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The impact of global climate change on water quantity and quality: A system dynamics approach to the US–Mexican transborder region

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ABSTRACT

The potential impacts of Global Climate Change (GCC) in zones where water is scarce, such as along the US–Mexico border is, and will continue to be, a key concern for the future sustainability of humanity. This paper estimates the variation in quality/quantity water due to climate change and assesses its impact on community development in the US–Mexico border region of the Rio Grande/Rio Bravo Water Basin. To estimate variation in different water quality parameters, we use a conservative model with most probable scenarios for temperature/precipitation produced by the International Panel on Climate Change. We propose a system dynamics model to understand the complex interaction of factors governing the quantity/quality of water and their effects on social and economic conditions. The model simulates, for a 70-year period, policies and decisions that have the potential to improve conditions and prevent risks that may lead to social unrest and hinder economic development.

1. Introduction

The availability of water resources is linked to the well-being of human societies that need it for industrial activities, agriculture, drinking, hygiene and recreation. Changes in the availability of water through precipitation, droughts and depletion of aquifer volumes, have significant consequences for the development of local villages and urban communities. Thus, availability and quality of water are critical risk assessment parameters, including forecasts associated with global climate change (GCC). The International Panel on Climate Change (Bates, Kundzewicz, Wu, & Palutikof, 2008), predicts a 1–5 degree centigrade temperature increase over 20–80 years in arid regions along the US–Mexico border. While water precipitation is predicted to decrease by 5–20 percent, there remains uncertainty about the trend in summer rainfall. These undetermined conditions, along with well-known influences of population growth, urbanization, land use changes, institutional robustness and resilience of water availability, make planning for changes in the availability of water resources and the depletion or recharging of aquifers particularly difficult.

The consequences of climate change are two-fold – water availability and water quality. Increases in the demand in regions of scarcity can force the use of poor or unsuitable water with drastic repercussions for industry, human health and the associated costs of health care. Established influences on water quality include population growth, urbanization and land use changes (Hunter, 2003), though the impact of global climate change remains unknown. If climate change leads to decreases in rainfall, water quantity and quality will worsen as populations increase and sanitation pollutants behave differently as a result of changes in environmental parameters. In the arid regions of the US–Mexico border, the estimation of the effects of climate change on water quality and the repercussions for this region is a critical issue for this key Latin America border crossing for trade with America, which needs to be addressed and planned for prior to problems arising. This paper models the potential impacts of global climate change on the water availability and quality in two locations along the US–Mexico border: Reynosa/McAllen and Laredo/Nuevo Laredo, and explores the consequences for community development and sustainability.

The paper is organized as follows: in the next section, we formulate the problem to be modeled by describing the socioeconomic conditions of the two sites researched, Nuevo Laredo and Reynosa, that lead to the proposed modeling approach for this study. In Section 3, we assess the complex interaction of factors governing the quantity and quality of water and their effects on social and economic conditions. For this purpose, we develop a system dynamics (SD) model to simulate, for an extended period

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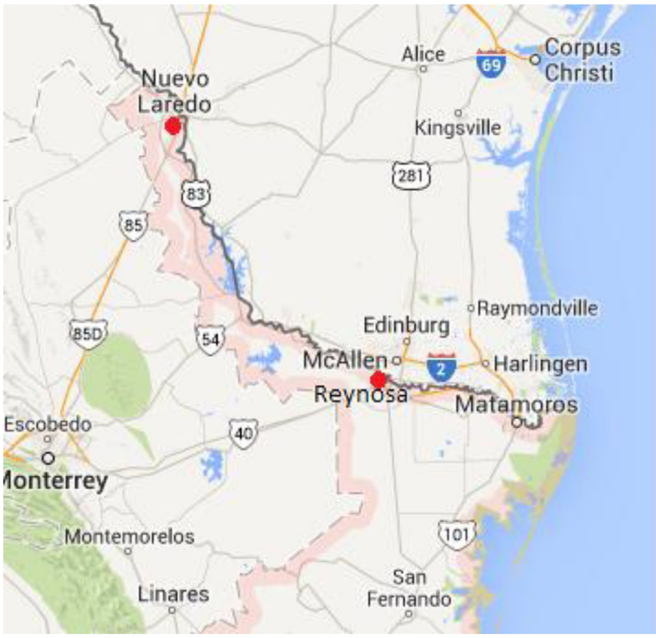

Fig. 1. Location of Nuevo Laredo and Reynosa along the US–Mexico border.

(2010–2080), the development of the main variables related to water quantity and quality. In Section 4, we examine some scenarios as a result of some changes in the level of greenhouse gas (GHG) and other control variables that represent the policies and decisions that, if implemented, would improve conditions and prevent risks that can lead to social unrest and hinder economic development. In the final section, some conclusions and further points for research to help social and economic policy-making are made.

2. Overview of the study area: formulating the problem and the modeling approach

This section details the demographic, social and economic environment of the research sites in this study. Nuevo Laredo is a border city in the Mexican state of Tamaulipas, close to El Paso, in the US and is the most important freight crossing point between Mexico and the US. Reynosa is the largest city in the state of Tamaulipas and is located across the Rio Grande (Río Bravo) from McAllen in Hidalgo County in the US state of Texas (Fig. 1).

2.1. Demographics

Nuevo Laredo covers an area of 1334.02 square kilometer (515 square miles) with a population of 395,185 in 2010. The population compound annual growth rate (CAGR) is expected to decrease from 2.12 percent in 2005–2010 to 1.16 percent in 2025–2030 (Consejo Nacional de Población (CONAPO), 2010) and this population growth is almost 80 percent larger than that for the state of Tamaulipas. This means that by 2030 Nuevo Laredo population will represent 14 percent of the whole Tamaulipas population while in 2010 it was 12.2 percent. The Reynosa metropolitan zone covers an area of 3156.34 square kilometer (1217 square miles) and includes two municipalities: Río Bravo and Reynosa itself. Altogether, Reynosa has a population of 720,125 in 2010. The population CAGR is expected to reduce from 2.76 percent in 2005–2010 to 1.39 percent in 2025–2030 (Consejo Nacional de Población (CONAPO), 2010). However, this population growth is almost 120 percent larger than that for the state of Tamaulipas, which means that by 2030 the Reynosa population will be 27.1 percent of Tamaulipas population while in 2010 it was 22.3 percent. In sum, projections show that the populations in both urban areas will continue growing and concentrate a larger proportion of people of the state of Tamaulipas.

2.2. Social

We used education, health, and housing as key indicators of social profiles (Instituto Nacional de Estadística Geografía e Información, 2009; Instituto Nacional de Estadística Geografía e Información, 2010). A comparison of the main social indicators between Nuevo Laredo and Reynosa together with the state of Tamaulipas is shown in Table 1.

To summarize these social data, both urban areas present deficiency in terms of education levels, health services, and housing conditions, as compared to the state of Tamaulipas. Even so, they show better state provision of utilities (water supply and drainage) when compared with all of Mexico, some lagging conditions are notable.

2.3. Economics

Both locations are characterized by large manufacturing and retail sectors, Nuevo Laredo also has a high transport service profile and Reynosa is home to the Petroleos Mexicanos (Pemex) oil refinery.

The economic structure of Nuevo Laredo has a high proportion of manufacturing which comprises 28.3 percent of the labor force or ∼22,000 workers (Instituto Nacional de Estadística Geografía e Información, 2009). Other important sectors in the city include transportation, warehousing, and retailing. In the manufacturing sector, the most important subsectors are concentrated mainly in transportation equipment and electrical devices. Reynosa's economic structure has a higher percentage of manufacturing comprising 52.3 percent of the labor force or ∼110,000 workers (Instituto Nacional de Estadística Geografía e Información, 2009). Other important sectors in the city include retailing, and in particular the mining industry which is represented by the oil and petroleum industry, including a Petroleos Mexicanos (Pemex) refinery, with 4641 workers. The manufacturing sector in Reynosa concentrates mainly on the electronic equipment, electrical devices, metal products, and equipment and machinery, with 42,232, 11,869, 7719 and 5290 workers, respectively.

2.4. Modeling approach

Nuevo Laredo and Reynosa are located in the VI Administrative Hydrological Region (RHA) Rio Bravo that covers 379,552 square kilometer and has a population of 10,982,077 inhabitants and 12,163 cubic hectometer [1] of renewable water in 2009. According to recent data in this region, water supply declined from 14,267 cubic hectometer in 2001 to 12,163 cubic hectometer, and water demand increased from 7071 cubic hectometer to 9243 cubic hectometer in the same period (CNA National Water Commission Mexico 2011). This has caused renewable water per capita per year in the region to decline between 2001 and 2009, from 1467 cubic meter to 1108 cubic meter. This fact reveals a high "*water stress*", which is a parameter that, according to worldwide standards, should not fall below of 1700 cubic meter (Gleick, 2002). Likewise, the Mexican Water National Commission (CNA) also reports a very high pressure from water consumption, measured by the percentage of water allocated to consumptive uses (household, industry, agriculture, and thermoelectricity generation) of the yearly water renewable supply. This has varied from 49.6 percent

[1] Cubic hectometer is a common aggregate measure of water supply and demand that equal 1E + 9 liters.

Table 1
Nuevo Laredo and Reynosa Social indicators.

Social indicators	Nuevo Laredo	Reynosa	Tamaulipas state
Basic education (percent of population over 15 years of age)	33.9 percent	33.4 percent	38.4
Health vulnerability (percent population not covered by any health scheme)	37.2 percent	36.7 percent	35.5 percent
Housing conditions (occupants per dwelling and people per room)	4 & 1.1	3.89 & 1.12	3.8 & 1.7
Access to public water	93.1 percent	90.4 percent	94.3 percent (*)
Access to drainage services	92.4 percent	80.2 percent	80.5 percent
Electricity supply	94.1 percent	89.8 percent	90.4 percent

* National.

to 76 percent from 2001 to 2009 when according to the CNA, this should not exceed 40 percent.

The US–Mexico border is both emblematic and exceptional in many different ways. Few international borders have such different levels of development on either side, and such a lack of transborder collaboration, mainly in water resources management. Water security, particularly in a transborder context, should take climate change under consideration. Relatively few works, however, have been reported related to climate change and the management of scarce water resources in the region (Gerlak, Varady, & Haverland, 2009; O'Brien, St. Clair, & Kristoffersen, 2010). Furthermore, most works are related to water quantity and very few address the problem of water quality (Varady et al., 2013).

Despite the importance of water quality and quantity for the sustainability of the US–Mexico border region, few efforts have been made that attempt to develop a properly designed water management plan for the area. The only current related policies are mostly geared towards the implementation of the polluter pays principle: fees and/or fines for unnecessary use. Other approaches such as efficient water pricing, searching for alternative water sources, water culture, or water recycling programs, have not been attempted, though many of these issues have been explored previously (Atkinson, Machado, & Mourato, 2000; Collins, 2004; Nash, 2000).

In this paper, we argue that this is complex system; and that understanding its dynamic structure is the most effective way to approach it. In this area, the ever increasing population, economic growth and increasing GHG emissions levels, will inevitably impact on climate change making sustainable water management a key challenge and a difficult task. This situation contains the typical components of a complex system, thus we propose to use a systems dynamics (SD) methodology to tackle it.

System Dynamics (SD), originally known as Industrial Dynamics, is a creation of Jay Forrester in the 1960s in the Massachusetts Institute of Technology (Forrester, 1961). SD is essentially a methodology, which uses the theory of stock accumulation, information feedback and control in order to evaluate organizations and situations. The basic idea underpinning this approach is that any complex situation can be described in terms of elements and flows; flows being the relationships between the elements. System Dynamics assumes that things are interconnected in complex patterns, that the world is made up of rates, levels and feedback loops, that information flows are intrinsically different from physical flows, and that non-linearities and time-delays are important to system behavior arising from the system's structure (Sterman, 2000). The focus of SD methodology is to capture the structure of the complex situation in terms of the interactions of the elements (flows and stocks) between them; this description constitutes the dynamic behavior of the system. SD has been used in a variety of contexts, as a problem evaluation on the premise that the structure of a system, that is the way the systems are connected generates its behavior (Richardson & Pugh, 1989; Stave, 2003; Sterman, 2000). While statistical forecasting models rely on equations developed ex post, i.e. following observations, SD aims first to determine the system's structure consisting of positive and negative relationships between variables, feedback loops, systems archetypes, and delays (Sterman, 2000; Wolstenholme, 1982; Wolstenholme, 2003) followed by ex ante projection where 'future system states are replicated from the SD model' (Winz & Brierley, 2007).

We draw on the established capacity of SD to make sense of a complex situation, in this study we specifically rely on the strong capacity of SD to bring together both the physical and socioeconomic behavioral aspects of the situation in a holistic and flexible way that is transparent for decision-makers and users. By utilizing SD for modeling different scenarios, these can be tested to facilitate engagement with detailed water management planning. Although modeling for improved water resources management has been studied using OR techniques, and mathematical programing has been used for water resources allocation (Condon & Maxwell, 2013; Millera et al., 2013; Wang, Fangb, & Hipel, 2008), by utilizing SD, this study contributes to understanding the impact of climate change in a flexible and transparent way.

It is apparent that the worrisome situation in Nuevo Laredo and Reynosa comes mainly from the effects of growing GHG emissions and that this will continue to pose increasing concerns for socioeconomic conditions in the region. From a systemic perspective, the problem we investigate and model is the dynamic relationship between water supply and demand in Nuevo Leon and Reynosa together with the effect of GHG on climate change. Although one possible solution would be a reduction of this type of emissions, we argue that policy makers can implement complementary policies and strategies directed to mitigate this problem. These comprise reduction in the water consumption and consequently its overall demand, the development of water infrastructure and better use of this, and the implementation of specific economic policies.

Changes in the supply, demand and quality of water are the result of structural changes demonstrated in previous sections and thus we advance the following modeling proposal:

> "In Nuevo Laredo and Reynosa, the increasing downward effect of GHG on the quantity and quality of water can be mitigated by managing water consumption patterns, water supply infrastructure and by implementing economic policies. The proposal of this paper is that the model provides several scenarios of the interplay of GHG emissions with water consumption patterns and it can be used to explore mitigating policy options."

3. A proposed modeling approach to simulate potential impact of global climate change on the availability/quality water in the US–Mexico border

It is clear, from the analysis of the research sites, that to achieve a sustainable and holistic understanding of the complexity faced by communities along the US–Mexico, we need to go beyond predicting the quality/quantity of water and population sizes in the region. Quality/quantity of water and economic, social variables interact dynamically with environmental and institutional variables.

SD has been used in exploring the Environmental Management and Sustainability in applications tackling problems concerning forestry in Indonesia, irrigated lands in Spain, renewable resource management in Norway, wildlife management in USA, blue–green algae bloom in the coastal waters of Australia, and the sustainable development of wetlands in Mexico (Cavana & Ford, 2004; Luna-Reyes, Duran-Encalada, & Bandala, 2013). It has also been applied successfully to improve water management resources in arid regions for simulations of a 40-year period (ShanShan, LanHai, HongGang, XiangLiang, & XueMei, 2013) and to analyze the long-term impact of various investment plans (Xia & Poha, 2013). These applications have revealed that modeling dynamically these complex problems with many stakeholders can enlighten the implementation of possible policies to alleviate the problem. SD has been used for general water management purposes, particularly in developing participatory models. In these applications, SD methodology has been used to encourage different stakeholders to become involved to create a 'transparent nexus of science, policy options and local knowledge that enhances discussion' (Beall, Fielder, Boll, & Cosens, 2011; Stave, 2011). Some failures to represent this dynamism are seen in the case of water scarcity on irrigated lands in south-eastern Spain (Martínez Fernández, & Esteve Selma, 2004). In this case, given the complexity of factors involved (water resources, available land area, irrigated lands, pollution sector, and profitability), the state mistakenly aimed to eliminate, or reduce, the water deficit when the driving factor of the system was the total area of irrigated land. These applications concentrate mainly on the dynamic structure related to water management and the long term environmental sustainability linked to the management of resources, they do not however, tackle the link between water quantity and quality and GHG which has not been fully investigated.

Our aim in this paper is to contribute to this body of knowledge developed in these previous studies and to extend the use modeling to fully explore the link between GHG and water quality and quantity. Our core justification for the use of SD is its power to capture important behavior-through-time phenomena that arise from the mathematical properties of accumulating asset stocks. The mathematics of accumulation provides, unavoidably, a more plausible model of reality than any model that ignores this phenomenon (Sterman, 2010; Warren, 2004; Warren, 2005). The stock-and-flow analysis, complete with quantitative time-path portrayal of all important system variables (especially of the stocks and flows themselves), cannot be avoided if confidence in the diagnosis, prognosis and policy response to real-world challenges is to be expected. In fact, for these same attributes, the authors recommend the use of SD for analyzing the relationships among greenhouse gas (GHG) emissions, atmospheric GHG concentrations, and climate change (Sterman, 2008; Sterman & Booth Sweeney, 2007). SD has proven to be a useful tool when complex systems should to be "re-oriented towards a greater sustainability through policies that are quite different from those currently being implemented and which should focus on the true driving factor of the system [...]" (Martínez Fernández & Esteve Selma, 2004). Our paper subscribes to these tenets and aims.

3.1. Developing the model

The structural relationship that has led to changes over time in the supply, demand and quality water is dynamic in type, and in this paper, we propose a SD model that captures these relationships. These dynamics are described in Fig. 2. The diagram indicates that *GHG* is an exogenous variable that increases *air and water temperature.* This rise in temperature decreases q*uantity of water* and *quality of water,* and both reduce *water adequacy.* As *water adequacy* diminishes there is a reduction in *population growth rate*, and consequently on *population.* As *population* diminishes, *water demand* also reduces, leading to a rise in *water adequacy.* Thus, *water adequacy,* through *population growth rate, population,* and *water demand,* describes a balancing (B) causal loop. There is another reinforcing (R) loop that is described by the process of water recycling: as *quantity of water* increases the *recycled water* also increases, and this leads to another increase in *quantity of water*.

Finally, there are some exogenous variables that affect the *quantity of water* and *water demand.* On the one hand, by having a *better distribution infrastructure*, one that reduces water leakages, the *quantity of water* can be expected to increase. In a similar way, by increasing *recycling capacity* the amount of *recycled water* will increase. On the other hand, by modifying *consumption patterns* (household, industry, agriculture, and virtual water) towards a better use, *water demand* will reduce. These exogenous variables are used later in the simulation model as leverages to improve the work of the system.

The simulation model was built using the *ithink* 10.0.2 software, and comprises four sectors, water demand, water supply, water quality, and performance and control; and six level variables. The model in *ithink* 10.0.2 syntax is included as Appendix A. The model was run for 70 years, from 2010 to 2080.

3.2. Validation of the model

Before carrying out the simulation we proceeded to validate the model. This is a key step in the System Dynamics modeling process and crucial to give the model team the necessary confidence in the 'soundness and usefulness' of the model (Forrester & Senge, 1980). To this effect we used graphical/visual and statistical measures to describe the behavior pattern (Barlas, 1996; Forrester, 1961). We understand calibrating as "the process of estimating the model parameters (structure) to obtain a match between observed and simulated structures and behaviors [as] a stringent test of a hypothesis linking structure to behavior", (Rogelio, 2003). Following these guidelines, we carried out a sensitivity analysis and calibrated the parameters in the model to reflect the evolution of water supply and demand in region VI Rio Bravo during 2001–2009, a period for which comparable and consistent data existed. We undertook the mean absolute percentage error (MAPE) in order to compare the simulated values with the historical values. The results are shown in Table 2.

These results show a generally low MAPE of 3.64 percent for water supply and of 5.34 percent for water demand. Additionally, we plotted these results in order to dispose of any possible bias in our simulation results. The model does not show any bias in estimation, describing a gradual fall in water supply and a rise in water demand during these years (Chart 1). It is important to note that the emphasis in this case was on pattern prediction (trends and phase lags) rather that point (event) prediction (Barlas, 1996). We note that in both cases, historical data show a steeper decline during the first years of this millennium, reflecting the exceptional reduction in rainfall precipitation experienced in the region which resulted from the meteorological phenomenon called "El Niño" (Arreola-Ortiz & Návar-Cháidez, 2010).

The results of the whole validation process of water quantity establish a high model confidence. The validation of water quality was achieved through the process of modeling the parameters used for the Water Quality sector, explained at the end of Section 3.5. In the next section, we describe each sector of the model in detail, along with the parameters used for the variables.

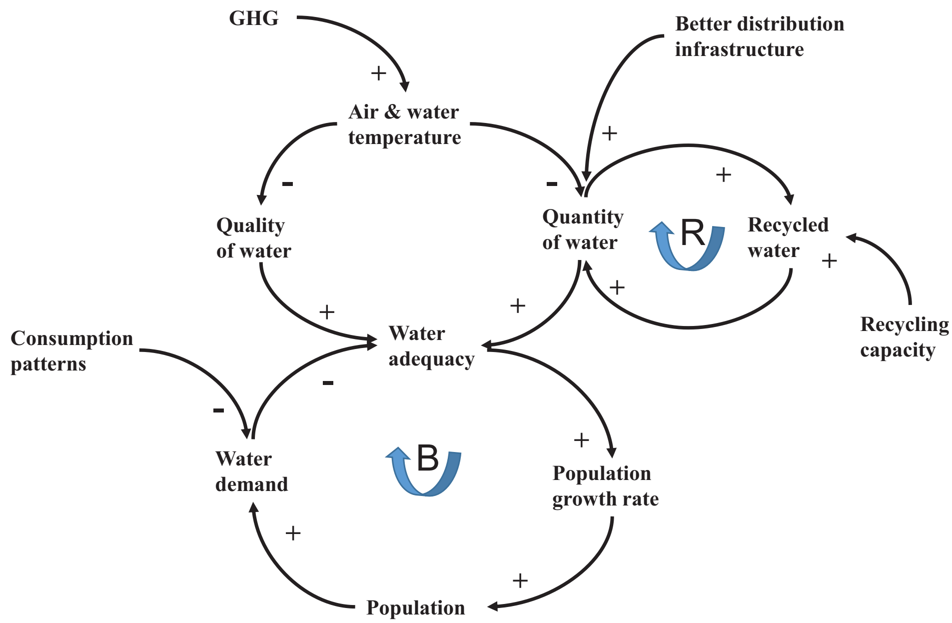

Fig. 2. Causal loop diagram of the model.

Table 2
Results of statistical test of comparison between simulation and available historical data series for water supply and demand.

Year	Water supply real (cubic hectometer)	Water supply simulated (cubic hectometer)	Water demand real (cubic hectometer)	Water demand simulated (cubic hectometer)	Water supply MAPE (percent)	Water demand MAPE (percent)
2001	14,267	14,409	7186	8284	1.00	15.28
2002	13,993	13,615	7472	8409	2.70	12.55
2003	13,718	13,406	7757	8536	2.27	10.04
2004	14,182	13,167	8539	8665	7.16	1.48
2005	12,477	12,898	9153	8795	3.37	3.91
2006	11,938	12,612	9112	8928	5.65	2.02
2007	12,024	12,528	9191	9063	4.19	1.40
2008	11,937	12,459	9235	9200	4.37	0.38
2009	12,163	12,408	9243	9339	2.01	1.04
				MAPE	**3.64**	**5.34**

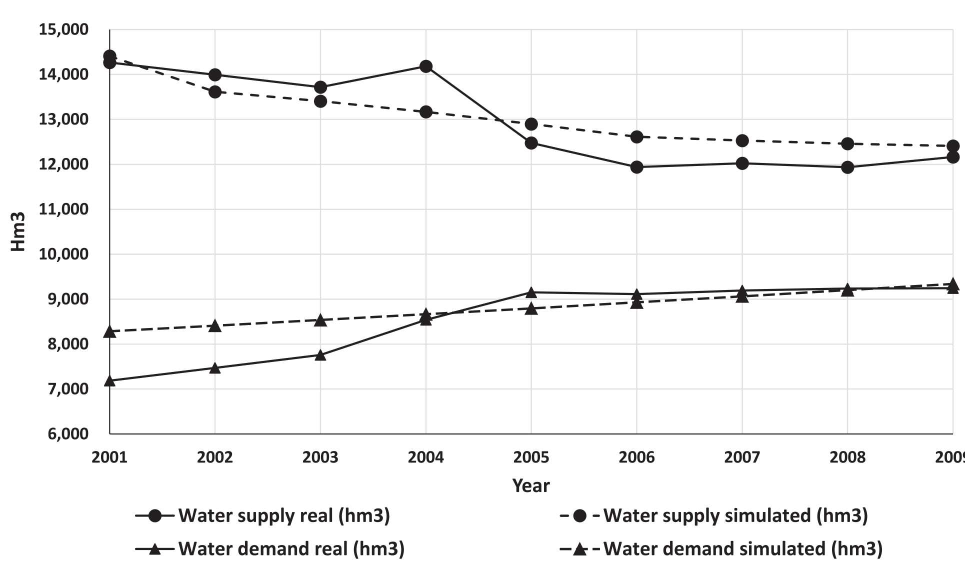

Chart 1. Historical and simulated water supply and demand series.

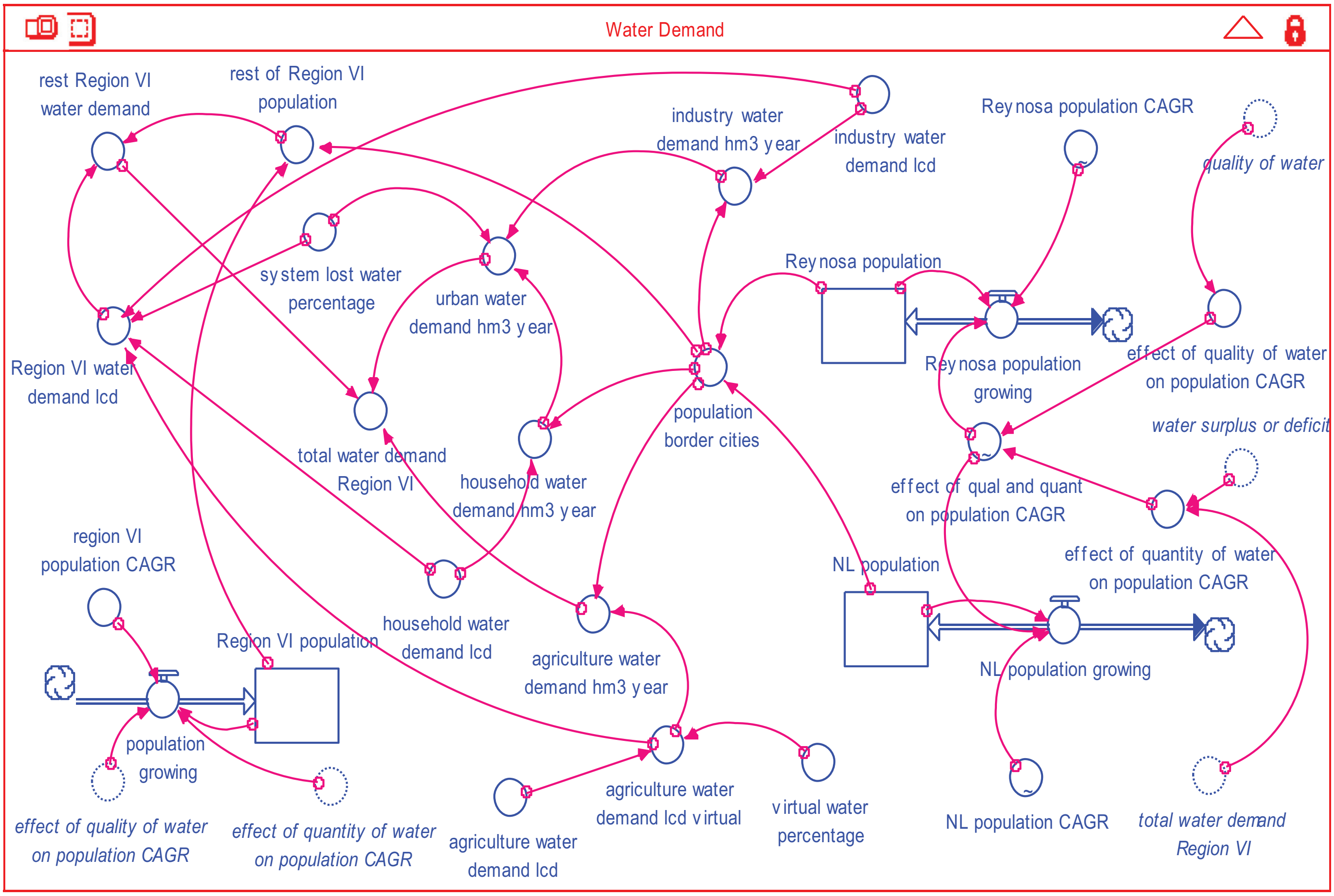

Fig. 3. Diagram of the water demand sector.

3.3. Water demand sector

The first sector, water demand (Fig. 3), estimates the total water demand of region VI Rio Bravo, and contains variables related to industrially, household, and agricultural water demands in Nuevo Laredo and Reynosa. Water requirements are linked to population forecasts and consumption per capita per year estimates in both cities. To estimate population growth we use the compound annual growth of rate (CAGR) provided by CONAPO (Consejo Nacional de Población (CONAPO), 2010). In the agriculture sector the model allows for the simulation of virtual water. The model makes allowances for water lost due to failures and leakages in the urban distribution system. Finally, this figure shows the water demanded by region VI, excluding Nuevo Laredo and Reynosa.

Water needs were estimated using accepted parameters for estimating water consumption in households, industry and agriculture.

3.3.1. Household water parameters

Data for Nuevo Laredo and Reynosa of the Water National Commission (CNA) in Nuevo Laredo and Reynosa show that household water consumption for the 2000–2009 period is approximately 300 liters per capita per day (l/c/d) (CNA National Water Commission Mexico, 2011). This seems to be a high parameter compared to data sources that establish the minimum amount of water required for social and economic sustainability of a city (Howard & Bartram, 2003; UNESCO, Water for People ,2003; VEWIN, Waterleidingstatistiek, 2005; World Health Organization/UNICEF, 2000). These approaches include assumptions about conservation technologies and their promotion, public education, and priority changes that can have an impact on water demand. Thus, the *Development Efficient Approach* suggests that 124.7 l/c/d are sufficient to support a high quality of life (VEWIN, Waterleidingstatistiek, 2005). This comprises: bathing 52.0; toilet flushing 36.0; clothes washing 20.0; food preparation and dish washing 8.7; drinking 1.6; and other 6.4 l/c/day. Recycling bathing water for toilet flushing could eliminate the use of 36 l/c/d of freshwater, giving a lower household consumption of 88.7 l/c/d. However, we need to consider some cultural and geographical patterns that are conducive to higher consumption in Mexico, particularly in the cities under review, where higher temperatures cause a higher consumption, mainly for bathing and drinking.

3.3.2. Industrial water parameters

In the case of water consumption for the industrial sector, we considered works that have estimated water needs by different industries (Bergkamp & Sadof, 2008; Lloret & Water, 2010; National Statistics Office, 2002). Water plays a threefold role in industry, each requiring a different approach to strategic management. First, water is a raw material input for industries such as beverages and chemicals. Second, water is a source of energy in sectors such as in mining and nuclear plants in these two roles, industry pays a price subject to market conditions. Third, water is an output or by-product, waste water is discharged and has pollution potential, from sectors such as textiles and automotive industries (Lloret & Water, 2010). Water is important for GDP, though different industries demand different water quality and quantities. Industry needs are relatively small compared to the needs of the agricultural sector, though in both cases, demand depends upon the composition of industry and the degree of recycling that is in place in each sector (Bergkamp & Sadof, 2008).

According to data from the CNA in Nuevo Laredo and Reynosa for 2000–2009 (CNA National Water Commission Mexico, 2011), industry consumed an average of 66 l/c/d. This amount, even though higher, is not far from some international standards that show that industry consumes 37.6 l/c/d: services sector, 29.6; manufacturing and construction, 4.2; and other uses 3.8 l/c/d (HMSO, 2002). Therefore, we can consider that as industry in Mexico becomes more efficient and technologically advanced, water consumption can be reduced. Additionally, we need to account for leakage from water infrastructure. Estimates of infrastructure loss range from 3 percent in Germany to 50 percent in Bulgaria (Chenoweth, 2008). Recent estimates for Mexico suggest that up to 35–40 percent of water is lost by failures and leakages in the water distribution system (El Mañana, 2010; Lee & Schwab, 2005), and given this high proportion of wasted water, a loss percentage is incorporated into our water requirement estimate in the model.

3.3.3. Agricultural and virtual water parameters

Though this analysis concerns water consumption in urban areas, we need also to consider water consumption needed to feed the population and to produce energy. Within the region VI Rio Bravo, both Nuevo Laredo and Reynosa are located the top third of 13 hydrological regions in Mexico which use water mainly for agricultural systems (CNA National Water Commission Mexico, 2011). This region consumed 7736 cubic hectometer of water for agriculture and 1183 cubic hectometer for energy (CNA National Water Commission Mexico, 2011). Together these amount to ~85 percent of water consumption in the region and represents agriculture and energy water consumption of 1900 l/c/d. A final consideration in the estimation of total water requirements per person is that of virtual water. This is defined as that amount of water needed to produce a good, product or service, for example, obtaining a ton of wheat, uses 1000 water tons, or 1000 cubic meter (Arreguin-Cortes & Lopez-Perez, 2007). The Harmonized System of Designation and Codification of Merchandise for international custom duties for imports and exports, suggests that in 2006 5395 cubic hectometer of exported virtual water and 35,256 cubic hectometer of imported virtual water resulting in the estimated net import of virtual water NIVW of 29,828 cubic hectometer (Arreguin-Cortes & Lopez-Perez, 2007) and that from 2000 to 2008 net imports have been increasing (CNA National Water Commission Mexico, 2011). The main virtual water imports to Mexico include cereals, meat, seeds and fruits, whilst exports comprise legumes, vegetables, and meat. Thus, virtual trade has been suggested as a way to alleviate water shortages in some countries and regions as it provides some potential to mitigate water scarcity (Orr, Cartwright, & Tickner, 2009). For this study, we considered water imports as a percentage of domestic water plus exported water, in order to assess the impact of water savings for agricultural use in both cities. If we consider that in 2006, domestic consumption in Mexico was 76,100 cubic hectometer, then this amount added to water exported made a total of 81,495 cubic hectometer. If imported water was 35,526 cubic hectometer, then this amounts to 43.6 percent of the water used that year in Mexico (domestic plus export). If we accept this figure as potential water savings from the agriculture water estimated above, we can determine that agriculture and energy consumption can be substantially reduced to 1072 l/c/d.

3.4. Water supply sector

The intervening variables that determine surface and ground water available in region VI Rio Bravo are depicted in the water supply sector in Fig. 4. This sector structure illustrates that water accumulates by rainfall, aquifers filtering and recycling processes, and drains by flowing to cover water demands. When accumulated surface water exceeds dam capacity, 15,476 cubic hectometer, there is a water overflowing. GHG affects rainfall through climate change, which converts the base rainfall into actual rainfall. The recycling process shows the surface and groundwater being recycled, so that after treatment water becomes available again. A portion of this water is not finally recovered.

For the rainfall base we use the normal rainfall precipitation of 438 millimeter per year for the last 30 years (CNA National Water Commission Mexico, 2011). Then, to obtain the actual rainfall we multiply the base rainfall by the GHG effect on climate. This effect is estimated according to the level of GHG that is expected to reduce precipitation by 5–20 percent in the following 70 years (Bates et al., 2008). Rainfall capture and groundwater filtering factors were obtained from the CNA, these values are 0.60 and 5300 cubic hectometer, respectively (CNA National Water Commission Mexico 2011). We include the possibility of recycling water, at the moment the recycled water amounts to 7.5 percent of the total available water

3.5. Water quality sector

Fig. 5 illustrates the GHG effect on the quality of water due to its impact on air and water temperature, and consequently on biochemical oxygen demand (BOD), chemical oxygen demand (COD), and fecal coliforms (FC). Climatic (air and water temperature) and water quality data (BOD, COD and FC) of the study sites were obtained from the CNA of Mexico together with historic data for the period 1970–2007 for the two sites in the Reynosa–McAllen region (Reynosa international bridge, R1, and Anzalduas dam, R2) and one in the Laredo–Nuevo Laredo region (Nuevo Laredo international bridge, NL1). To avoid the presence of non-typical values, Chauvenet's criterion to determine atypical data was used. To understand climate change, data on variation in air and water temperatures were obtained from the Mexican Institute of Water Technology for the two most probable scenarios of climate change, AB1 and A2 of the Intergovernmental Panel on Climate Change (Bates et al., 2008; Instituto Mexicano de Tecnología de Agua IMTA, 2011).

Estimation of the variation of BOD, the COD, and fecal coliforms assumed that COD and BOD in water represent 82 and 52 percent of the theoretical oxygen demand (TeOD) (Radwan, Willems, El-Sadek, & Berlamont, 2003; Ramalho, 1977). The ratio between the actual BOD and the ultimate BOD (BOD_u), BOD/BOD_u is 0.77 (Eckenfelder, 1970) and the duplication time for fecal coliforms is 11 hours. We considered the contaminants involved with these water quality indexes as related only to specific potential sources of contamination, that is wastewater. The estimates of the expected amount of fecal coliforms in water were based on the microbial duplication model (Prescott, Harley, & Klein, 1993). Details of the formulae for both, the estimation of BOD and the duplication model are presented as Appendix B.

Historical and estimated fecal coliforms concentrations were compared against the World Health Organization (WHO) guidelines for drinking water quality (World Health Organization, 1995). The amount of fecal coliform (in CFU/100 milliliter) for the different scenarios assessed (AB1 and A2) were compared with the concentration quality criteria proposed by National Water Commission of Mexico (CNA). The amount of fecal coliforms (in CFU/100 milliliter) has decreased since the 1970s, (probably as result of wastewater treatment in the region), from over 7×10^4 CFU/100 milliliter in the 1970s to less than 100 during the 2000s. This is a very acceptable level of concentration that does not seem to pose any hazard to the public health for the foreseeable future.

Next, we describe the way we related these variables in the model. First, based on the increase on air temperature of

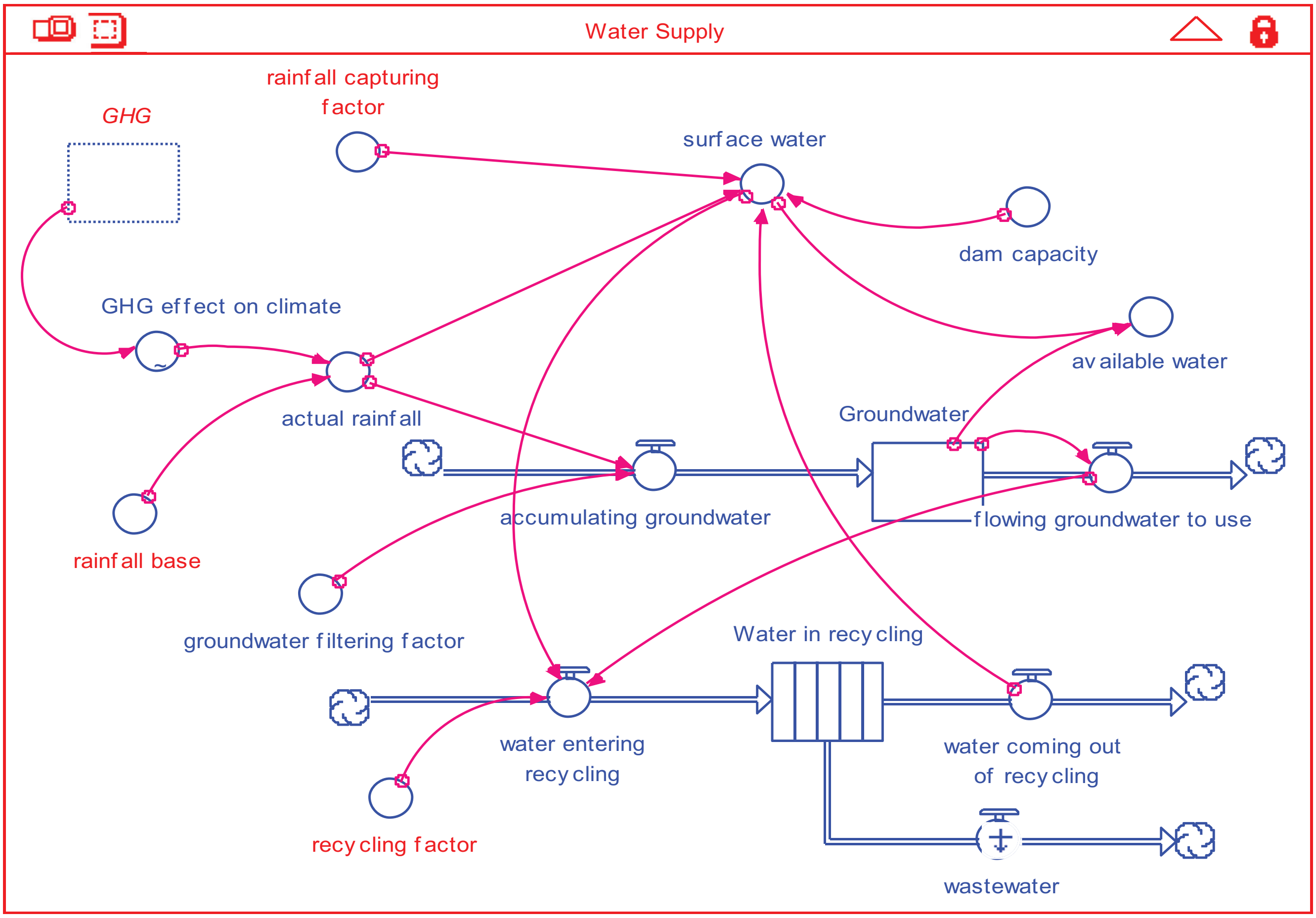

Fig. 4. Diagram of the water supply sector.

approximately 3 degree centigrade expected in the level of GHG (Bates et al., 2008), we calibrated the GHG generation factor and the dissipating GHG parameter. Departing from an initial index of 100 for GHG, this is expected to increase more than one third in a period of 70 years (Bates et al., 2008). To reach this amount we fixed the GHG generating factor with an annual value of 1 and the dissipating parameter with a value of 0.5. However, this annual dissipating capacity is expected to reduce as the level of GHG increases (Bates et al., 2008). Second, we regressed the water temperature on the air temperature with the six different scenarios provided by the CNA in the Reynosa–McAllen and Nuevo Laredo–Laredo regions (Instituto Mexicano de Tecnología de Agua IMTA, 2011), and selected the one with the best adjustment. These scenarios correspond to the two most probable scenarios of climate change (AB1 and A2) and data coming from the three sites mentioned (R1, R2, and NL1). The selected equation was: $y = 27.12\ln(x) - 65.145$, where y is the water temperature and x the air temperature, and $R^2 = 0.9815$. This regression confirmed the linear function between temperatures, air and water, as suggested in the literature (Michael, O'Driscoll, & DeWalle, 2006). Third, we regressed each one of the three water quality parameter, BOD, COD, and FC, on the six water temperature scenarios (a combination of climate change and sites), to identify the curves with the best adjustments for each. The selected equations were: for BOD, $y = 4\text{E} - 11\text{e}^{1.0319x}$; for COD, $y = 3\text{E} - 09\text{e}^{0.8957x}$; and for FC, $y = 20.638\text{e}^{0.0366x}$, where y is the parameter value and x the water temperature; R^2 are 0.9475, 0.9815, and 0.9782, respectively. Fourth, we converted the water quality parameters into criteria indexes that range from 1 = *excellent* to 5 = *strong contaminate* (this is detailed in the duplication model in Appendix B). Finally, the quality of water is defined according the maximum value achieved by any of the parameters, considering that a higher value means more contamination. This quality of water value feeds back to the population growth of cities, in the water demand sector, influenced by the increasing level of contamination which makes it less attractive to live in or migrate to these urban areas. We note that by following this procedure we were able to validate the results of water quality simulation with the historical data, which were used to construct the functions included in this sector.

3.6. Performance and control sector

The final sector, performance and control, represents the core results of the model and the control variables (Fig. 6). Water surplus or deficit is determined by comparing water availability with demand. Also, we calculate the renewable water per capita as an indicator that measures the amount of water per capita per year, an indicator related to water stress or water pressure. The water surplus or deficit feeds back to population growth in the cities, in the water demand sector, as the appearance of water deficit again makes it less attractive to live or to migrate to those urban areas. The sector also includes the simulated quality of water. The control variables included are: household water demand; industry water demand; agriculture water demand and the percentage of water to be recycled; the percentage of water lost in the urban distribution system and the percentage of virtual water used.

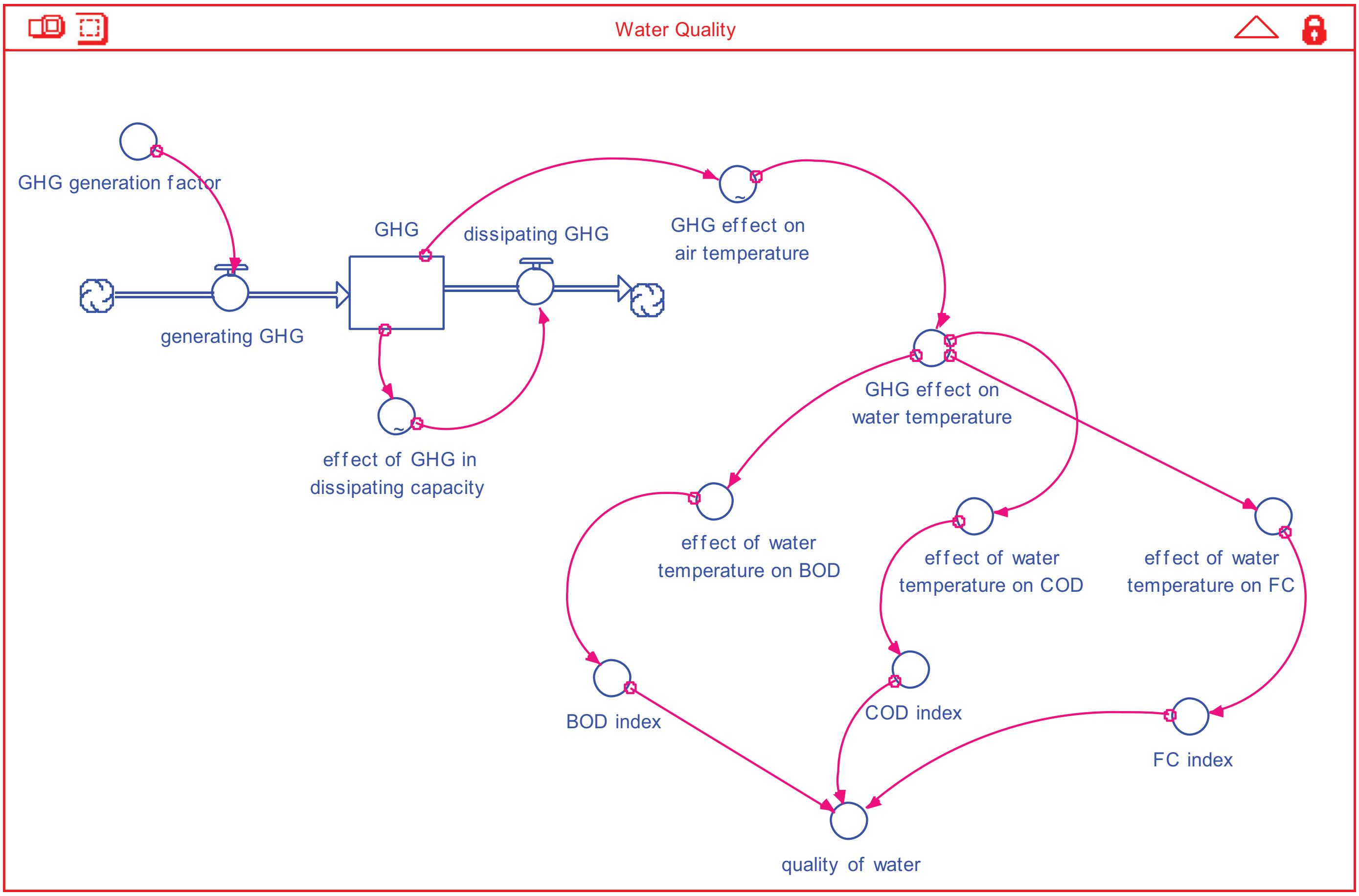

Fig. 5. Diagram of the water quality sector.

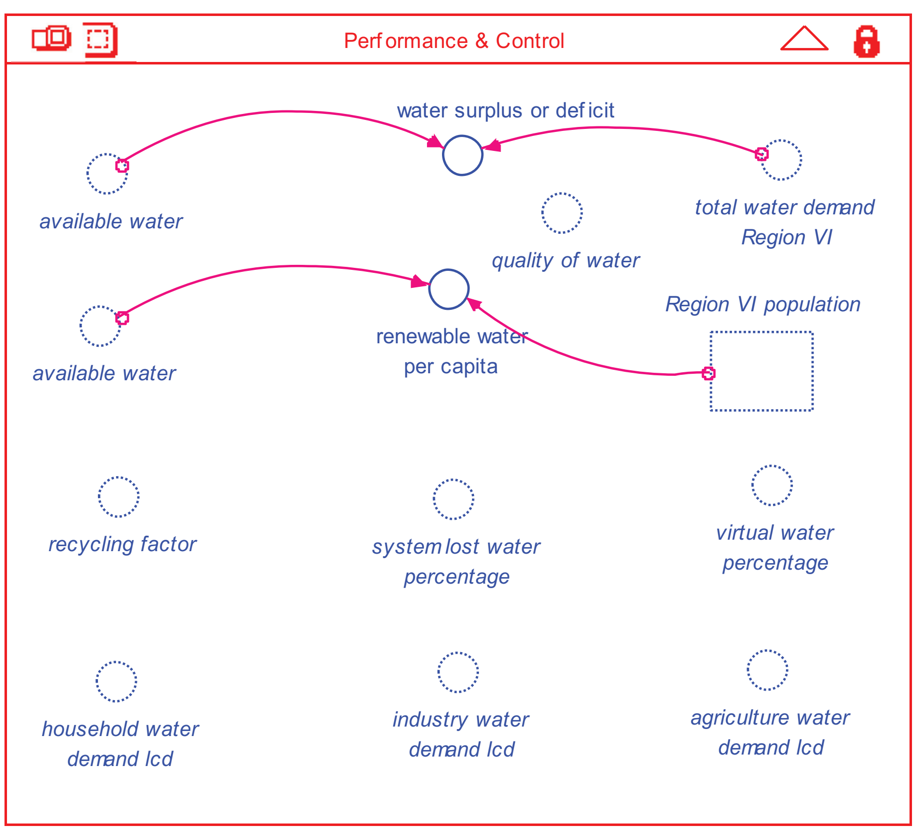

Fig. 6. Diagram of the performance and control sector.

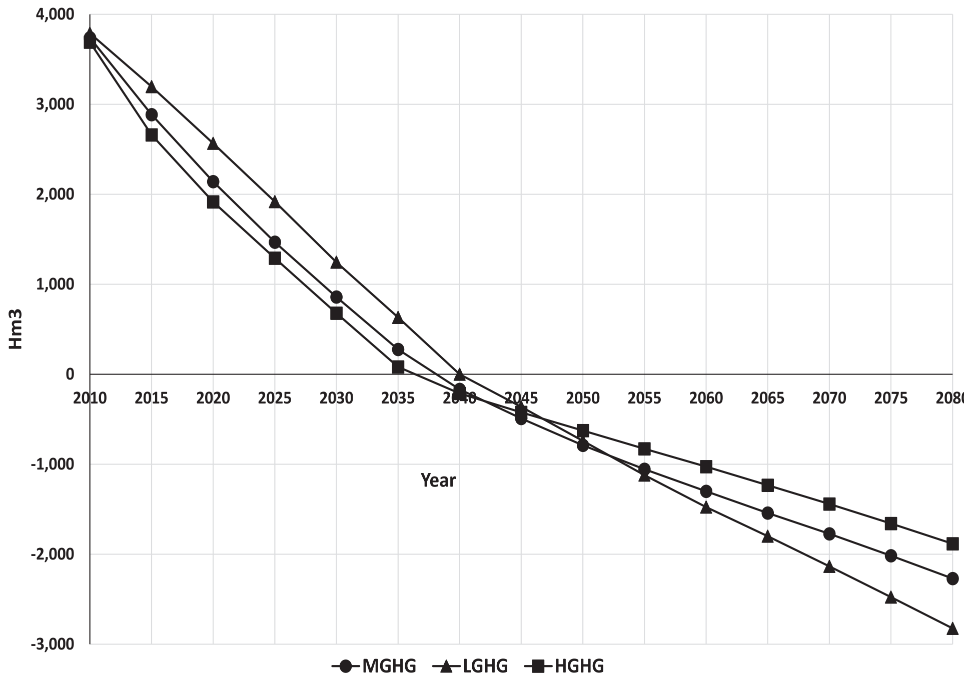

Chart 2. Water surplus or deficit scenarios.

4. Simulated scenarios

Once the model was validated, we ran the model to extrapolate results from 2010 to 2080. In this section, we present the results of the extrapolation produced by this simulation. First we simulated the effect of current parameters of water demand and water supply with the rate of GHG growth (base scenario); second, we simulated a scenario in which policies such as better infrastructure, reducing water demand and changes in broader economic variables are introduced (scenario with policy changes).

4.1. Base scenario: current parameters of water demand and supply

We present the base scenarios using the parameter of present water demand and water supply. On the demand side, we maintain the household, industry and agriculture with the following consumption parameters: 300, 66, and 1900 l/c/d, respectively. On the supply side, we use two important variables that influence the available water, the percentage of water recycled and that of water lost by urban distribution leakages, with the values of 7.5 percent and 35 percent, respectively. Only the rate at which the IPCC prediction of GHG growth takes place is modified (Bates et al., 2008). That is, according to IPCC there will be an increase of up to 5 percent in air temperature and a reduction of 20 percent in rainfall precipitation temperature in the years considered in the model. We built three scenarios, one using the validated trend for GHG growth that we call the medium scenario (MGHG), and other two that show a reduction of 50 percent in GHG emissions rise (LGHG) and an increase of 50 percent in that level of emissions (HGHG). The results of the simulation are shown in Chart 2.

The results show that water deficit appears in the year 2038 under the MGHG scenario, whereas this appears in years 2040 and 2036 under the LGHG and HGHG scenarios, respectively. That is to say, the simulation shows that water availability has little sensitivity to the speed at which the IPCC forecast is fulfilled. It should be noticed that after each scenario reaches the water deficit point, or equals zero, the curves bend, reducing the declining slope as a result of the negative effect of water deficit on population growth. In fact, the three scenarios modify radically their behavior by the end of the period (2080), demonstrating that the HGHG scenario leads to the lowest deficit because of its largest effect on population reduction CAGR.

The effect of these scenarios on water quality is shown in Chart 3. Under the MGHG scenario water quality reaches the status of contaminate by year 2028 and strong contaminate by 2047. For the LGHG scenario, the contaminate stage is reached by year 2058, while strong contaminate status never occurs in the simulation horizon. In the HGHG situation, water quality reaches a contaminate stage by year 2021 and strong contaminate status by 2033. Therefore, water quality, is clearly more sensitive to GHG changes than water quantity.

4.2. Scenario with the effect of some policy options

In this section, we examine those measures that can affect water quantity and quality. In relation to water quantity, we simulate three types of policies: those directed to create a better infrastructure to cope with water supply, those that focus on reducing water consumption, and finally one that has to do with a broader economic policy that modifies the participation of virtual water. For all cases, the scenario MGHG was used as a backdrop.

To simulate the effect of an enhancement in infrastructure we modify the percentage of water that is recycled, from an initial amount of 7.5–30 percent, and reduce water lost by leakages, from an initial amount of 35–10 percent. We understand that actions taken to grow and improve infrastructure cannot be implemented immediately, therefore we introduce these changes gradually, across a five-year period.

In the case of modifying water consumption patterns or habits, we introduce the following changes based on the international standards previously discussed and consider their feasibility in the Mexican context. The household water consumption reduces from 300 to 150 l/c/d, industry water consumption from 66 to 40 l/c/d, and agriculture water consumption from 1900 to 1500 l/c/d. Taking into account that to modify these patterns is more complex, we consider a 10-year period for their gradual introduction.

The scenario based on virtual water participation is concerned with introducing measures to reduce water used for agricultural

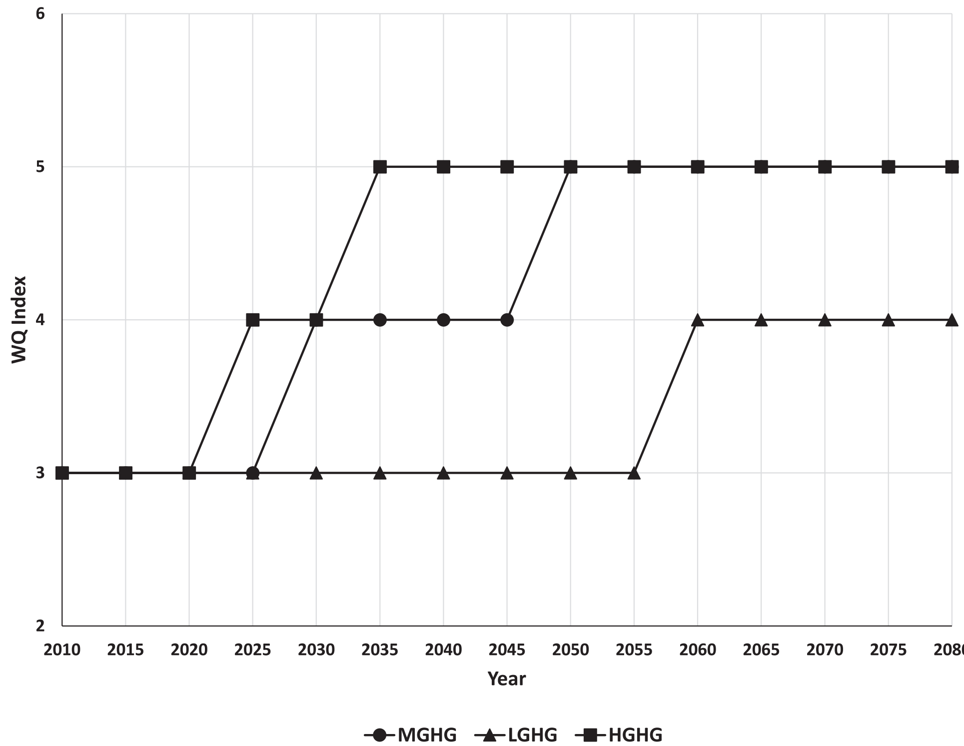

Chart 3. Water quality scenarios.

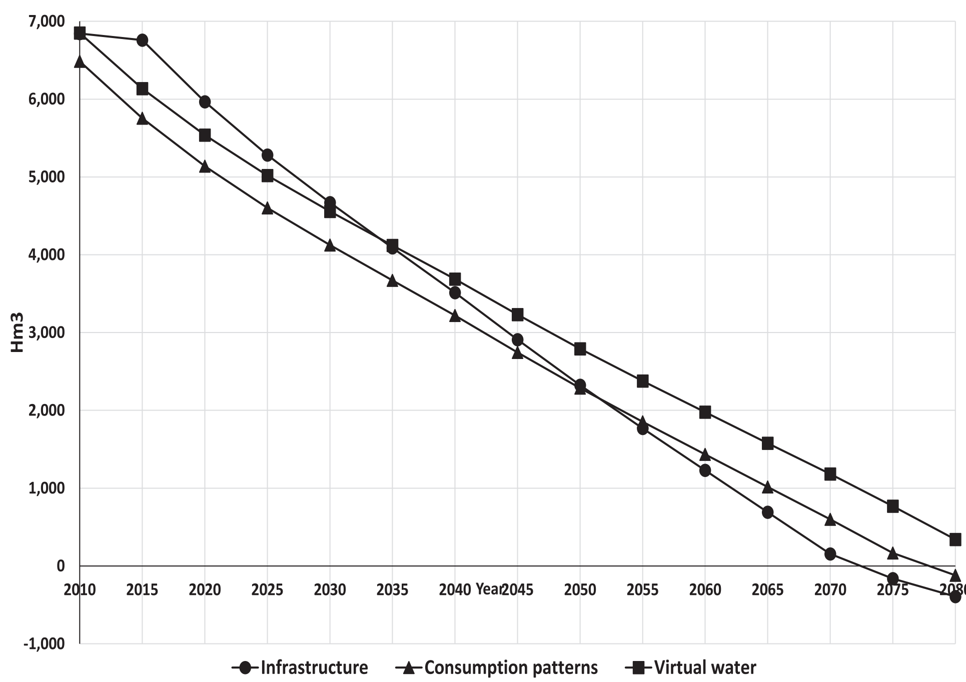

Chart 4. Water surplus or deficit by policy.

purposes. We modify virtual water percentage from an initial amount of zero up to 40 percent over a period of 10 years, as this would mean a deep structural change in the economy of the region.

In relation to water quantity none of the scenarios modifies the fact that the contaminate stage is reached by the year 2028, and very contaminate stage by 2047, as expected. However, as available data shows, only 5.4 percent of the water consumed at the beginning of the simulated period is treated by potable water plants.

Chart 4 indicates that infrastructure policies achieve a more immediate effect on water surplus or deficit but later this is overcome by the other policies. The implementation of a better infrastructure is able to delay the appearance of water deficit until the year 2072. This is achieved by increasing water availability from 12,268 to 15,175 cubic hectometer in the region by the year 2080.

Although the policies directed to modify water consumption initially have a lower effect on water surplus or deficit they subsequently become more effective than infrastructure policies, and defer water deficit by the year 2077. By 2080 these policies reduce water consumption from 14,538 to 12,388 cubic hectometer in the region. The virtual water policy allows maintenance of water surplus until the year 2080. This is done by reducing water consumption in the region from 14,538 to 11,927 cubic hectometer by 2080.

5. Conclusions

The availability and quality of water is a key factor for sustainable industry and households. Moreover, population growth and global climate change are critical issues facing this trans-border region. Changes in temperature have predictable impacts on both water quantity and quality. Economic prosperity and social well-being are both strongly dependent, either directly or indirectly, on water quality and availability. Both small local villages and large urban centers need to be prepared to overcome the risks posed by the scarcity and contamination of water, though some populations are already experiencing shortages in water distribution and drainage services.

In the case of Nuevo Laredo and Reynosa, we have shown how climate change can modify available water that is necessary to maintain quality of life. Furthermore, the growing population, and the demands posed by the dynamism of the economic activities in these cities could worsen some variables. It is possible for policy and decision makers in local and national agencies in Mexico and the US to implement programs to mitigate the most negative effects of global climate change on water quality and quantity. These policies include: more reasonable water consumption patterns; efficient water distribution systems in urban areas and promoting more favorable exchange of agricultural and other goods. Industry has the opportunity to increase recycling which will reduce their economic costs, and local governments can initiate economic incentives for water conservation by inhabitants. Local and national governments and agencies can introduce legislation to regulate environmental flow requirements and avoid unilateral strategies of self-protection.

Future water availability in these border cities poses some potential problems in terms of both quantity and quality. Water scarcity imposes risks on markets and social stability. The manner in which people respond to water scarcity (using groundwater more intensely, the opportunistic breaching of legislation, violation of environmental flow requirements, pursuing unilateral strategies of self-protection, and becoming embroiled in conflict) involve additional risks, many of which are not attributed directly to water scarcity. Analyses of such issues tend to under-represent the problem by ignoring the accumulating stocks and associated flows before encountering feedback processes that often compound water scarcity risks. It is also important to note that risks arise from water scarcity which is not directly related to the use of water.

Our results suggest various measures that could alleviate water shortages. While virtual water has the potential to help mitigate water scarcity, it should be recognized that most trade is not based on rational determinations of comparative advantage based on water, but rather on broader political and economic factors (Orr et al., 2009). Therefore, feasibility points to collaboration between key local actors toward the implementation of initiatives such as those that would modify water consumption habits and establish better water distribution and recycling processes.

We have provided key decision-makers both in the border cities and in national agencies with a tool and examples that can stimulate informed and science-driven decisions related to water quantity and quality under different scenarios and conditions, including those that will eventually impact as a result of impending global climate change. We are aware that, as is the case with any modeling exercise, there are some shortcomings. In this case, certain feedbacks on water quality/quantity have not been taken into account for practical reasons and also the lack of data to inform some of the parameterization of the model. Nevertheless, the model makes key predictions and serves as a starting point from which the predictions can be experimentally tested and other data developed and collected to better inform the structure and parameterization of the model. An important parameter to be incorporated in later versions of the model is the financial resource necessary to implement such policies and strategies in their implementation. Moreover, some key aspects related to water quality for public health and trade impacts should be incorporated, such as an increase in drinking water plants capacity. Importantly, the model will allow scientists and decision-makers to establish important initiatives focusing on reducing GHG emissions that influence air and water temperature to improve water quality. Also, an important contribution of the model is as a high level mapping and scenario testing tool that plays a key part of what could be more detailed hydrological and civil engineering planning approaches. However, before arriving to this level of analysis, more research along the lines mentioned needs to be developed.

SD operates, in general, under a positivistic paradigm based on ontological assumptions that systems, causes and events along with process and mechanisms operate more or less independently of the observer. The emphasis of SD is on the structure, and the processes within that structure. It explicitly assumes that dynamic behavior in the ‘real world’ can be best characterized by these structures and associated embedded processes. Broadly, SD assumes that “analysis of a situation can be undertaken form an external objective viewpoint and that the structure and dynamic processes of the real world can be re-created” (Flood & Jackson, 1991). In this paper we adhere to this fully, relying solely on SD methodology.

Nevertheless, we are aware that combining/amalgamating SD with other methods or using another conceptual approach may have enhanced or shed further light on the results. Critical realism (CR) could provide supportive methodological concepts to investigate the links between the elements in this situation, i.e. the link between GHG and quantity/quality as the apparent main reason for poor water quality. Using this perspective one could design a hypothesis assuming a *retroductive* research methodology approach. *Retroduction*, in contrast to *induction* and *deduction* and otherwise known as *abduction* is a CR method that posits candidate generative mechanisms that produce observed data. In broad terms: “We take some unexplained phenomenon that has been observed and propose hypothetical mechanisms that, *if they existed*, would generate or cause that which is to be explained. [...]. Such hypotheses do not of themselves prove that the mechanism exists,” [63:385]. Using these ideas, we could have taken the observed event of poor quality water and proposed a mechanism of GHG that would generate the unexplained event (poor water quality). These ideas also resonates with recent developments in the SD literature that have explored the role of *abductive* inference-based framework, arguing that if the structural basis of SD modeling is regarded as an *abductive* process, new insights on SD methodological position can be gained. (Barton & Haslett, 2006; Mollona, 2013). But, as stated earlier, in this study we have embraced the core tenets of SD methodology leaving for future research the exploration of these links possibly by utilizing a combination of approaches and methodological stances in a multi-methodological fashion.

Finally, we recognize that the results of our model are based on data covering and specific geographical area with its own characteristics and history of water usage which should be taken into account when using these results. Also, our model is based and to some extent influenced by the IPCC prediction of global climate change that for some authors is a rather conservative view (Auld, 2008; Auld, MacIver, Klaassen, Comer, & Tugwood, 2007; Canadian Standards Association, 2010). However, the structure of the model is able to cope with changes in this forecast as the events begin to unfold, uncovering new patterns of parameter behavior.

Appendix A

System dynamics model in iThink

GHG(*t*) = GHG(*t* − d*t*) + (generating_GHG - dissipating_GHG) ∗ d*t*
INIT GHG = 100
INFLOWS:
generating_GHG = GHG_generation_factor
OUTFLOWS:
dissipating_GHG = effect_of_GHG_in_dissipating_capacity
Groundwater(*t*) = Groundwater(*t* − d*t*) + (accumulating_groundwater − flowing_groundwater_to_use) ∗ d*t*
INIT Groundwater = 5300
INFLOWS:
accumulating_groundwater = (actual_rainfall/actual_rainfall-1)+groundwater_filtering_factor
OUTFLOWS:
flowing_groundwater_to_use = Groundwater
NL_population(*t*) = NL_population(*t* − d*t*) + (NL_population_growing) ∗ d*t*
INIT NL_population = 395,185
INFLOWS:
NL_population_growing = NL_population∗NL_population_CAGR ∗effect_of_qual_and_quant_on_population_CAGR
Region_VI_population(t) = Region_VI_population(*t* − d*t*) + (population__growing) ∗ d*t*
INIT Region_VI_population = 11,117,000
INFLOWS:
population__growing = (Region_VI_population ∗region_VI__population_CAGR)∗(effect_of_quality_of_water _on_population_CAGR+effect_of_quantity_of_water_on _population_CAGR)/2
Reynosa_population(t) = Reynosa_population(*t* − d*t*) + (Reynosa_population__growing) ∗ d*t*
INIT Reynosa_population = 720,125
INFLOWS:
Reynosa_population__growing = Reynosa_population∗Reynosa _population_CAGR∗effect_of_qual_and_quant_on_population_CAGR
Water_in_recycling(t) = Water_in_recycling(*t* − d*t*) + (water_entering__recycling – water_coming_out__of_recycling – wastewater) ∗ d*t*
INIT Water_in_recycling = 694
TRANSIT TIME = 1
INFLOW LIMIT = INF
CAPACITY = INF
INFLOWS:
water_entering__recycling = (flowing_groundwater_to_use +surface_water)∗recycling_factor
OUTFLOWS:
water_coming_out__of_recycling = CONVEYOR OUTFLOW
wastewater = LEAKAGE OUTFLOW
LEAKAGE FRACTION = 0.2
NO-LEAK ZONE = 0
actual_rainfall = rainfall_base∗GHG_effect_on_climate
agriculture_water_demand_hm3_year = (agriculture_water _demand_lcd_virtual∗population__border_cities∗365)/1,000,000,000
agriculture_water_demand_lcd_virtual = agriculture _water__demand_lcd∗(1-virtual_water__percentage)
agriculture_water__demand_lcd = 1900
available_water = Groundwater+surface_water
BOD_index = if(effect_of_water_temperature_on_BOD>120) then 5 else if (effect_of_water_temperature_on_BOD>30) then 4 else if(effect_of_water_temperature_on_BOD>20) then 3 else if(effect_of_water_temperature_on_BOD>3) then 2 else 1
COD_index = if(effect_of_water_temperature_on_COD>200) then 5 else if (effect_of_water_temperature_on_COD>40) then 4 else if(effect_of_water_temperature_on_COD>20) then 3 else if(effect_of_water_temperature_on_COD>10) then 2 else 1
dam_capacity = 15,476
effect_of_quality_of_water_on_population_CAGR = if(3/quality _of_water)>=1 then 1 else (3/quality_of_water)
effect_of_qual_and_quant_on_population_CAGR = GRAPH (effect_of_quality_of_water_on_population_CAGR∗effect_of_quantity _of_water_on_population_CAGR) (0.00, -0.25), (0.1, -0.2), (0.2, -0.1), (0.3, 0.05), (0.4, 0.305), (0.5, 0.515), (0.6, 0.735), (0.7, 0.895), (0.8, 0.96), (0.9, 0.995), (1, 1.00)
effect_of_quantity_of_water_on_population_CAGR = if(water _surplus_or_deficit>0) then 1 else water_surplus_or_deficit /total_water_demand__Region_VI
effect_of_water_temperature_on_BOD = .00000000004 ∗EXP(1.0319∗GHG_effect_on__water_temperature)
effect_of_water_temperature_on_COD = .000000003 ∗EXP(.8957∗GHG_effect_on__water_temperature)
effect_of_water_temperature_on_FC = 20.638 ∗EXP(.0366 ∗GHG_effect_on__water_temperature)
FC_index = if(effect_of_water_temperature_on_FC>4000) then 5 else if(effect_of_water_temperature_on_FC>600) then 4 else if(effect_of_water_temperature_on_FC>20) then 3 else 2
GHG_effect_on__water_temperature = 27.12∗LOGN(GHG_effect _on__air_temperature)-65.145
GHG_generation_factor = 1
groundwater_filtering_factor = 5300
household_water__demand_hm3_year = (population__border _cities∗household_water__demand_lcd∗365)/1,000,000,000
household_water__demand_lcd = 300
industry_water__demand_hm3_year = (industry_water__demand _lcd∗population__border_cities∗365)/1,000,000,000
industry_water__demand_lcd = 66
population__border_cities = Reynosa_population+NL_population
quality_of_water = MAX(BOD_index,COD_index,FC_index)
rainfall_base = 12,967
rainfall_capturing__factor = 0.6
recycling_factor = 0.075
Region_VI_water__demand_lcd = agriculture_water_demand _lcd_virtual+(household_water__demand_lcd+industry_water __demand_lcd)/(1-system_lost_water__percentage)
region_VI__population_CAGR = 0.008821
renewable_water__per_capita = (available_water/Region_VI _population)∗1,000,000
rest_of_Region_VI_population = Region_VI_population-population__border_cities
rest_Region_VI__water_demand = (Region_VI_water__demand _lcd∗rest_of_Region_VI_population∗365)/1,000,000,000
surface_water = if(actual_rainfall∗rainfall_capturing__factor) <dam_capacity then (actual_rainfall∗rainfall_capturing__factor +water_coming _out__of_recycling) else (dam_capacity+water_coming_out__of _recycling)
system_lost_water__percentage = 0.35
total_water_demand__Region_VI = urban_water__demand _hm3_year+agriculture_water_demand_hm3_year+rest_Region _VI__water_demand
urban_water__demand_hm3_year = (household_water __demand_hm3_year+industry_water__demand_hm3_year)/(1-system_lost_water__percentage)
virtual_water__percentage = 0

water_surplus_or_deficit = available_water-total_water_demand__Region_VI

effect_of_GHG_in_dissipating_capacity = GRAPH(GHG)

(10.0, 0.5), (19.0, 0.494), (28.0, 0.487), (37.0, 0.458), (46.0, 0.419), (55.0, 0.353), (64.0, 0.296), (73.0, 0.257), (82.0, 0.229), (91.0, 0.212), (100, 0.206)

GHG_effect_on_climate = GRAPH(GHG)

(100, 1.00), (106, 0.921), (113, 0.887), (119, 0.863), (125, 0.845), (131, 0.825), (138, 0.812), (144, 0.806), (150, 0.804), (156, 0.801), (163, 0.801), (169, 0.8), (175, 0.8)

GHG_effect_on__air_temperature = GRAPH(GHG)

(100, 28.3), (105, 28.5), (110, 28.6), (115, 28.9), (120, 29.3), (125, 29.8), (130, 30.8), (135, 32.2), (140, 32.8), (145, 33.1), (150, 33.3)

NL_population_CAGR = GRAPH(TIME)

(2010, 0.0216), (2015, 0.0206), (2020, 0.0185), (2025, 0.014), (2030, 0.0116), (2035, 0.0116), (2040, 0.0116), (2045, 0.0116), (2050, 0.012), (2055, 0.0116), (2060, 0.0116), (2065, 0.0116), (2070, 0.0116), (2075, 0.0116), (2080, 0.0116)

Reynosa_population_CAGR = GRAPH(TIME)

(2010, 0.0279), (2015, 0.0267), (2020, 0.0242), (2025, 0.0162), (2030, 0.0141), (2035, 0.0139), (2040, 0.0139), (2045, 0.0139), (2050, 0.0139), (2055, 0.0139), (2060, 0.0139), (2065, 0.0139), (2070, 0.0139), (2075, 0.0139), (2080, 0.0139)

Appendix B

Climate change and water quality index estimation

The constant rate for the use of biodegradable organics by microorganisms in water may be estimated the following equation (Ramalho, 1977):

$BOD = BOD_u\ (1-10^{-5k})$

Where: BOD = the amount of biochemical oxygen demand at the environmental conditions produced by the model

BOD_u is the ultimate BOD, the extent of biodegradable organics in the water

k is the degradation kinetic constant, which determines the speed of the BOD reaction. Dependence of k with water temperature was estimated using the van't Hoff–Arrhenius equation:

$k_T = k_{\ 20}\ \theta^{\ (T\text{-}20)}$

Where: k_T is the value of the degradation rate constant at temperature T

k_{20} is the value of the degradation rate constant at 20 degree centigrade

θ is an adjusting value depending on temperature and has the following values dependent on temperature range $\theta = 1.135$ (4–20 degree centigrade) and $\theta = 1.056$ (20–30 degree centigrade).

The estimated water quality indexes for the different scenarios assessed (AB1 and A2) where compared with the water quality criteria proposed by the National Water Commission of Mexico for BOD and COD data (CNA National Water Commission Mexico, 2011). Historic water quality (1970–2008) has been between good and excellent. The index criteria for BOD are: excellent, 3 milligram per liter or less; good, more than 3 up to 20 milligram per liter; acceptable, more 20 up to 30 milligram per liter; contaminate more than 30 up to 120 milligram per liter; and strong contaminate, more than 120 milligram per liter. The index criteria for COD are: excellent, 10 milligram per liter or less; good, more than 10 up to 20 milligram per liter; acceptable, more 20 up to 40 milligram per liter; contaminate more than 40 up to 200 milligram per liter; and strong contaminate, more than 200 milligram per liter.

Microbiological contamination estimation

The estimates of the expected amount of fecal coliforms in water, were based on the microbial duplication model (Prescott et al., 1993). This model assumes that the amount of cells produced after a time t may be determined by the equation: $N_t = 2^n N_0$, where N_0 is the initial cell number in water, N_t is the amount of cells at time t and n is the number of cell generations produced during time t. The growth rate during the exponential phase in a discontinuous culture may be expressed by the growth rate constant (k_T) considered as the number of cell generations by time unit (h). Values for k_T for the growth of *E. coli* in water systems were used (Camper, McFeters, Characklis, & Jones, 1991). Historical and estimated fecal coliforms concentrations were compared against the World Health Organization (WHO) guidelines for drinking water quality (World Health Organization, 1995). The amount of fecal coliform (in CFU/100 milliliter) for the different scenarios assessed (AB1 and A2) were compared with the concentration quality criteria proposed by the National Water Commission of Mexico (CNA, 2010). The amount of fecal coliforms (in CFU/ 100 milliliter) has decreased thee 1970s, probably as result of wastewater treatment in the region, from over 7×10^4 CFU/100 milliliter in the 1970s to less than 100 during the 2000s. This is a very acceptable level of concentration that does not pose any hazard to the public health, even for the foreseeable future.

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