTP). When completed, the facility will have a capacity of 17.2 millions of gallons per day (MGD) and is anticipated to accommodate flows from *ambos* Nogales as well as portions of Rio Rico and Peña Blanca, two small towns located nearby (NADB, 2000).

As part of the lower Colorado River Basin, the Santa Cruz River system serves the *ambos* Nogales area. The only other major river in the immediate area is the San Pedro, roughly 30 miles east. The Potrero Creek, a tributary of the Santa Cruz River, and the Nogales Wash flow through the city of Nogales, Arizona. The waterways are ephemeral, flowing during the flood season and in the case of backwashes from the treatment plant, which is located 10 miles north of the border.

The Nogales Wash originates 7 miles south of the border and runs north through each city's center before reaching the NIWTP. The perennial flow in the wash is fed by springs near its head, grey-water (recycled water) and sewage. Depending on the season, rainfall, *etc*., the depth varies from a few inches to several feet. For health reasons, the City of Nogales (Arizona) began adding chlorine to the Nogales Wash over a decade ago (Renning, 1994). Reminiscent of regular pool maintenance, the daily deposition of chlorine, to a well located within a few yards of the border[3], is commonplace and scarcely noticed by would-be border crossers from the south, nor the border patrol agents to the north.

The NIWTP has faced many challenges since it opened in 1972. A much-needed facility upgrade was completed in March of 1990. Six years later, the International Boundary and Water Commission took over administration of the facility from the City of Nogales. According to one city employee (anonymous, 1999), when the IBWC first took over, it was using outdated EPA standards and therefore not fully treating the wastewater. CDM Camp Dresser & McKee Inc., consultants to the City of Nogales, report that the facility is not working efficiently due to problems with plant components (1997). Other concerns stem for the large amounts of sand and debris coming in from the sewer collection system, especially during storms. In addition, concentrations of ammonia in the effluent leaving the plant are potentially toxic to aquatic life.

The current renovation project is obviously necessary; whether it will be sufficient is a different question. A careful look at table 3 intimates the first possible problem. In 1996 the twin cities combined produced 13 million gallons of effluent per day on average. Assuming their population and wastewater projections are accurate, the plant's maximum planned capacity of 17.2 MGD will be surpassed before 2020, in which an expected 23.9 MGD will be produced by both cities, as shown in the fourth column of data. Determining exactly when the 17.2 MGD threshold will be reached could prove useful in terms of planning the next renovation or upgrade.

<<insert table 3 here>>

[3] NGW #8 is one of the wells established by the ADEQ in 1993 for monitoring purposes.

Results

As shown previously in figure 3, the population model for *ambos* Nogales is linked to the variable labeled *effluent*, which pictorially represents the amount of wastewater produced by the two cities, albeit on a monthly, rather than daily, basis. For simplicity's sake, all data given in daily units were multiplied by 30 for conversion to monthly units for the Nogales' model. For example, 15 MGD would be modeled as 450 millions of gallons per month. More importantly, the upgraded NIWTP's maximum of 17.2 MGD becomes 516 millions of gallons per month.

Figure 4 shows the effluent produced by *ambos* Nogales from January of 1980 to June of 2017. This "run" of the Stella model, *i.e.*, the results, are based upon the aforementioned demographic variables and *maquiladora* employment in Nogales, Sonora.

<<insert figure 4 here>>

Shown in the third column for each time period listed in table 3, the average per capita daily effluent flow for both cities is roughly 63 gallons. This figure, 63.322 GPCD, was utilized in the *ambos* Nogales population model. There are two concerns with using this figure, however. First, estimates of effluent, or wastewater entering the Nogales system, range from 12 to 16 MGD for early 1999 (City of Nogales, 1999). One way to deal with this variance is to use the software's random feature, with the upper and lower bounds of 16 and 12 MGD, respectively. While technically more accurate, this methodology downplays the importance of population growth in effluent production, as the population does not vary from day to day as greatly as the effluent appears to.

Secondly, even assuming the 63.322 GPCD remains constant over an entire year (1996), it is projected to change several times over the next several decades, as listed in table 3. The average daily per capita effluent production is projected to increase slightly over the next two decades and then decrease so that by 2050 the two cities produce an average of 61.4841 GPCD, with the Arizona side responsible for the larger, but decreasing, proportional share. Given that the time frame of the first run of the model, shown in figure 4, ends before the per capita effluent is supposed to change in 2020, however, this second concern is less important.

Recall that the current renovations will allow the NIWTP to handle 17.2 millions of gallons per day. Given that daily flows to the plant already approximate 16 MGD, this upgrade seems shortsighted. Figure 4 demonstrates that this threshold will be crossed at some point before 2017, although the scale is too broad to pinpoint in which year. By zooming in, figure 5 isolates the maximum effluent capacity of 17.2 MGD, or 516 millions of gallons per month.

<<insert figure 5 here>>

Clearly, the monthly maximum of 516 millions of gallons is reached in the year 2009. The *ambos* Nogales population model predicts that the NIWTP will surpass its expanded capacity during the month of May 2009. With an expected completion date of June 2002, the current upgrade appears inadequate.

Estimating *E. coli* in the New River

As effluent discharge is a ubiquitous problem in the most concentrated border sites, a logical use for the *ambos* Nogales population model would be to replicate it for other *maquila* sites. Indeed, the model was duplicated for Mexicali, the capital of Baja California and, as mentioned, the third largest *maquila* site in terms of employment. Just as Nogales' treated and untreated effluent flows into the Nogales Wash, sewage from Mexicali, at various stages of treatment, enters the New River. The amount of *E. coli* present in the New River can effectively be linked to the city's *maquila* employment by combining a population model for the city of Mexicali with a hydrologic model created for the New River. In that sense, the basic Nogales model forms the basis for a more complete model of a more complex system, namely that of Mexicali and an associated major waterway, the New River.

The river originates approximately 10 miles south of Mexicali, curves slightly, and then flows north to the Imperial Valley, emptying into the Salton Sea. There are five rivers flowing into the Salton Sea, and there is no outlet. The other four, the Alamo and Whitewater Rivers and the San Felipe and Salton Creeks, flow in from California. For several years the US Geological Survey (USGS) considered the New River to be "the dirtiest river in America" (Sklair, 1993: 95).

Despite its dangers,[4] many migrant workers attempt to cross the border via this highly polluted waterway.

The EPA (1997) lists four sources of pollutants to the New River, all of which are linked to economic growth and increased population: solid wastes from the municipal dump, untreated or partially treated personal sewage, irrigation drainage, and, lastly, slaughterhouse and industrial wastes. Identical to the situation in Nogales, when the first *maquiladoras* opened in Mexicali in the late 1960s, employing a few thousand workers, the city's population was much smaller, estimated at roughly fifty thousand people (Brown, 1997). The industry now employs close to 200,000, while the city's population has grown to over one million (INEGI, 2001).

According to a report by the EPA (1997), the city first initiated construction of sewer collectors and waste stabilization ponds in 1964, and the projects were completed in 1986. In the same year, the IBWC approved a directive calling for the elimination of domestic and industrial wastewater discharges into the New River at the border[5]. To this end, the first wastewater treatment facility was built in 1990. During the next few years, Mexico continued to upgrade the water and sewage systems, with a total cost of US$37.4 million. In 1992, the IBWC issued an environmental plan that required treatment of Mexicali's wastewater before discharge to the New River.

However, during the summer of 1994, three of the plant's six pumps failed. Mader (1995) estimated that the facility treated only 60% of Mexicali's raw sewage that year. While a second facility has been added, combined they cannot adequately handle all of the effluent the municipality currently produces, let alone will produce as Mexicali's population continues to grow. For example, one of the plants was designed to handle 1.82 MGD of wastewater, yet already receives 6.85 millions of gallons per day (NADB, 2001). Altogether, the EPA estimates that up to 20 million gallons of raw or partially treated sewage enters the New River daily (1997). Clearly, the long-term solution, the BECC's $57 million project,[6] is much needed. What

[4] Signs written in Spanish, posted along the water's edge, warn would-be crossers to leave the water immediately. If while giving chase an INS agent comes in contact with the river's water, he follows the same standard procedure as that for toxic waste contamination (Dallas Morning News, 1996).
[5] See Minute 274, passed in 1987.
[6] The NADB will fund $20.62 million of the total $57.36 million upgrade and expansion of the two existing systems in Mexicali.

are the municipality's choices in the short-run, given that the anticipated upgrades will not be completed until 2005?

As stipulated earlier, part of the problem lies in the underestimation of the city's true population. While the NADB website states that the proposed project will benefit a population of 640,600, population estimates were as high as 1,000,000 for the city in 1996. While it is certainly true that not all of the population has access to sewage collection, and therefore treatment, it would seem logical to include this segment of the population as well, as they are likely to be part of the future demand for such services. Further, considering the city's rapid rates of population increase, stemming from the *maquila* industry in Mexicali, there are likely to be many more households demanding wastewater treatment than currently assumed.

Model Structure

The dynamic model created for the New River follows the basic format of other hydrologic models but it is augmented with the aforementioned population model. As noted, the New River model is similar to McKelvey's (1996) work and based upon research by Hannon (1995), Ruth and Hannon (1997) and Deaton and Winebrake (1998).

The basic structure of the model is two-fold, with one sub-model tracing *E. coli* through time and space, that is, along the river, and a symmetrical sub-model tracing the flow of water. Similar to other hydrological models, flow rates are utilized at each section of the river, as listed in table 4. Due to data restrictions, the river was divided into three sections, representing the origin, or the Mexican portion of the waterway, the section immediately across the border, and the river's end, the Salton Sea. The break down of these sections is discussed in greater detail later in this section.

<<Insert table 4 here>>

As stipulated previously, determining which time scale to use is vital. The more frequent the time unit, the more complex the model, which does not necessarily yield the most robust results. Again the chosen *dt*, (really $\delta\tau$, which stands for change in time), was one month, allowing the model to be run for a number of years. The equations for the parallel sub-model, namely the *E. coli* that can be traced back to Mexicali's sewage, are presented in table 5.

<<insert table 5 and figure 6 here>>

The key variables for the New River model, included in the equations in tables 4 and 5, are also shown graphically in figure 6. There are four parts to this model, which will be referred to as and the hydrologic and *E. coli* sub-models, as outlined previously, and Sectors 1 and 2, which are labeled in the diagram. Sector 2 contains the same basic population model first introduced for the *ambos* Nogales *maquila* site. This model follows a duplicate framework, that is, employment in the *maquila* industry is coupled with demographic factors. Any increase in Mexicali's population is marked by the corresponding increase in effluent, which if untreated will cause *E. coli* levels in the New River to rise. Factors relevant to the bacteria's growth, such as its rate of decay and water temperature, are enclosed in Sector 1, as highlighted in the following section.

As listed in the equations, the water flow is combined with the amount of *E. coli* at each section of the river. The critical variable is the concentration of this pollutant in the water, labeled *concCS* for concentration at the USGS testing site near Calexico, California. Referring to figure 6, this concentration is depicted between the two rectangles labeled CS, the amount of *E. coli*, and *WaterCS*, the volume of water.

Most of the data utilized in this model were collected by the USGS and compiled by the Imperial Irrigation District (IID). As the time frame for this research focuses on the implementation of the North American Free Trade Agreement, the model was first utilized to represent the maquila industry from 1994 onward, as discussed in the following section. Thus, the crucial initial values listed in table 6 are as of January of 1994, or, when found, the end of December, 1993.

<<insert table 6 here>>

A few factors regarding table 6 should be mentioned. First, the last two rows of the table are included to signal the units underlying those particular variables. Secondly, the initial value of *E. coli* present in the US-Mexico border in 1994, labeled CS above, was generated in previous runs of the model, based upon the same rates of effluent discharge but lower population and employment figures, as the data indicated. The final point is in regards to the sources used. Population and employment data were found on the INEGI web site. The initial values of *E. coli* were estimated based upon the level of effluent, as will be discussed; and the IID (1997) is the source for all hydrologic data, as documented in the following section.

Model Description

The first variables of interest in the Stella dynamic framework are the **stocks**, which are depicted visually by a rectangle. These typically represent an accumulation over time, the equivalent to integration in calculus. There are two stocks in the population sub-model, labeled Sector 2: maquiladora *employment* and Mexicali's *population*. In the *E. coli* sub-model, the first stock, named *MC*, symbolizes the amount of *E. coli* found in the initial section of the New River. At any time, *t*, the stock *MC* contains the total amount of the pollutant that were in the stock the time step before, *t-dt*, plus any net inflow (or minus any net outflow) during that time step. Similarly, the stock named *CS* represents the amount of the pollutant at any time *t* found in the second section New River, on the US side of the border. Within the parallel sub-model located below, two stocks represent the volume of water in those same two sections of the river: *WaterMC* and *WaterCS*.

The initial values placed in the stocks are important. In the first run, zero was the amount of *E. coli* assumed to be in the New River at $t = 0$, or the base year of 1994. As listed in table 6, this assumption was later relaxed, given that effluent had in fact been entering the New River for decades. The population estimate of Mexicali at the end of 1993 used was 640,000; at the time there were 19,578 workers employed in the city's *maquiladoras* (INEGI, 2001). Data for the key hydrologic variables, including flow rates, temperatures and the volume of water in each section of the river are subsequently listed.

The second step is to identify the in and out flows to and from the stocks. In the *E. coli* model, there is only one type of **outflow**, the decay of *E. coli*. These two variables are labeled, in order, *DecayMC* and *DecayCS*. In the same manner, two additional variables allow for water evaporation to reduce the volumes: *Mevap* and *USEvap*. In the population sub-model the outflow is labeled *pop decline*.

Similarly, *pop growth* is the initial **inflow** in the population model. In the *E. coli* sub-model the inflow is appropriately labeled *initial e-coli*. After flowing into the stock *MC*, the bacteria can then proceed via the second and third inflows, *EFlowMex* and *EFlowUS* to the destination, the Salton Sea. The hydrologic sub-model contains five inflow variables. *Initial Water* pumps water into the system, which then flows via *WFlowMex* across the border and into Calexico, California.

At this point, tributaries increase its flow, represented by the variable named *Tributaries*. *WFlowUS* is their product.

The final step in the creation of a Stella model is the building and linking of **control** variables. These variables may help determine the in and out flows to and from the stocks. For instance, one control variable determines the *Initial Ecoli* flow, *Effluent* is determined by two control variables: *emigration* and *death rate*. The emigration rate used was the national average, 2.87 per 1000 people (CIA, 2001). Similar to the Nogales' scenario, a strong case for a higher out-migration can be made for the city of Mexicali, and indeed any other US-Mexico border crossing point, but this same force would also cause higher in-migration, as well. And there is typically a lag time, that is, an individual or family tends to spend a few days in the border town as they attempt to cross into the United States (Conover, 1987). In the population sub-model, *in-migration* and *birth rate* are the two control variables that determine the inflow, *pop growth*.

The second and third inflows, *EFlowMex* and *EFlowUS* are determined from linked control variables that represent flow rates, *MFlowR* and *EndFlowR*. Four other control variables are used to help regulate the decay of the bacteria or pollutant. Two are labeled *Death Rate* and *DRSS*, for death rate in the Salton Sea. The former is used along the New River, the second is specific to the Salton Sea. The remaining two, *Temperature* and *TempSS* control the death rates.

The hydrologic sub-model contains three control variables that are also used in the main model, *TempSS*, *MFlowR* and *EndFlowR*. The temperature variable joins with *Evap Rate* to mandate evaporation from the system. In addition to the two flow rate variables aforementioned, there are two others used. *USFlowR* regulates the flow of the New River's tributaries. All of the variables that are based upon time, such as the water flow rates and temperatures, are linked to the *Month Counter* variable, which does exactly as it is named: it counts months, allowing the variables to re-set themselves at (t = 12) back to January.

There are five more control variables in the sub-model. The first one, *DepthMC* is itself tied to *MFlowR*, which helps determine the depth of the New River from Mexicali to Calexico. This depth, along with the width and length of this section of the river, *WidthMC* and *LengthMC* help determine the volume, *VolumeMC*, which is used for the initial water inflow.

The software allows for separate **sectors** within any model. For organizational purposes, seven of the listed control variables are placed in *Sector 1*. Water measurements, such as depth, width, temperature, flow and death rates, can be easily input if found in a central location. As noted earlier, the population model driving the effluent and therefore *E. coli* amounts are presented in a separate sector, as well, *Sector 2*.

The second inflow, *EFlowMex*, moves a portion of the bacteria that is left in the first section of the river, *MC*, based upon the ratio: *MFlowR*/*Water MC*. Thus the more water that flows, the more *E. coli* flows with it. This pattern is repeated along the second section of the river, north of the city of Calexico, California. Once the bacteria reach the Salton Sea, any bacteria flowing in from other US waterways could join them. There is no evidence to support the presence of significant levels of the bacteria in the other rivers, however, and thus this potential additional amount is not modeled.

In the hydrologic sub-model, the volume of water initially entering the system is estimated based upon McKelvey's Wetlands vs. Channelization model (1996). The formula he used is $V = A \times L$, where V stands for volume, A is the area, and L is the length of the river section. McKelvey suggested other river shapes, but in this model the shape of the river was assumed to be a three-dimensional trapezoid where the bottom width is calculated as 6/10ths that of the measurable width on the surface. The equation for the area then is: $A = .8 \times W \times D$, where W stands for the average width on the surface and D is the average depth. While both W and D are easily measurable, data for these variables were not found. The surface width was assumed to be five meters and the depth varies based upon the current flow as given by the Rodriguez (1997) and Kidwell (1997). The third and final dimension, the length, is approximately 30 kilometers in this section (Rodriguez, 1997; the New York Times, January 1997). The river volume of this section thus equals 108,000 cubic meters.

The water flow rate variables are represented by graphs, which depict average flow rates for each section. The model continues to cycle through the year's worth of flow rates; the evaporation rates along the New River are calculated so as to keep a constant amount of water in the system year by year. This water, less any that evaporates, then flows onward to the second section of the river. Here additional tributaries add to the flow, which are not represented in the New River model, as their inclusion is not crucial for the main purpose, which was to evaluate *E. coli* levels in the river as it crosses the US-Mexico border.

As mentioned previously, the data available dictated the functionality of the model. For example, some observations were recorded daily, others monthly. As the month was the time step utilized, a *month counter* was included, based upon Hannon's (1995) work. A related tool, which is labeled *year counter*, was then added. Acting as a metronome, the first variable clicked off the months, advancing the *year counter* by one every twelfth time step. These two aides are depicted in the bottom of figure 7, which highlights the connection between *maquila* employment, population growth and effluent output in Mexicali.

<<insert figure 7, tables 7 and 8 here>>

As noted in figure 6, effluent drives the amount of bacteria, which decays as a function of the river's temperature; see table 8. Listed in table 7, the New River reaches its warmest temperature in August, with an average monthly daytime temperature of 31.7 degrees Celsius; the coldest month is January. There are seasonal variations in the New River's flow, with the peak flow in May on the Mexican side of the border, and in April further north, near the river's end at Salton Sea. The lowest rates are in November and February, respectively. The California tributaries add to the river's flow, as noted by the higher US flow rates.

The estimated rates of bacterial decay depend upon the water temperature, as suggested in Linsley *et al.* (1982). In the model, a relatively smooth line graph between the two variables was used. Select data points are listed in table 8.

Results

Given the proposed completion date of 2005 for the Mexicali I and II sewage treatment plant renovations, a second run of the New River model was performed for the period 2000 to 2005. Conservative estimates for the initial 2000 values were utilized, such as the 2000 census population estimate for Mexicali, 680,000. Effluent flow already surpasses the two treatment plants' capacity, as documented in Hansen (1994), Mader (1995), EPA (1997) and NADB (2001). Depending on the source and time, it is estimated that at least 5 to 20 million gallons of untreated or partially treated sewage flow into the New River daily. Converted to the number of

E. coli per cubic meter, using 50 million bacteria per 100 cc of effluent,[7] a conservative estimate of 11 MGD effluent was assumed to be in the New River at $t = 0$, or the base year of 2000. Using the growth in the *maquila* industry, an initial employment of 56,000, and other demographic factors as outlined earlier, the amount of effluent increases in the same manner as described for Nogales.

As mentioned previously, neither the amount of effluent nor bacteria is important when considering river dynamics. What is crucial, and therefore modeled, is the concentration of bacteria per unit of water. Included in figure 8 are the concentration levels of *E. coli* in the New River before and after it crosses the US-Mexico border, labeled *ConcMC* and *ConcCS*, respectively. As expected, there are more bacteria present earlier on in the water's flow. Note that the units shown on the Y-axis, representing million of bacteria per 100 cubic centimeters, are on two different scales, with the top, smaller number, highlighting the concentration of *E. coli* on the US side of the border.

<<insert figure 8 here>>

Over the next 60 months, or until the expected completion date of 2005, *E. coli* concentrations in the first segment of the river increase, following the annual water flow and temperature data built into the hydrologic model. Of greater importance, at least to the California Regional Water Quality Control Board, which tests the New River monthly, is the concentration of *E. coli* just over the border, in Calexico, California. In particular, the agency is concerned when counts in the New River are above the recommended 200 million per 100 cc of water considered safe for human contact (EPA, 1997). Demonstrated in figure 9, which is a close-up of figure 8, the concentration remains above this threshold from the fourth month onward. At least in terms of potential *E. coli* contamination, the Mexicali renovations could not come soon enough.

<<insert figure 9 here>>

According to the BECC-NADB Joint Status Report, dated March 31st, 2002, the Mexicali upgrades will increase sewage treatment by close to 20 MGD, nearly doubling the total maximum daily capacity, with increases from 22.4 to 29.67 MGD for the Mexicali I system and from 1.82 to 20 MGD for Mexicali II. Even utilizing the upper bound of all estimates, such as a

[7] According to Jim Royer, with the UC Sanitary District (1997), there may be between 10 to 100 million *Escherichia coli* per 100 cc untreated sewage.

population of one million, increasing at an annual rate of 3%, meaning Mexicali's population will double in 24 years, and the most aggressive growth in *maquiladoras*, such as that which characterized the introduction of NAFTA, the planned renovations should be adequate until after 2020. Of more immediate concern, however, is the current concentration of *E. coli* in the New River, in addition to other health hazards caused by the rapid industrialization of Mexicali.

Sensitivity Analysis

Recall that an *E. coli* concentration of more than 10 bacteria per 100 cc of water is unsafe to drink. In an effort to determine how much less effluent needs to enter the river system at Mexicali for the river to not exceed this health requirement, a sensitivity analysis was performed on the *Population* stock. Through numerous iterations, it was found that a 10% reduction in Mexicali's population would lower the effluent output sufficiently to achieve this threshold, after seven months and given current water flow rates. As displayed in figure 10, which depicts a 2%, 4%, 6%, 8% and 10% reduction in population, consecutively, at 8% the concentration of *E. coli* holds relatively stable at 50 bacteria per 100 cc water, which is still too high.

<<insert figure 10 here>>

Further Extensions and Conclusions

The Nogales and Mexicali models underscore the importance of accuracy in regional planning, both in terms of critical data inputs as well as applying model results to assess infrastructural needs and health thresholds. Extensions to the basic population-effluent models included in this paper would further increase their efficacy. The population basis for the economic forces provided an instructive first step, but could easily be supplemented with more specific economic variables. For example, given total costs of treatment, average and marginal treatment costs can be modeled simultaneously with their corresponding effluent levels under the current and proposed systems. The benefit would be to define the optimal treatment capacity for future generations, after weighing both social costs and benefits. Specifically for the bi-national waterways, the expected costs of bacterial contamination, for US and Mexico citizens, can be modeled alongside the *E. coli* concentrations.

In terms of policy, an effluent per worker charge could be determined for all new *maquiladora* employees. However, as Sargent and Matthews (2000) discuss, given the current business atmosphere, it seems unlikely that such a tax would be assessed to the firms, as municipalities already waive many of the new *maquila* fees under NAFTA. Nonetheless, the schematic shown in figure 11 portrays this scenario. As mentioned previously, the modeling framework can be extended to incorporate cost factors, in this case with a *maquila* tax per employee; *i.e*., Maquila Tax = f {Maquila Employment}. The diagram also demonstrates how the link between average household per capita income and effluent could be modeled. Recall that the populace of Nogales, Arizona, with a higher household GDP/capita, produces 4 times the amount of effluent, measured in millions of gallons of effluent per day, than the population in Nogales, Sonora. Figure 11 depicts this functional relationship: Effluent = f {Population, Income}.

<<insert figure 11 here>>

In addition to the joint economic/ecological models proposed, which are based upon population, and thereby effluent levels, any non-point or source pollutants relevant to the *maquila* industry could be modeled. Earlier studies of the Nogales Wash identified carcinogenic solvents, which can escape the treatment process altogether (Dwyer, 1994). Even if the source of such solvents cannot be accurately determined, predictions of their levels could be useful.

Neither is water the only medium that can be studied. For example, the diffusion of airborne pollutants, such as chemical or vehicle emissions, can be estimated, including the costs and benefits of abatement. Via subpoena, the EPA learned that in 1993, 95 US-owned *maquiladoras* in Mexicali used over 5 million pounds of chemicals and admitted to releasing circa 50,000 pounds of chemicals via air, water or on land (EPA, 1997). One contemporary issue already under review involves hazardous materials. In the late 1990s the EPA developed HAZMAT, a method of tracking hazardous materials from *maquila* and other industrial sites along the border. The timing of the HAZMAT model is crucial, as NAFTA stipulates that the *maquiladoras* are no longer required to return their hazardous wastes to the US for processing. Furthermore, as noted in Sánchez (1994), Mexico does not currently have the facilities to manage such a large quantity of hazardous wastes.

The analysis presented in this paper offers a modest step in presenting a link between economic and ecologic systems so that policy makers can begin to understand the role of external spillovers in the process of economic development. In ecologically sensitive parts of North

America, development of the kind attracted to the *maquila* regions presents significant environmental costs, many of which have not been incorporated into the cost functions of the productive activity. The suggestion of an imposition of a tax per employee to cover some of these costs is unlikely to find much support; adding additional charges might further erode the *maquiladora's* competitive advantages, especially in the light of challenges from cheaper cost locations in SE Asia. Nonetheless, the environmental and potential health impacts are real, and are being generated by the industrial growth that drives the modeling in this paper. The *maquila* region also features the additional complications of marrying two national legal systems in addressing environmental problems.

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Table 1: 1990 vs. 1980 population in border *maquila* cities

	1990 population	1980 population	% change
Ciudad Juarez, Chihuahua	798,000	567,000	41%
Tijuana, Baja California	743,000	461,000	61%
Mexicali, Baja California	602,000	511,000	18%
Matamoros, Tamaulipas	303,000	239,000	27%
Reynosa, Tamaulipas	282,000	211,000	33%
Ensenada, Baja California	261,000	175,000	49%
Nuevo Laredo, Tamaulipas	218,000	203,000	7%
San Luis, Sonora	112,000	93,000	20%
Nogales, Sonora	107,000	68,000	57%
Piedras Negras, Coahuila	98,000	80,000	18%

Source: Hansen (1994)

Table 2: *ambos* Nogales Population Model Equations

Variable	Explanatory Variables
Immigration =	f {Maquila Employment, Ind_Growth}
Pop_Growth =	f {Immigration, Birth Rate}
Pop_Decline =	f {Emigration Rate, Death Rate}
Population =	f {Population, Pop_Growth, Pop_Decline}
Effluent =	f {Population, Income Level}

Table 3: Projected population for *ambos* Nogales (by state) and wastewater produced

	1996			2020		
	wastewater (MGD)	population (thousands)	per capita (GPCD)	wastewater (MGD)	population (thousands)	per capita (GPCD)
Arizona	3.8	19.0	200.0000	4.1	26.6	154.1353
Sonora	9.2	186.3	49.3827	19.8	350.2	56.5391
Total/Ave	13.0	205.3	63.3220	23.9	376.8	63.4289
	2035			2050		
	wastewater (MGD)	population (thousands)	per capita (GPCD)	wastewater (MGD)	population (thousands)	per capita (GPCD)
Arizona	5.0	33.6	148.8095	6.2	40.5	153.0864
Sonora	23.0	411.6	55.8795	28.6	525.5	54.4244
Total/Ave	28.0	445.2	62.8931	34.8	566.0	61.4841

Note: MGD = millions of gallons per day; GPCD = gallons per capita per day

Source: Wastewater and population figures: Ambos Nogales Wastewater Facilities Project Update (CDM Camp Dresser & McKee Inc., 1997) and City of Nogales (1999).
Gallons per capita per day calculated for the expressed purpose.

Table 4: Hydrologic Sub-Model Equations

Variable	Explanatory Variables
Initial_Water =	f {VolumeMC}
VolumeMC =	f {AreaMC, LengthMC}
AreaMC =	f {DepthMC, WidthMC}
DepthMC =	f {MflowR}
MflowR =	f {month}
WaterMC(t) =	f {WaterMC(t - dt), Initial_Water, Mevap, WflowMex}
WFlowMex =	f {MflowR}
WaterCS(t) =	f {WaterCS(t - dt), WflowMex, Tributaries, USEvap, WflowUS}
Tributaries =	f {USFlowR}
USFlowR =	f {month}
WFlowUS =	f {EndFlowR}
EndFlowR =	f {month}
WFlowUS =	f {EndFlowR}
EndFlowR =	f {month}

Table 5: *E. coli* Sub-Model Equations

Variable	Explanatory Variables
Initial_Ecoli =	f {Effluent}
Effluent =	f {Population}
MC(t) =	f {MC(t - dt), Initial_Ecoli, DecayMC, EflowMex}
DecayMC =	f {MC, MflowR, Death_Rate}
Death_Rate =	f {Temperature}
Temperature =	f {month}
EFlowMex =	f {MC, WaterMC, MflowR}
CS(t) =	f {CS(t - dt), EflowMex, DecayCS, EflowUS}
DecayCS =	f {CS, USFlowR, Death Rate}
EFlowUS =	f {CS, WaterCS, EndFlowR}
Maquila_Employment(t) =	f {Maquila_Employment(t - dt), Net_Employment_Growth}
Net_Employment_Growth =	f {Maquila_Employment}
Population(t) =	f {Population(t – dt), Pop_Growth, Pop_Decline}
Pop_Growth =	f {Birth_Rate, Inmigration, Population}
Pop_Decline =	f {Death_Rate, Emigration_Rate, Population}
Inmigration =	f {Net_Employment_Growth}
SS(t) =	f {SS(t - dt), US_other_river_sources, EflowUS, DecaySS}
EFlowUS =	f {CS, WaterCS, EndFlowR}
DecaySS =	f {SS, DRSS}
Year(t) =	f {Year(t - dt), Year_Counter}
Year_Counter =	f {Month_Counter}
ConcCS =	f {CS, WaterCS}
ConcMC =	f {MC, WaterMC}
ConcS =	f {SS, WaterSS}

Table 6: Select Initial Values and Variable Units

Variable	Initial Value and Units
Year (t = 0)	1994
Population (t = 0)	640,000 people
Maquila_Employment (t = 0)	19,578 people
MC (t = 0)	633,199,000,000 million bacteria
CS (t = 0)	200,407,483,500 million bacteria
WaterMC (t = 0)	40,000 cubic meters
WaterCS (t = 0)	50,000 cubic meters
ConcMC, ConcCS, ConcS	million of bacteria per 100 cc of water
DecayMC, DecayCS, DecaySS	million of bacteria per month

Table 7: 1996 Select Hydrologic Data for the New River (Source: IID, 1997)

Month	Temperature (° Celsius)	Initial Flow Rate (cubic meters per month)	US Flow Rate (cubic meters per month)
January	13.9	12,660	24,690
February	17.7	14,610	24,280
March	18.3	16,930	35,150
April	21.4	14,470	40,140
May	27.5	19,290	34,720
June	28.0	12,490	36,140
July	30.1	10,530	36,070
August	31.7	10,080	34,700
September	30.9	10,315	30,580
October	26.1	9,101	35,710
November	24.4	6,818	28,630
December	19.5	7,021	29,560

Table 8: Estimated Decay Rates of *E. coli* in the New River

Temperature (° Celsius)	E. coli decay (Percentage)
7.5 (and colder)	100.0
10.0	95.0
12.5	93.5
15.0	85.5
17.5	74.0
20.0	66.0
22.5	60.0
25.0	48.0
27.5	38.5
30.0	27.0
32.5	15.5
35.0	5.50

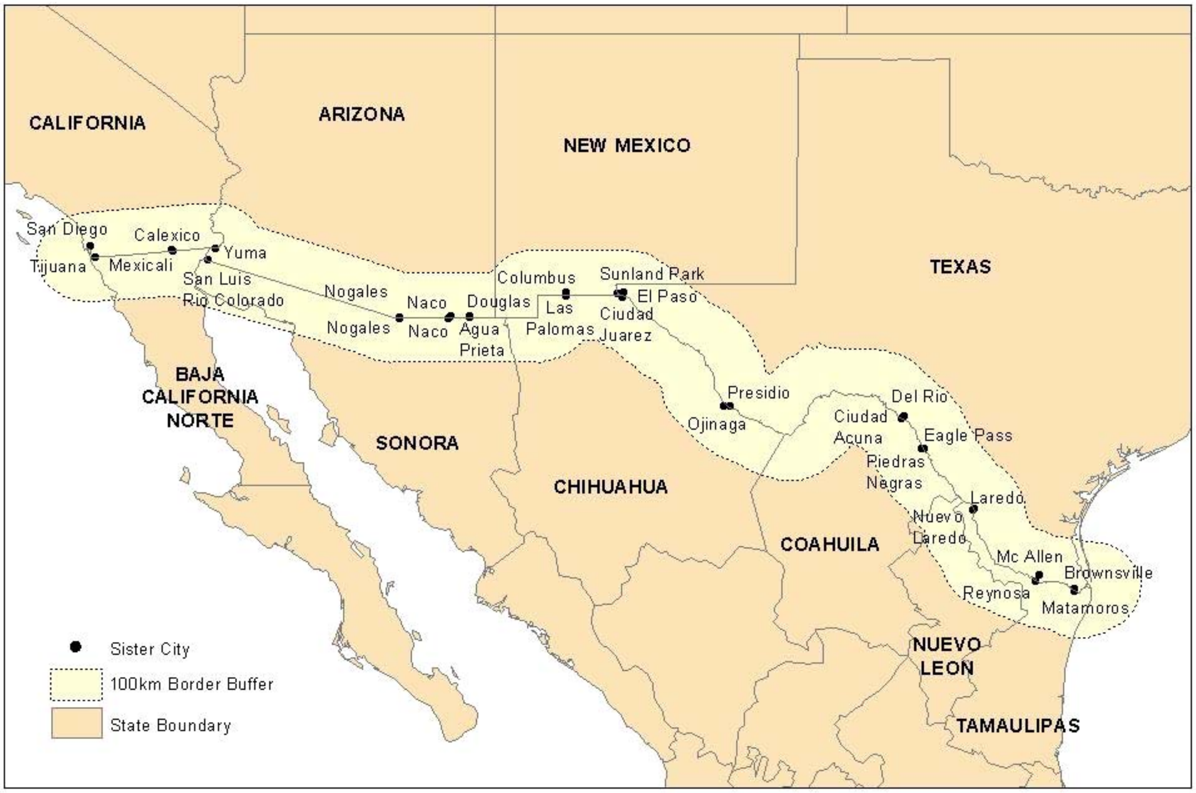
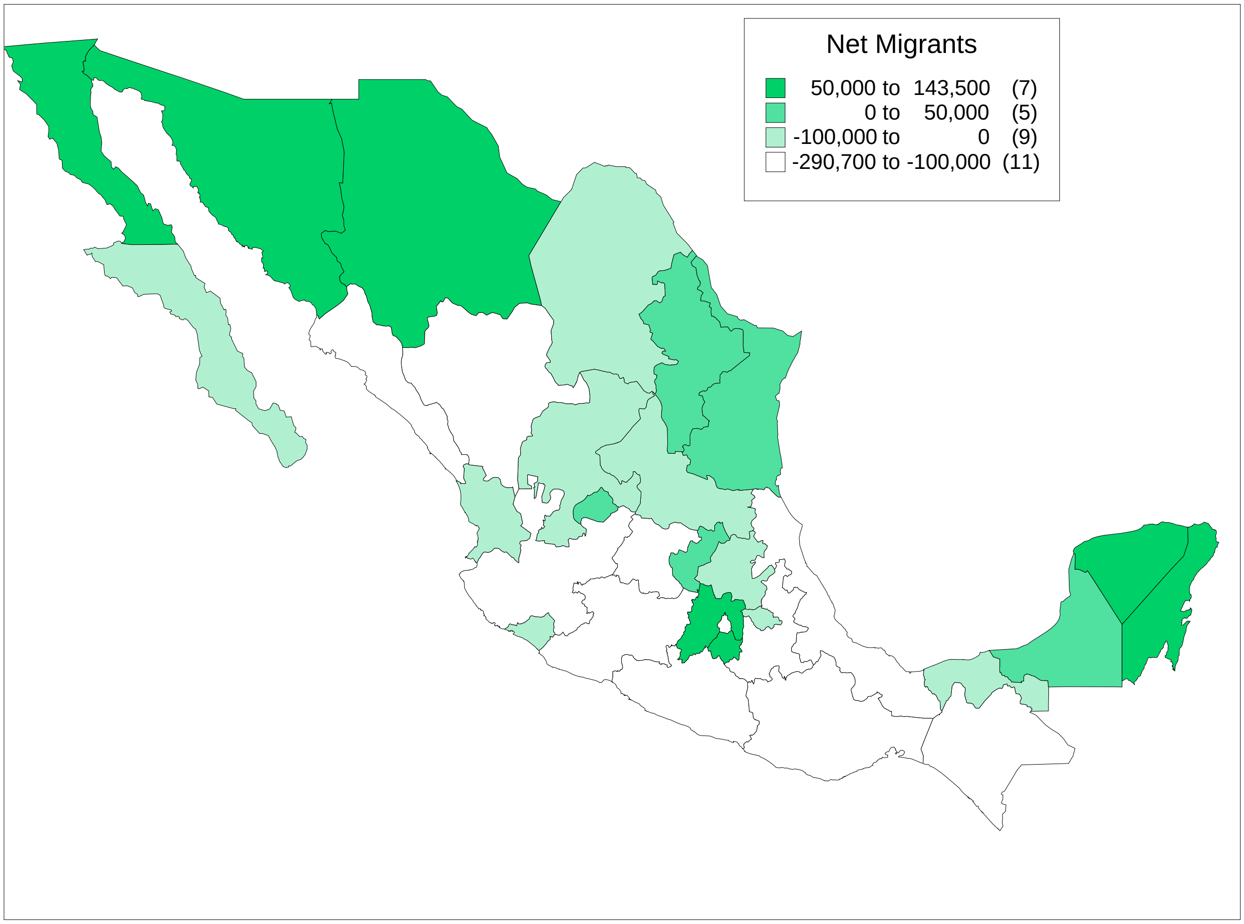


Figure 1: The US-Mexican Border Communities



Source: INEGI (1997).

Figure 2: Mexican Internal Migration, by State, from 1992 to 1995

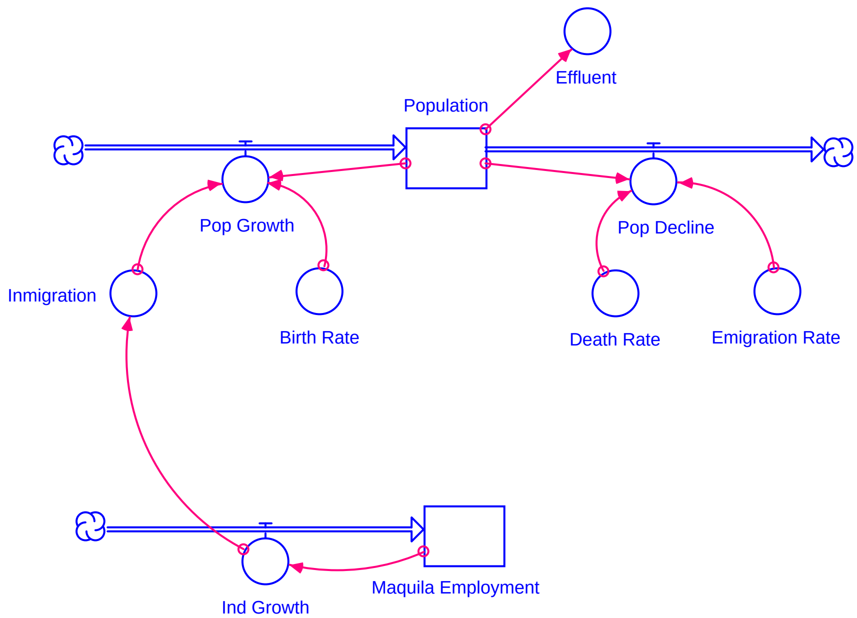


Figure 3: *ambos* Nogales Population Model Diagram

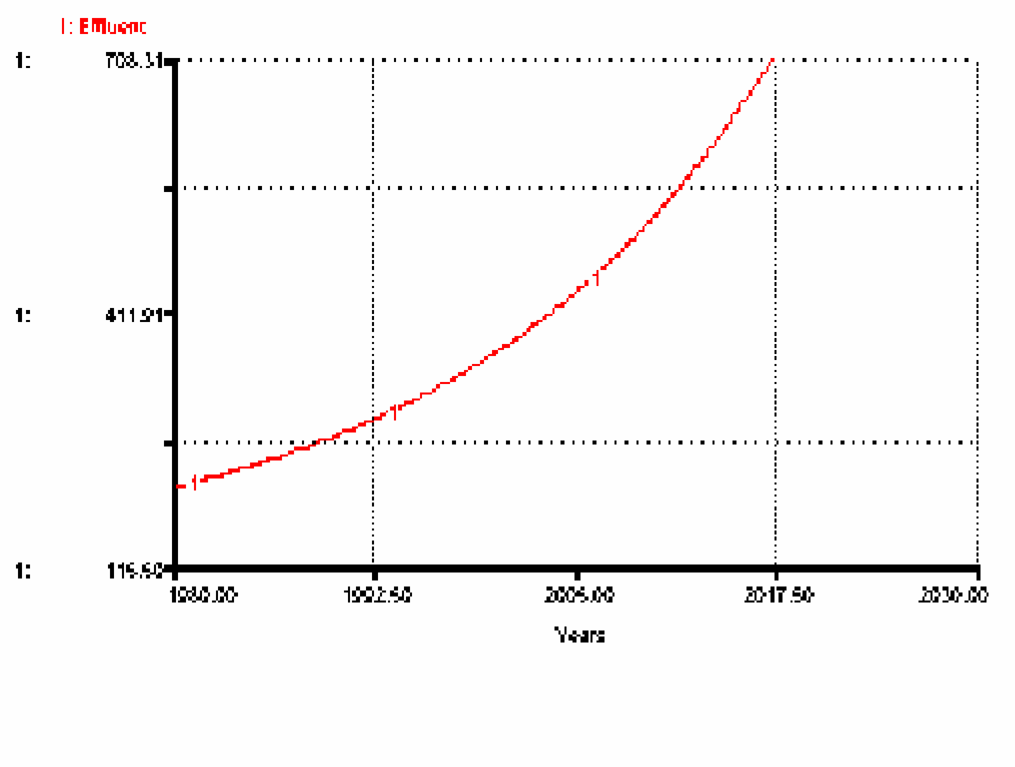


Figure 4: Monthly Effluent Production in *ambos* Nogales (millions of gallons)

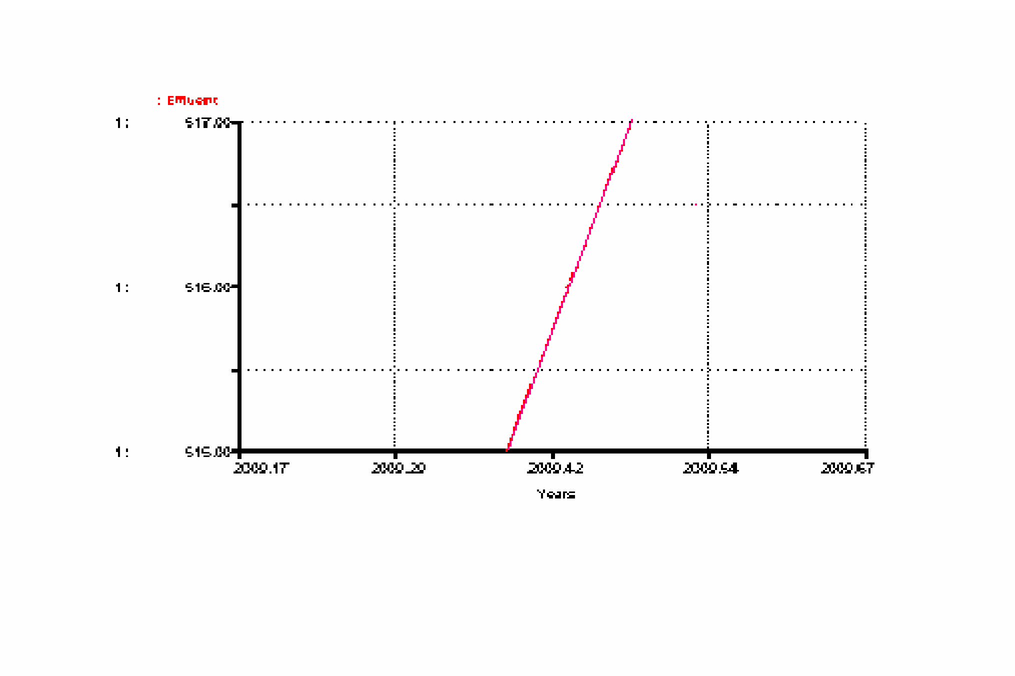


Figure 5: Monthly Effluent Production in *ambos* Nogales (millions of gallons)

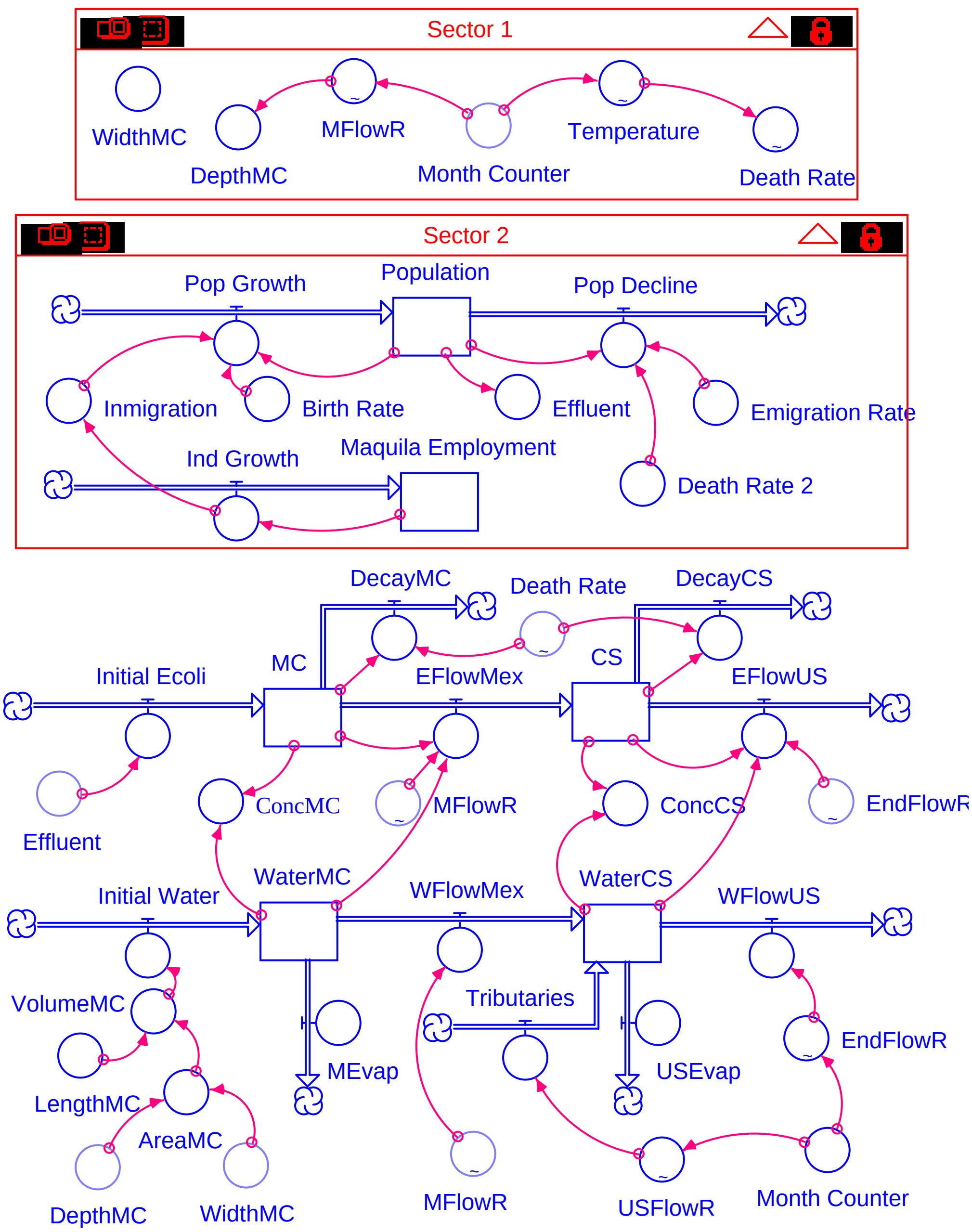


Figure 6: *E coli* Concentration Model – New River

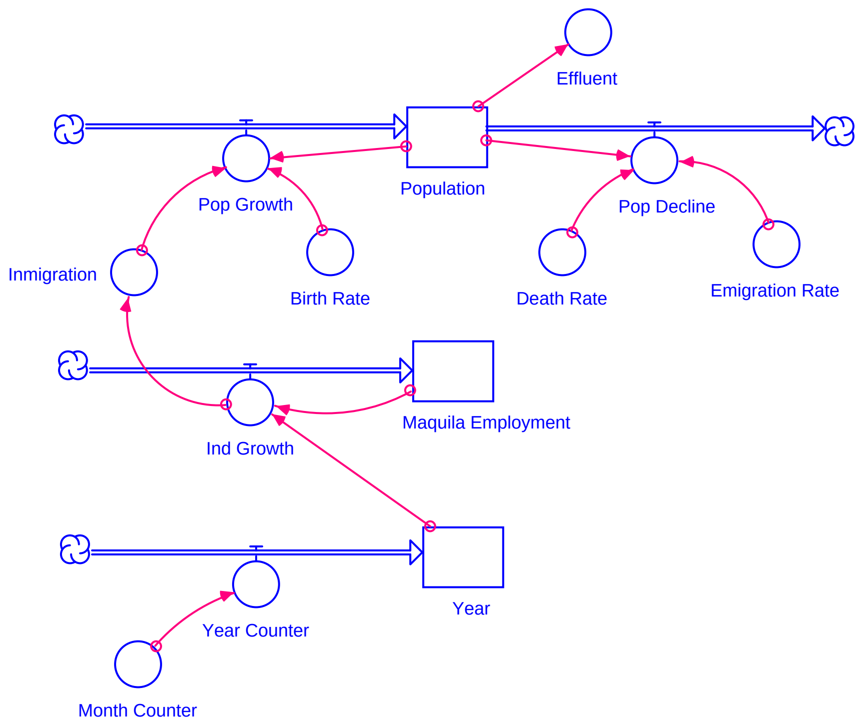


Figure 7: Mexicali Population Sub-Model

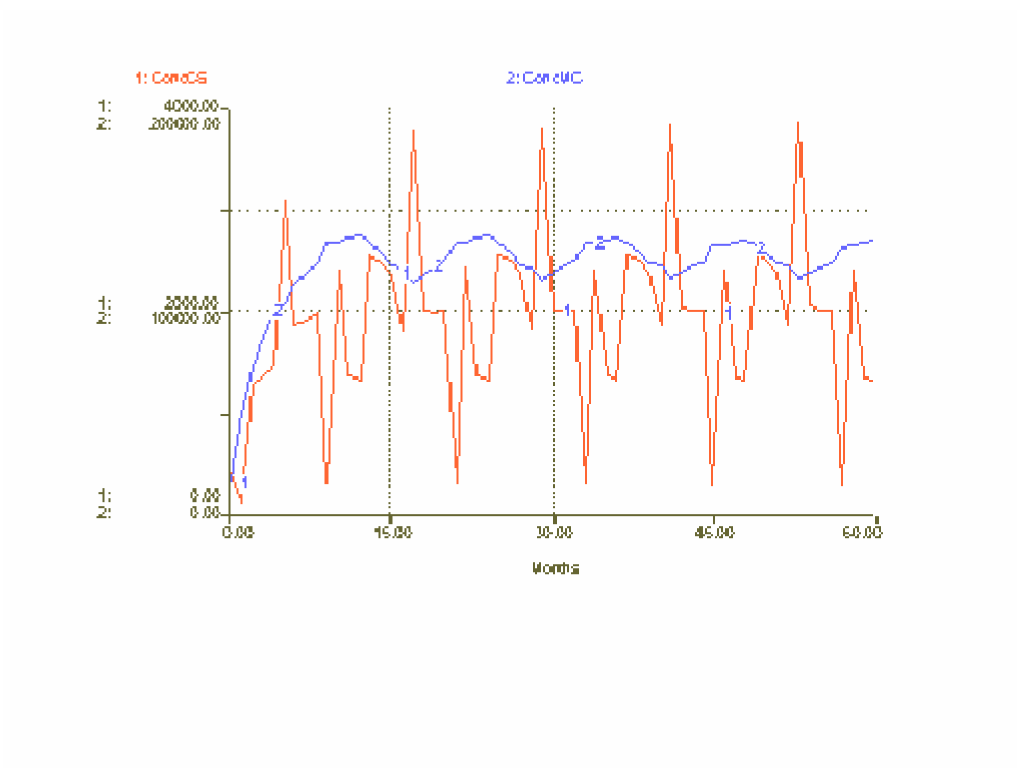


Figure 8: *E. coli* Concentrations in the New River

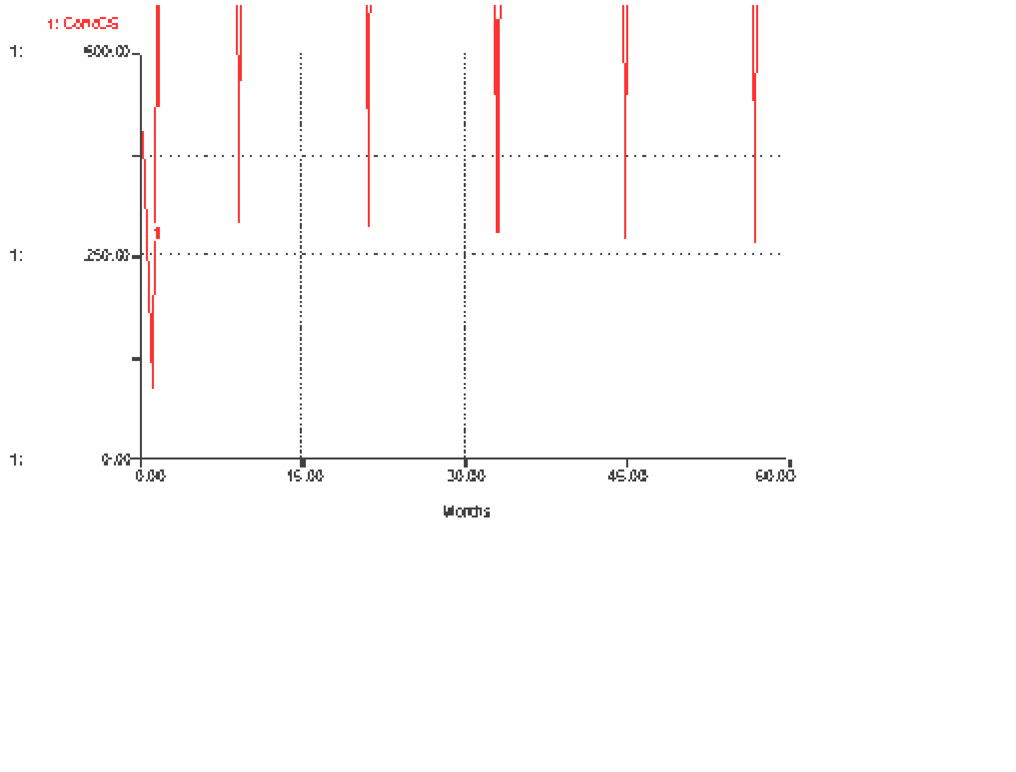


Figure 9: *E. coli* Concentrations in the New River

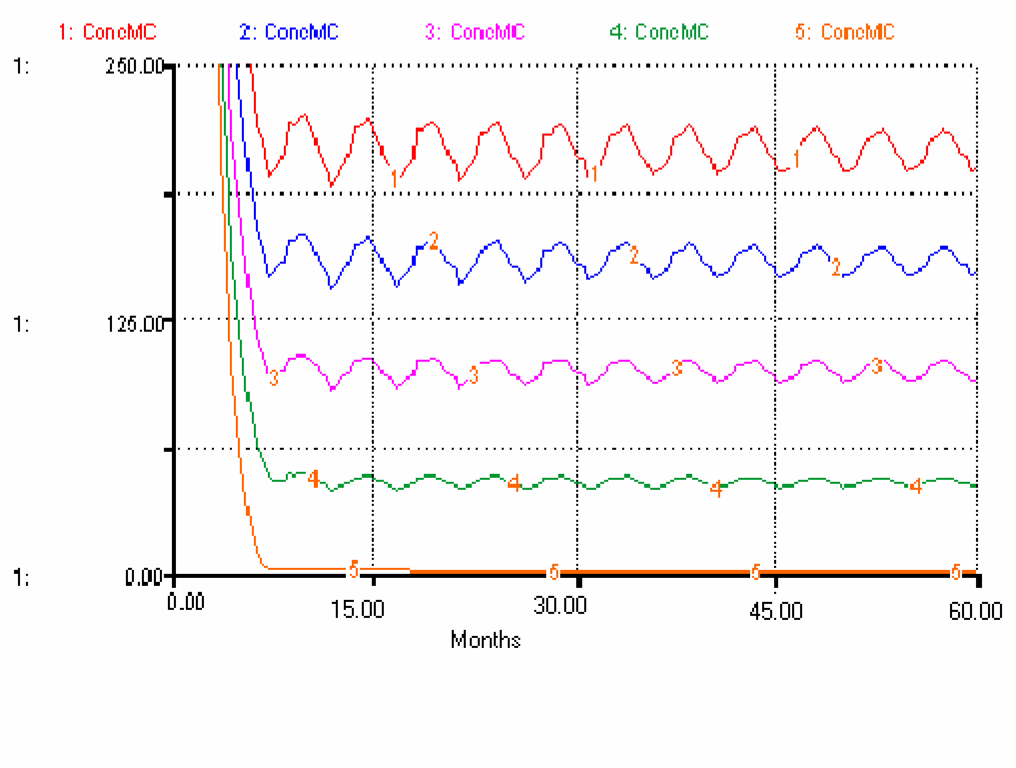


Figure 10: *E. coli* Concentration in Mexicali

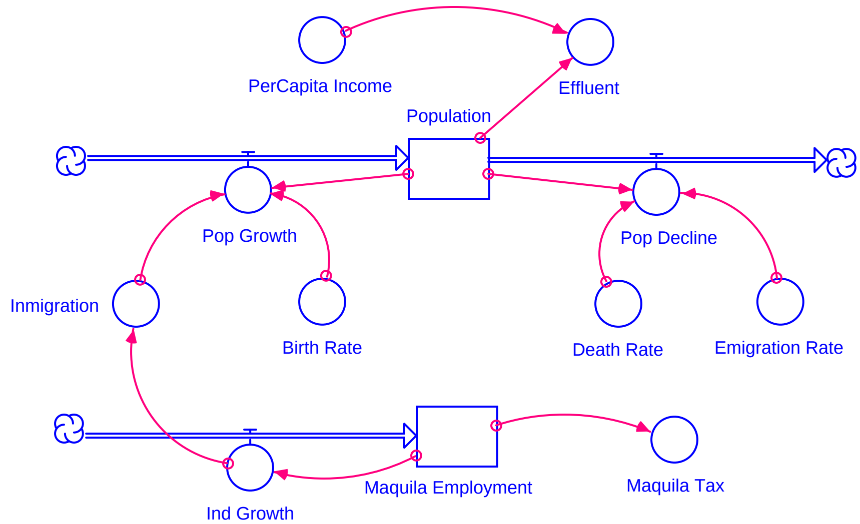


Figure 11: Joint Economic/Ecological Model of *ambos* Nogales