# A System Dynamics Approach to Examine Climate Change Impacts: The Case of the State of Guanajuato, México

**Juan M. Huerta**

JUAN M. HUERTA, INC.
3461 Tallywood Circle, Sarasota, FL 34237
941-240-1440
juan.huerta@usa.net

**Marcos I. Esquivel-Longoria, Fabiola Arellano-Lara**

Centro de Ciencias Atmosféricas de la Universidad de Guanajuato
Callejón Jalisco S/N, Valenciana
Guanajuato, Guanajuato, México 36240

+ 52 + 473-732-9548

mesquivel@astro.ugto.mx fabiola@astro.ugto.mx

**Sergio Dominguez-Ruíz, Fernando Rosales-Flores**

Instituto Estatal de Ecología de Guanajuato
Calle Aldana 12, Pueblito de Rocha
Guanajuato, Guanajuato, México 36040

+ 52 + 473-735-2600

sdominguez@guanajuato.gob.mx frosalesf@guanajuato.gob.mx

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***ABSTRACT***: *Global climate change is affecting the rain-runoff process around the world since "normal rain patterns" are giving way to short periods of strong precipitation, followed by long periods without rain. In addition, temperature and evaporation are expected to increase about 20% over the next 20 year worldwide. The State of Guanajuato in Central Mexico utilizes 87% of all available water for agricultural production and is extremely concerned about the impacts of climate change on water supply and demand for its various uses in the short and medium term. To explore the impacts of climate change in Guanajuato a two-component approach was developed: (1) an atmospheric interface that generates synthetic precipitation, temperature and evaporation time series; and simulates the characteristics of these three meteorological variables and (2) a system dynamics model that beginning with the rain-runoff process generates time related behavior for natural and man-made process for each of 13 watershed that make up the States geography. Base Line and Climate Change scenarios have been generated from the present through 2030 to examine the impacts that this phenomenon is having on each watershed; recommendations have been drawn to assist these areas in adapting to new climate conditions.*

**Keywords:** Global Climate Change, Regional Climate Change Scenarios, Foresight Analysis of Regional Water Resources, Socioeconomic-Environmental System Dynamics Modeling

## The Global Climate Change

Evidence from around the world indicates that global climate change is causing weather incongruities which are outside the range of what can be considered "normal weather anomalies."

- The melting of glaciers in Alaska, Argentina and the Himalayas has considerably reduced the yearly snow pack stored in them and has caused flooding in the winter and low flows of water currents in the summer.
- The shifting of yearly rains in many countries from normal patterns to random events characterized by strong thunder storms that unload several inches of rain in a matter of hours. These storms are usually followed by long periods without a drop of rain therefore leading to drought.
- The thawing of permafrost regions in Alaska and Siberia softens the ground and makes large trees fall over.

## Problem Background

In light of the above, authorities and society of the State of Guanajuato, located in the geographic center of Mexico about 220 miles northwest of Mexico City, are deeply concerned about the impacts which the global climate change is going to have on their State.

Over the last 20 years Guanajuato has been adding sectors to its productive base such as the manufacture of automobiles and auto parts. Also, some of the older sectors like footwear manufacturing and leather processing have been modernized. Nevertheless, agricultural production is still the largest single productive activity in Guanajuato as measured in terms of employment and gross value generated. (Although the car industry has a higher gross value, only part of it stays in Guanajuato.) And most significantly, agricultural production utilizes 87% of all surface and underground available water in Guanajuato.

## Objectives of the Present Study

The present study has as its objectives:

- to examine past and present climatology of the various regions of Guanajuato in search of evidence that shows how the climate is changing,
- with this knowledge, to focus on the specific climate effects that are present in each region,
- to examine the natural and man-made processes in each region and to determine how they may be impacted by the effects of the climate change, and
- to propose policies and mechanisms that will lead to actions of mitigation or actions of adaptation to the new climate conditions.

## Methodological Approach

The majority of climate change studies focus on the use of General Circulation Models (GCMs) of the world's atmosphere that have been created to test the effect of increased *carbon dioxide* accumulation over time. The results of these models are given in a time scale measured in decades and a geographic scale measured by whole regions of the world.

The purpose of the GCMs, and the *carbon dioxide scenarios* that they generate, has been to provide awareness to high level country executives - presidents, prime ministers and the like – of the expected impacts of climate change in the various regions of the world. They have been utilized in support of the negotiation process of world climate forums like the recent COP16 in Cancún, México.

As well as supporting high level negotiations, the *carbon dioxide scenarios* have also been employed by individual countries to ascertain the impacts they can expect from the climate change in the long run. Using the knowledge in these analyses some of the countries are designing programs to counter act the effects of climate change.

Mexico is one of the countries that has already been engaged in several studies that utilize GCMs such as Geophysical Fluid Dynamics Laboratory Model (GFDL-R30), from NOAA; the Canadian Climate Model (CCC), from the Canadian Climate Center and the Modelo Termodinámico de la Atmósfera of the National University of México (UNAM) [Magaña, 1997]. From the global scenarios generated by the above models, and utilizing stochastic and statistical methodologies such as the Long Ashton Research Station-Weather Generator (LARS-WG) and the Statistical Down Scaling Model (SDSM), the Mexican researchers have scaled down the global results to apply to the geography of Mexico and to specific regions within Mexico.

## The Context of the Foresight Scenarios of Guanajuato

Today, the probably competing concerns in one of Guanajuato's watersheds are related to the following questions:

- Will there be enough irrigation water to finish the agricultural cycle that has been started?
- Will there be enough rainfall to extend the quantity of potable water stored beyond the next six months?

These short time scale problems for small geographic areas cannot be solved using the scaled down results of GCMs since this leads to a "top-to-bottom" approach [UNFCCC, 2006] which is not always directed towards the needs of the region under study and can result in uncertainty regarding the climate projection (e.g. what would it happen if the $CO_2$ contents in the atmosphere is not twofold in volume for the 2025 – 2050 period as had been assumed).

What is needed in Guanajuato instead is a "bottom-to-top" approach that begins by considering that "climate change will affect the rain-runoff process". This statement has been considered to be the "stepping stone" [UNFCCC, 2006] for understanding and anticipating climate change for the following reasons:

- In years to come rain will be abundant but, in contrast to "normal patterns," it will rain in short periods of strong precipitation that will be followed by long period without rain. [Trendberth, 2003].
- Temperature in the next decades will increase between 1.5 and 3.0 degrees centigrade above the norm resulting in more evaporation from land and sea that will feed strong downpours. [Maderey, 2000]

In addition, since the concerns of the people from Guanajuato are the problems of specific regions within the state that extend from present day to 20 or 25 years into the future, the context that emerges unsurprisingly supports a "bottom-to-top" examination which:

- considers all processes that will be impacted by the changes in rain-runoff,
- identifies the impact of the vulnerabilities of these processes, and
- permits that policies and mechanisms of mitigation and adaptation to new climate condition can be devised and then instrumented.

Also, because the "bottoms-to-top" approach is anchored in the present, the "initial boundary" conditions for the *foresight scenario process* are known for each watershed of the State. The water cycle parameters (precipitation, temperature and evaporation) are known. The parameters of man-made processes (population, productive activities outputs, etc.) are also known. Through the planning process trajectories for future expansion have already been created. The only remaining question is what would be the "terminal boundary" conditions of the climate variables in Mexico in 2030?

**Scenarios of $CO_2$ in Mexico**

The first step is to consider the expected global environment in 2030. Unless large contributors of green house gases like the U.S., China, and the European Union agree to drastically reduce their emissions in the near future, the realization of a global scenario in which the contents of $CO_2$ in the atmosphere will have doubled by the period 2025-2050 is very likely. When this happens the State of Guanajuato and the rest of the world need to have developed policies and mechanisms that will enable them to adapt to the new climatology.

Since we are assuming that this global scenario will emerge, the task in hand is to obtain from the global scenario for Mexico and preferably for the region of the State of Guanajuato, temperature, precipitation and evaporation for 2030.

Among the global climate change studies developed in Mexico there is one entitled [Maderey, 2000], *"Los Recursos Hidrológicos del Centro de México Ante un Cambio Climático Global,"* of Laura E. Maderey and Arturo Jiménez in which the scale reduction of three GCMs is performed for the Lerma River Basin. Since 50% of the area of this basin is within the boundaries of State of Guanajuato the values of temperature, precipitation and evaporation from this study provide the necessary terminal boundary for the *foresight scenarios of Guanajuato*.

## Foresight Scenarios Generation

Having set the initial and terminal boundaries for the climate variables we proceed to build the construct which will generate the *foresight scenarios of the State of Guanajuato* that is made up of two elements:

1. **The Atmospheric Interface** generates the:
   (a) daily rain patterns that mimic the expected short bursts of powerful storms that would be followed by dry weather of the expected climate change and
   (b) daily temperature and evaporation patterns with upward tendencies as they are also expected in the future.

2. **ProEstado/MAUA/Clima®, (**MAUA**),** is a System Dynamics (SD) model that utilizes as inputs the meteorological variables from the Atmospheric Interface for each of the 13 watershed into which the State of Guanajuato has been broken down.

## Description of the Construct Elements

### 1. Atmospheric Interface

Two distinct scenarios have been prepared and tested with MAUA to evaluate the impacts of climate change. The first scenario assumes that for the simulation horizon of 31 years there are no effects of climate change. This *Base Scenario*, which is being used as a base of comparison, requires daily precipitation time series from November 1st, 1999 until October 31st, 2030. For each of the 13 watersheds of the State synthetic time series (Base Series) have been developed by the repetition of a "normal pattern" of precipitation for the period 1999-2008. This "normal pattern" was defined as the rain pattern that exists between two maximum rain events.

For the *Climate Change Scenario*, considering that extreme events will be intensified in magnitude and frequency, the periods between atypical extreme maximum events were selected. After that, the selected periods were reduced by 50% which is equivalent to doubling the frequency.

A further step included the selection among the atypical maxima, the year with the maximum-maximorum. The same was done for atypical minima and both the maximum-maximorum and minimum-minimorum atypical extremes were inserted in the Base Series.

These heuristic procedures to create synthetic daily time series of rain seem to be corroborated by an additional analysis performed for the 2010 decade in which drastic reductions in precipitation for various zones of Guanajuato were found.

## 2. MAUA

MAUA is SD model built on theory, information, knowledge and data [Huerta, 2001]. It is also built on first-hand field visits to establish the "Ground Truth"; that is, which systemic elements to be modeled – whether natural or man-made - exist on the terrain.

MAUA breaks down the state of Guanajuato into three major rivers' basins (see *Figure 1*, below):

1. the Lerma River Basin in the southern part of the State has 10 sub-watersheds;
2. the Northeast Basin has two watersheds – the Laguna Seca which is a closed watershed and the Pánuco River which is the beginning of one of Mexico's largest rivers whose waters flow into the Gulf of Mexico and,
3. the Northwest Basin that is the Verde River Basin.

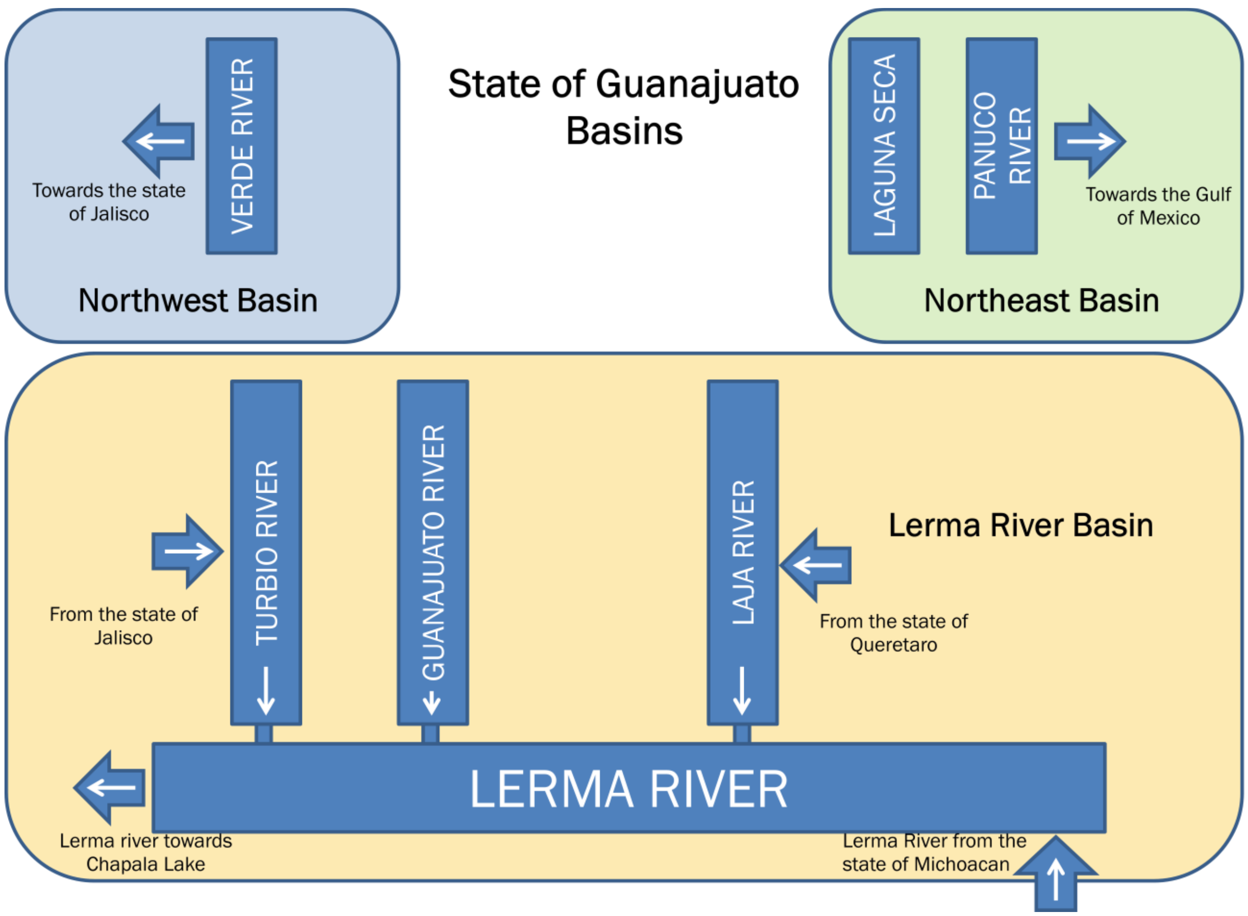


Figure 1. State of Guanajuato Main River Basins

For each watershed (or sub-watershed) MAUA can generate time related behavior at three levels of the physical environment (see Figure 2 below):

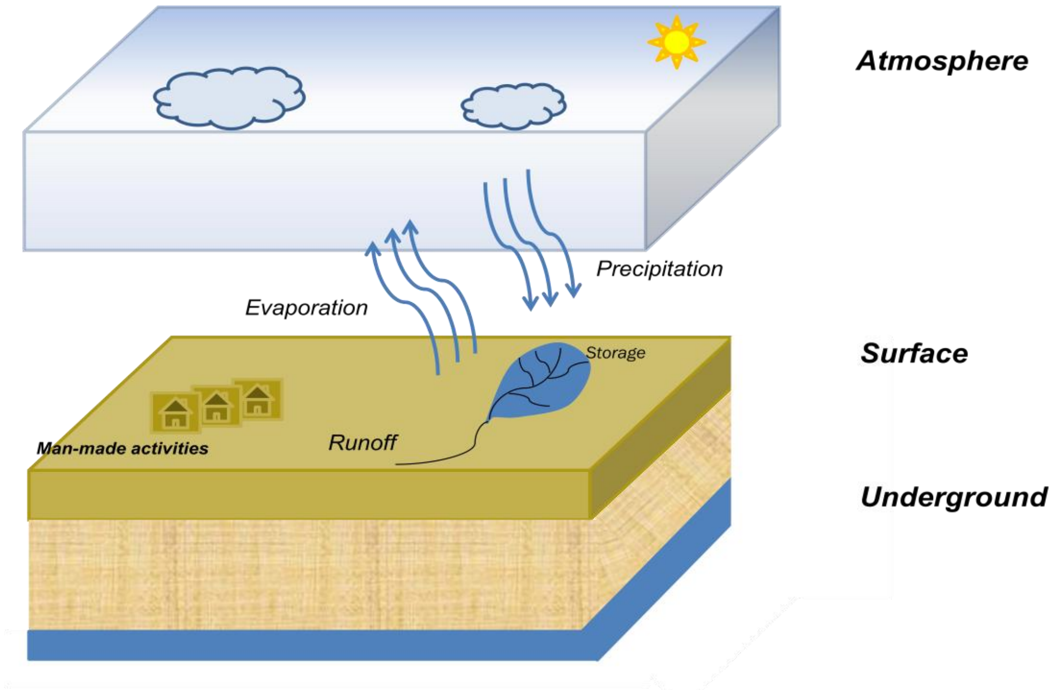


Figure 2. *MAUA's* three level view of a watershed

1. *ATMOSPHERE LEVEL*: Precipitation, temperature and evaporation are represented, and are being simulated by the **Atmospheric Interface**.
2. *SURFACE LEVEL*: The following components are modeled:
   a. Man-made processes (see Figure 3) are modeled with the following components:
      *i.* **Socioeconomic**. This sub-model has three related components - Population; Education, Labor Force and Employment.
      *ii.* **Productive Activities**. The industries that this sub-model considers are leather, footwear, agro industry, automotive, auto parts, clothing manufacturing, chemical, metals and machinery, petroleum, power and water, financial services.
      *iii.* **Agricultural Production**. For its large water use agricultural production is considered as a special productive activity and has its own sub-model. The sub-model represents crops for the spring-summer production cycle and also, for the fall-winter production cycle. It also considers the production of perennial crops. The primary objective of this module is to generate production inputs with emphasis on water, land and labor.
      *iv.* **Human Settlement**. The objective of this sub-model is to concentrate population, agricultural production and industrial production into one geographic entity, in order to compute water demands per use type, as well as wastewater.
   b. Land Portion of the Water Cycle. This sub model has the following components: runoff, infiltration, evaporation, water storage in rivers, lakes, dams, impoundments as well as water extractions by type of use: agricultural, domestic, industrial.
3. *UNDERGROUND LEVEL*: The extractions and aquifer recharges for the more than twenty aquifers of Guanajuato are handled by this sub-model.

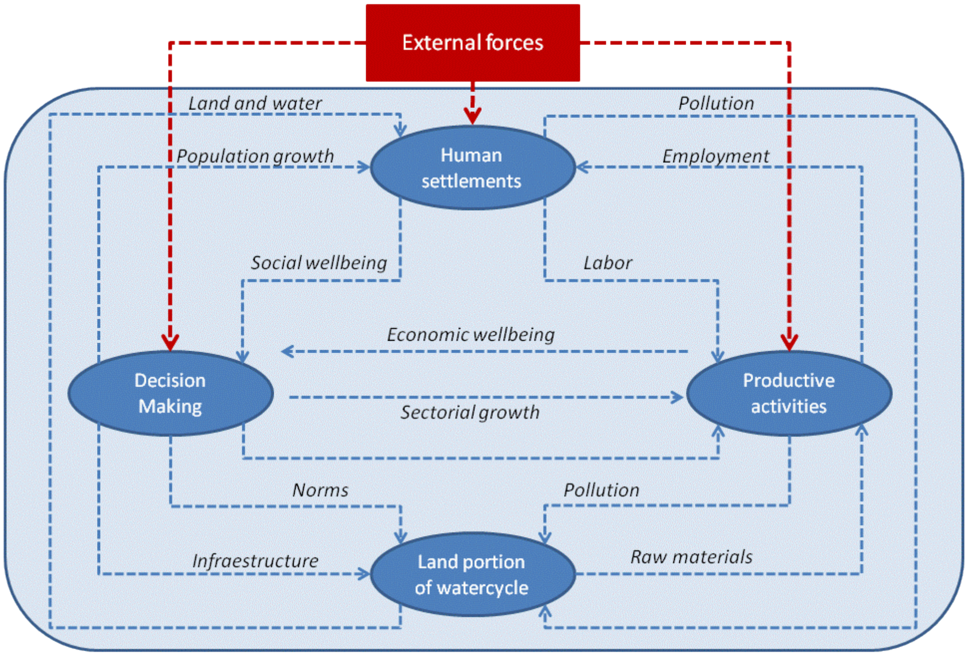


Figure3. Man-made Process Sub-model

## Foresight Climate Change Scenarios for Guanajuato

The results of the simulation of the Base and Climate Change Scenarios are presented for the Solis Dam which regulates the Lerma River Basin in Guanajuato. The Turbio-Palote watershed, which is part of the Lerma River Basin, has been selected as an example because it has a varied productive activities and the largest human settlement in the State of Guanajuato. Of course, the other 12 watersheds of Guanajuato are also part of the integrated model..

The Simulation Horizon extends from November 1st of 1999 to October 31st of 2030. From November 1st of 1999 to October 31st of 2004 was the period used to calibrate the model for a previous project. From November 1st of 2004 to October 31st of 2007 was the period to recalibrate the model for the present project. Beginning November 1st of 2007 to October 31st of 2030 is the scenario horizon.

The MAUA variables selected to trace the results of each scenarios are the following:

**For the Lerma River Basin:**

1. **Volume of Solis Dam (*Presa Solis*)**, in cubic meters, is the variable that represents the daily values of the volume of Solis Dam. This dam provides water to the irrigation District 011 and also regulates the flow of the Lerma River towards Chapala Lake in Jalisco, south of the city of Guadalajara.
2. **Annual Surface Planted in the Irrigation District 011 *(Superf Annual Sembrada DR011)***, in hectares, is the variable that represents the annual values of areas planted.
3. **Accumulated agricultural production (*Producción Accum DR 011*)**, in thousands of tons, represents the integrated values of the daily aggregation of all crops produced in District 011 for the simulation horizon.

**For the Turbio-Palote Watershed**:

1. **Socioeconomic status of the watershed *(Población, Empleo, Valor de la Producción)***. In one graph three variables are presented: Population; Employment; and Value of Production which is the aggregation of the annual output of 19 productive activities in billions of constant Mexican pesos in the year 2000.
2. **Accumulated demand of potable water (*Dem Acum Agua Urb1*)**, in millions of cubic meters, represents the integrated values of daily potable water demand along the simulation horizon.
3. **Accumulated demand of industrial water (*Dem Acum Agua Urb1*)**, in millions of cubic meters, represents the integrated values of daily industrial water demand along the simulation horizon.
4. **Accumulated agricultural production *(Produccion Acum T. Palote1)***, in thousands of tons, represents the integrated values of the aggregation of all crops along the simulation horizon
5. **Accumulated agricultural underground water *(Acum Pozo Agro T.Palote1)***, in millions of cubic meters, represents the accumulation of all underground daily extractions for agricultural use for the simulation horizon.
6. **Accumulated agricultural surface water *(Acum Sup Agro T.Palote1)***, in millions of cubic meters, represents the accumulation of all surface daily extractions for agricultural use along the simulation horizon.
7. **Volume of Turbio-Palote Aquifer *(Acu1 Turbio Palote)***, in cubic meters, represents the daily values of the volume of Turbio-Palote aquifer.

## Lerma River Basin Scenarios

*Base Scenario*. The Base Scenario assumes that there is no change in precipitation, temperature and evaporation outside of the "normal climatology" of the State of Guanajuato.

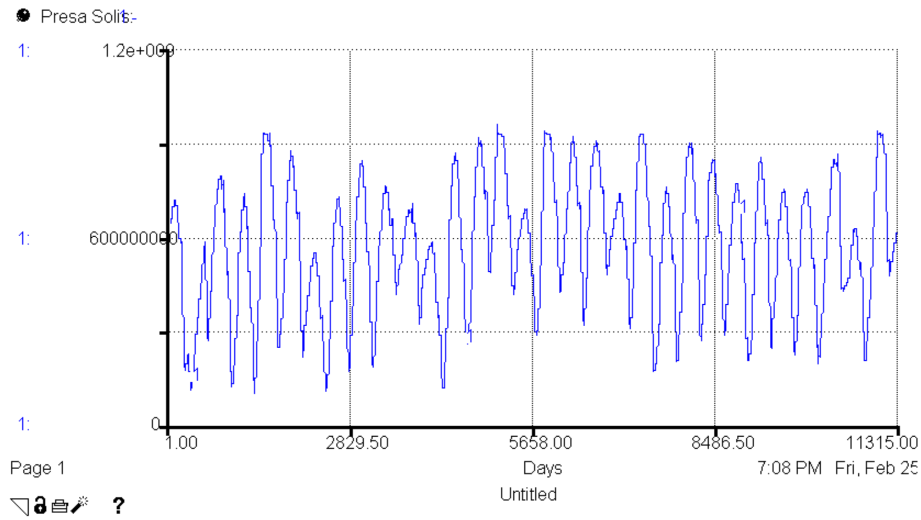


Figure 4. Volume of Solis Dam under the Base Scenario

As it can be seen from Figure 4, the minimum volume of Solis is never below 180 million cubic meters. This is the floor that the federal water authorities of Mexico who operate the dam have determined. Experience shows that beginning from this minimum volume the dam would have enough water when it fills up to supply water to the irrigation DR 011 and also to provide flow to the Lerma River.

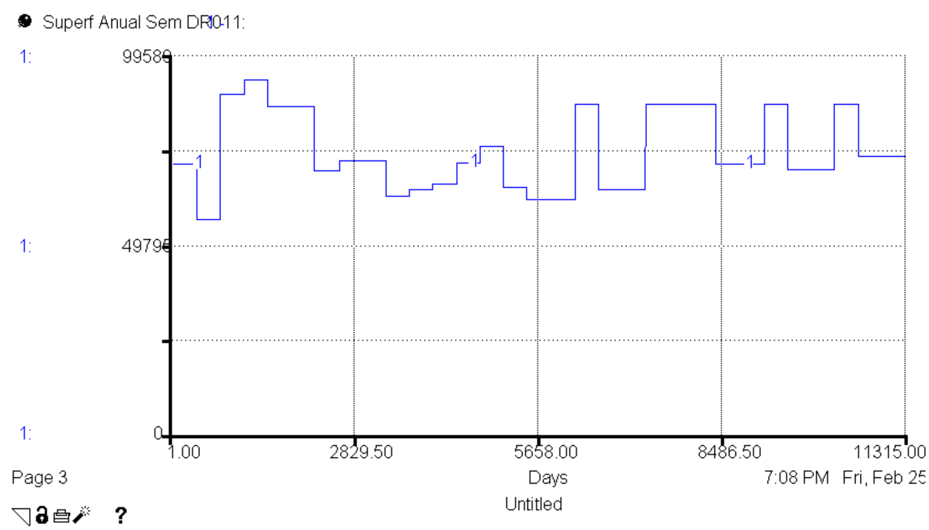


Figure 5. Annual Surface Irrigated in the District 011

Figure 5 shows that the water provided by Solis is enough to irrigate between 60,000 and 90,000 hectares per year in the DR011.

**Climate Change Scenario**. This scenario includes: (1) changes in rain patterns to "imitate" those observed under climate change conditions that are supplied to MAUA by the Atmospheric Interface; (2) an increase in the average temperature and the average evaporation in accordance to the global $CO_2$ scenario for the Lerma River basin [Huerta, 2004].

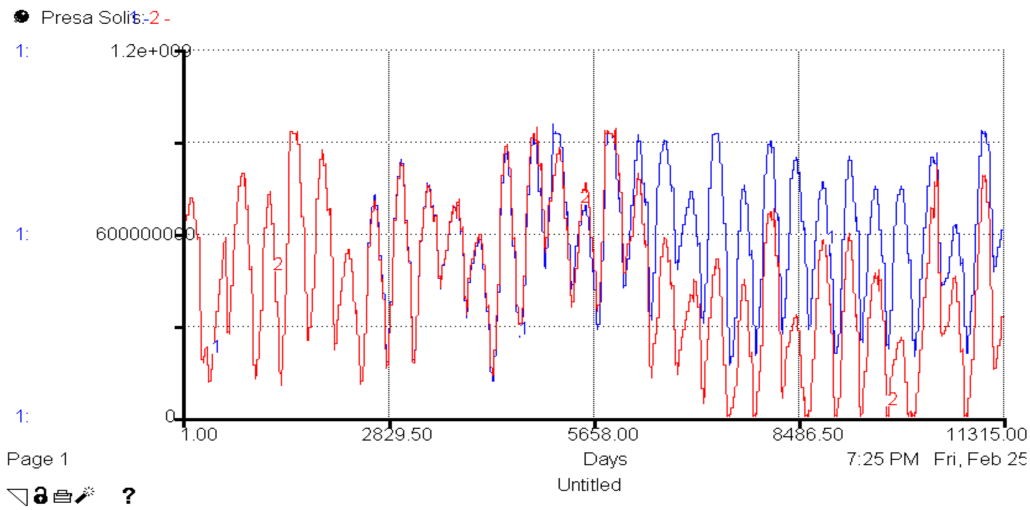


Figure 6. Solis under the Base (in blue) and Climate Change (in red) scenarios

As can be seen in Figure 6, under climate change conditions, the demand of water for irrigation increases because of raising temperature and evaporation and the minimum level of the dam goes to zero repeatedly. Still the water of Solis is enough to irrigate the area shown in Figure 5, but the minimum level of 180 million cubic meters does not hold and unfortunately federal authorities will not accept this form of operation of the dam.

It is then necessary to reduce the planted surface of DR011 to a point that the restriction imposed on the minimum level holds. Figure 7 shows two trajectories for surface planted in DR011: (1) and (2) for the Base Scenario, (3) for the Climate Change. The reduction of the planted surface in DR011 is sufficient to restore the minimum level of Solis to over 180 million cubic meters. However, the planted surface suffers a considerable reduction from a maximum of 90,000 at the beginning of the simulation to a maximum of 42,000 hectares towards the end.

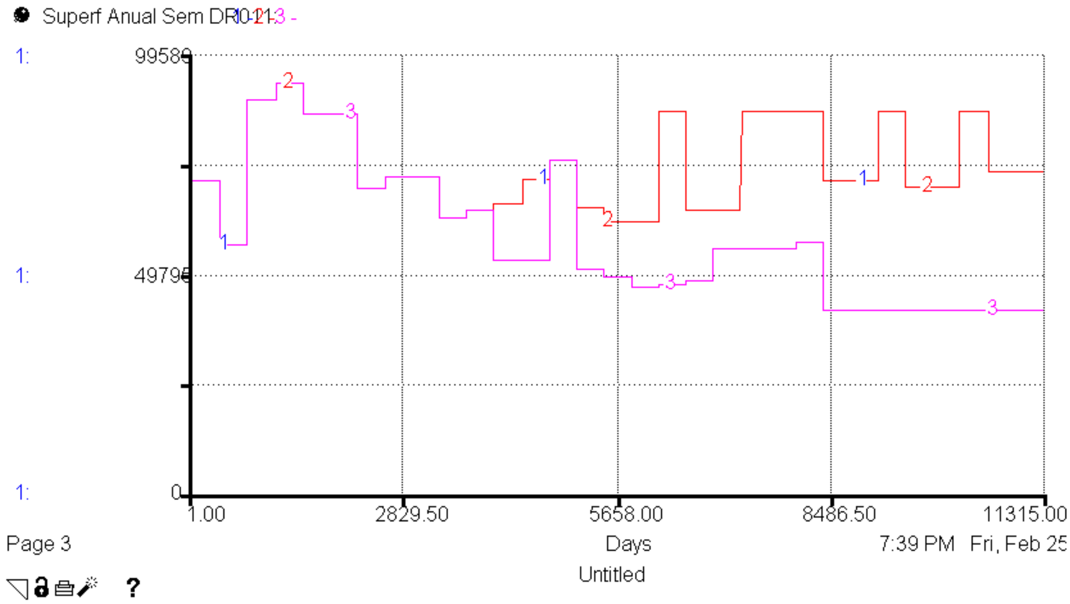


Figure 7. DR011 under the Base scenario (trajectories 1 & 2) and after reducing the area (3)

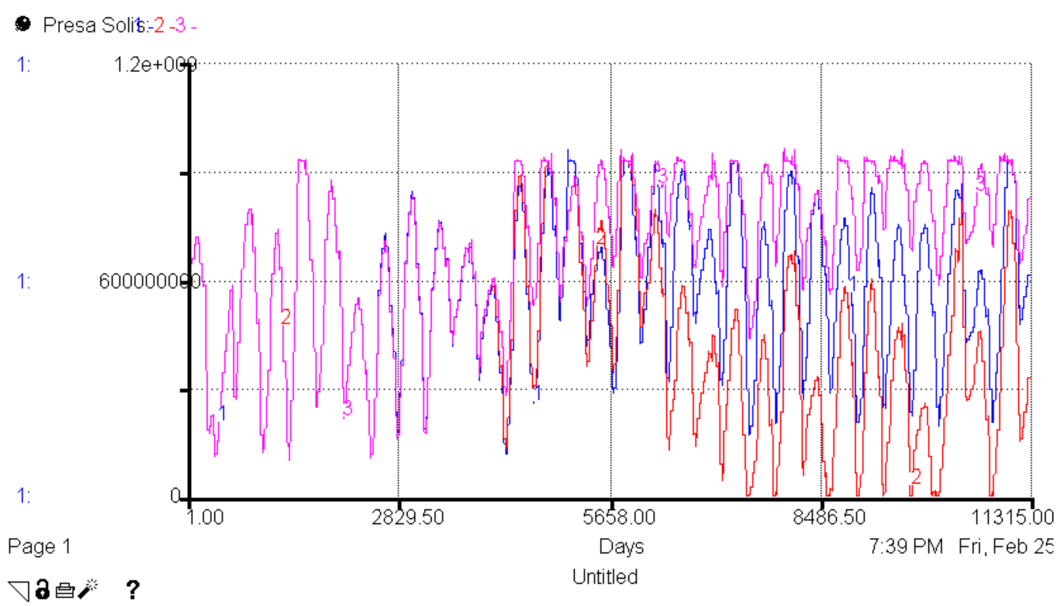


Figure 8. Behavior of Solis under the Climate Change scenario conditions after reducing the planted surface (in magenta)

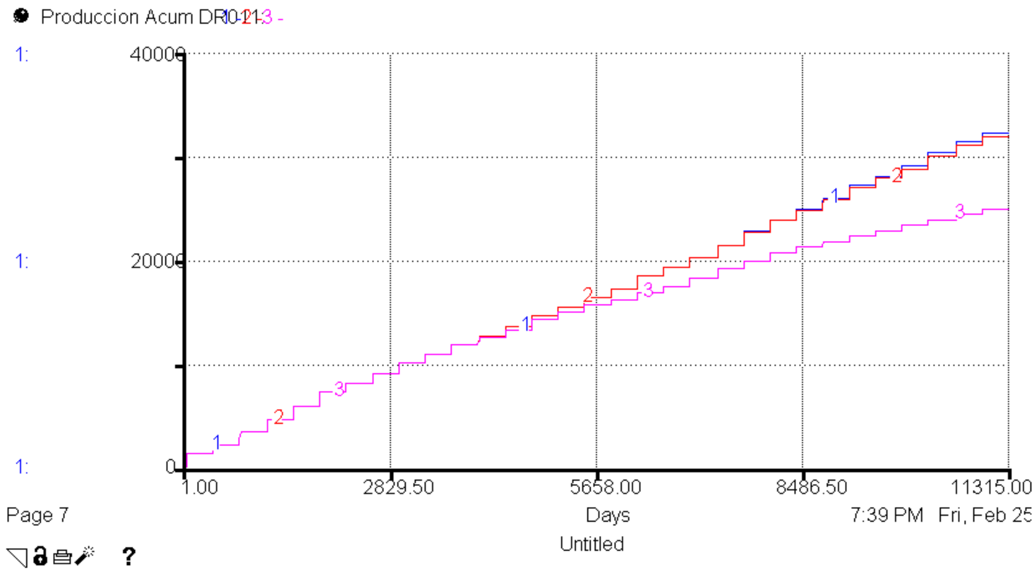


Figure 9. Accumulated production in DR011 in thousand tons en miles

Figure 9, shows that the Accumulated Production 32.2 million tons for the Base Scenario to 25 million for the Climate Change scenario a reduction of 29%.

## Turbio-Palote Watershed Scenarios

Figure 10, shows a fast growth for the socioeconomic indicators of the Turbio-Palote watershed.

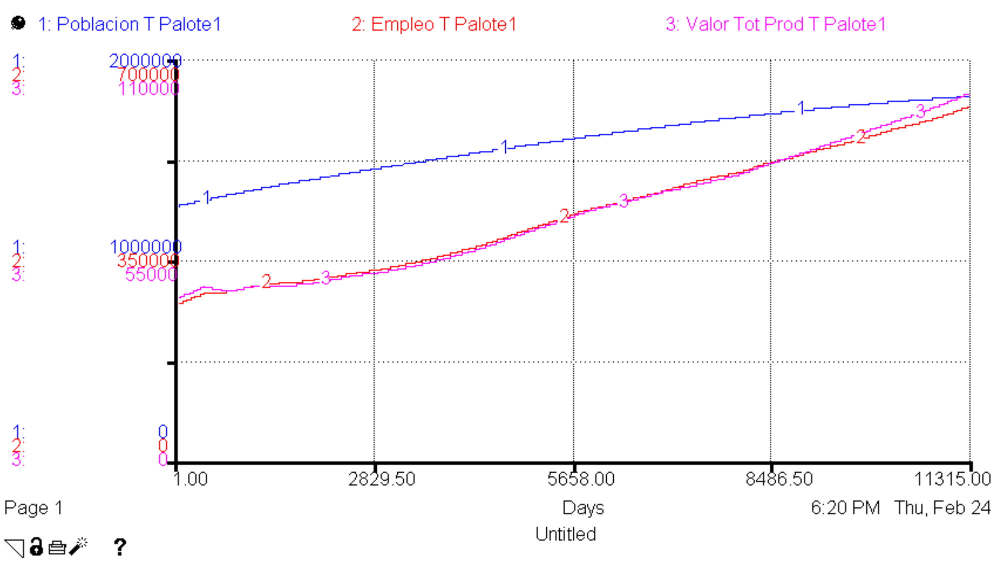


Figure 10. Socioeconomic indicators for the Turbio-Palote watershed

During the 31 years, Population grows by 43.3% from 1,269,212 to 1,818,350. Employment more than doubles from 273,320 to 617,075 employees. The Value of Production increases also from 44.5 billion pesos to 100.6 billion pesos a whopping 56 billion.

With the accelerated growth expected in this watershed the potable water demand climbs to 5,032 millions of cubic meters and to 6,000 million with the climate change.

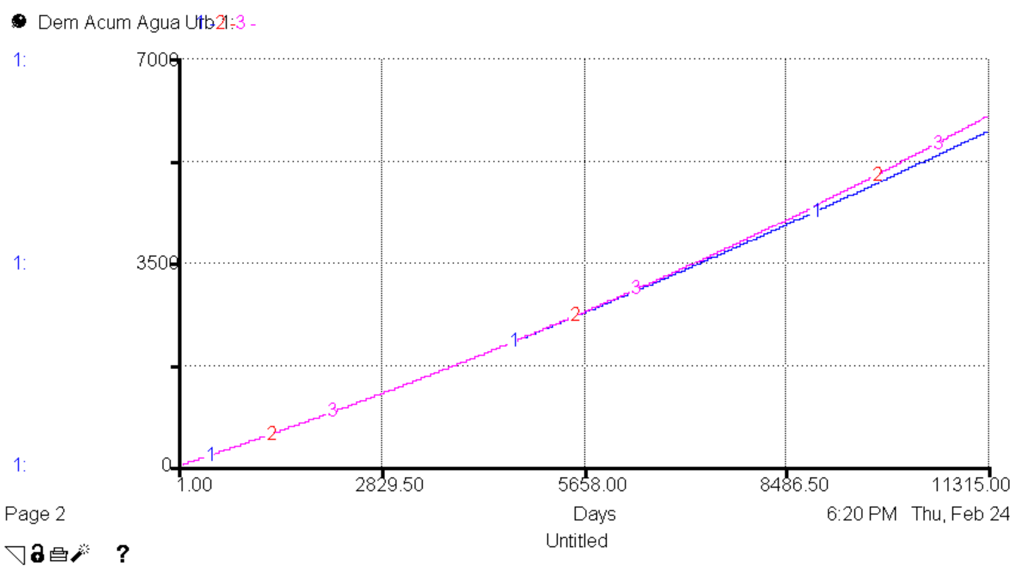


Figure 11. Accumulated demand of urban water in millions of cubic meters

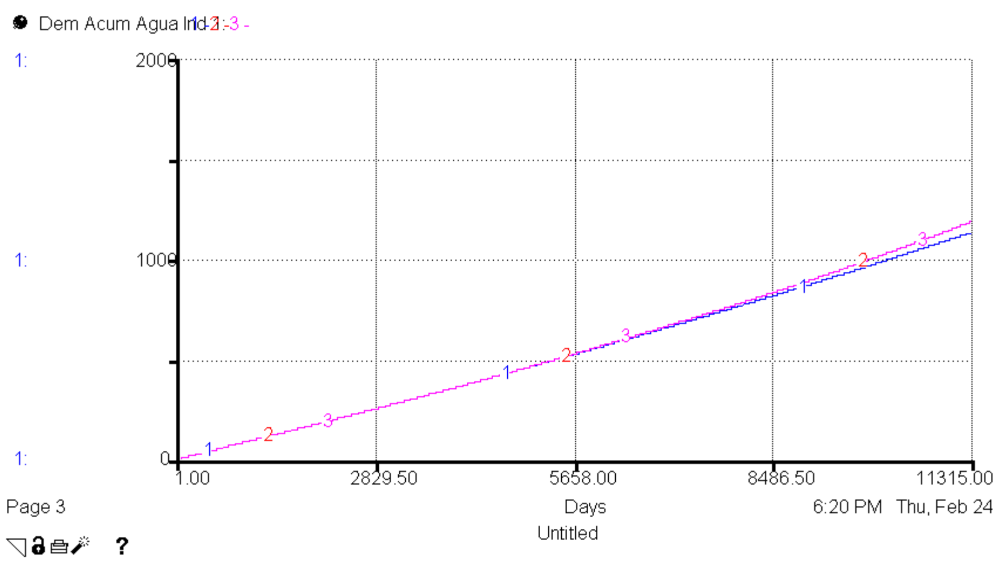


Figure 12. Accumulated demand of industrial water in millions of cubic meters

At the end of the simulation horizon the accumulation of industrial water reaches 1,132 millions of cubic meters for the Base scenario and 1,182 for the Climate Change Scenarios.

The accumulation of the agricultural production is of 8.7 million tons for the Base Scenario and of 8.6 for the Climate Change.

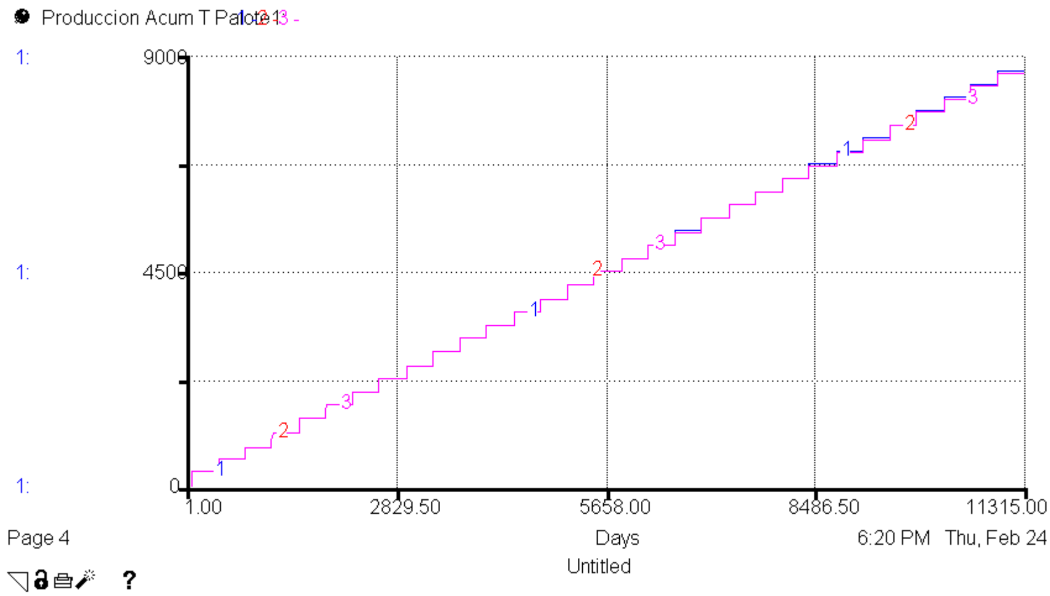


Figure 13. Accumulated demand of agricultural production in thousand tons

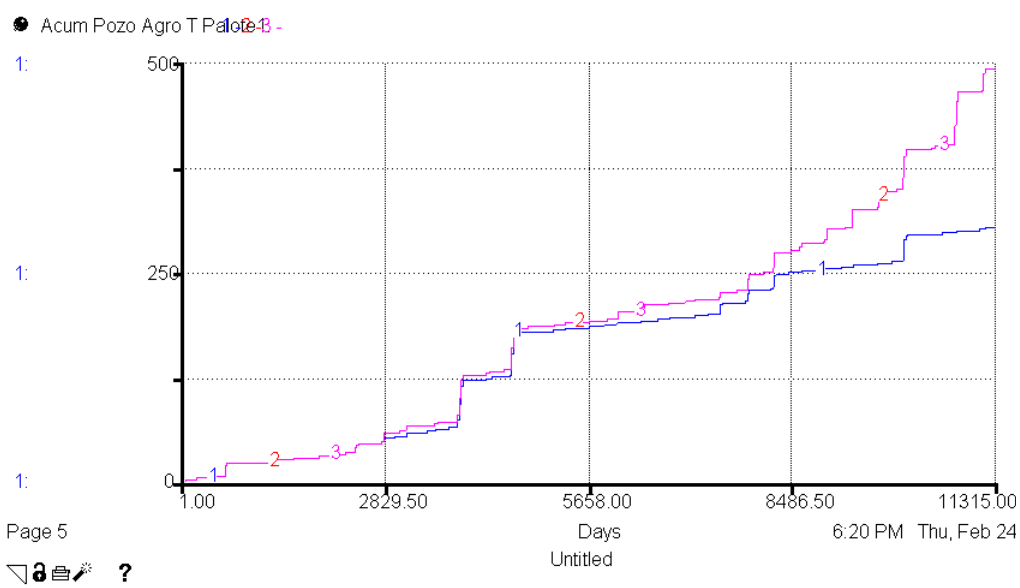


Figure 14. Accumulated demand of underground agricultural water in million cubic meters.

The Figure 14 shows that underground water demand jumps when it has to supply additional volumes of water to offset the increase in evaporation. On the other hand the increase of the demand for surface water is almost negligibly as it show in Figure 15. The reason for this is federal authorities tightly control surface water.

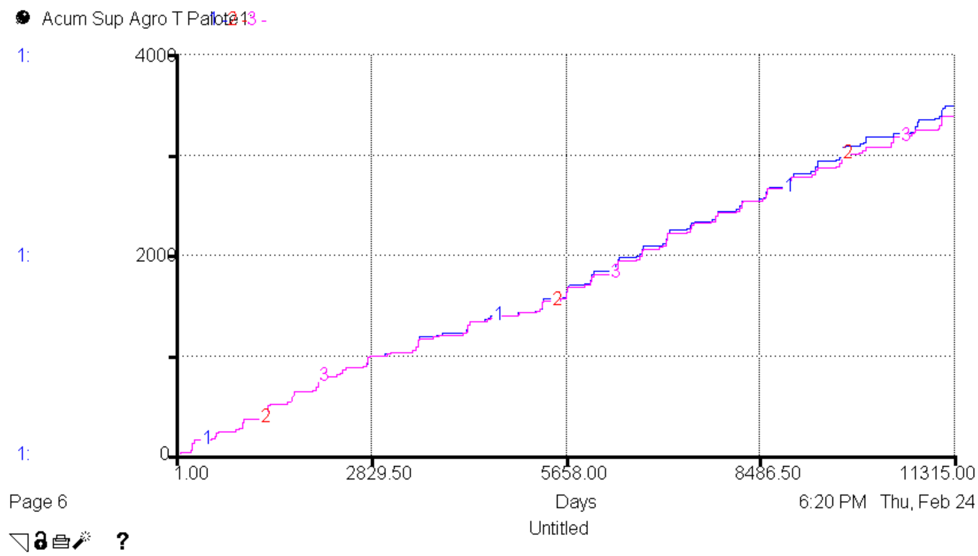


Figure 15. Accumulated demand of surface agricultural water, in million cubic meters.

With additional extractions for all uses of water the Turbio-Palote aquifer shows a severe unbalance, defined as recharges minus extractions, of 2,647 million cubic meters for the Base and of 3,167 for the Climate Change Scenarios. This is shown in Figure 16.

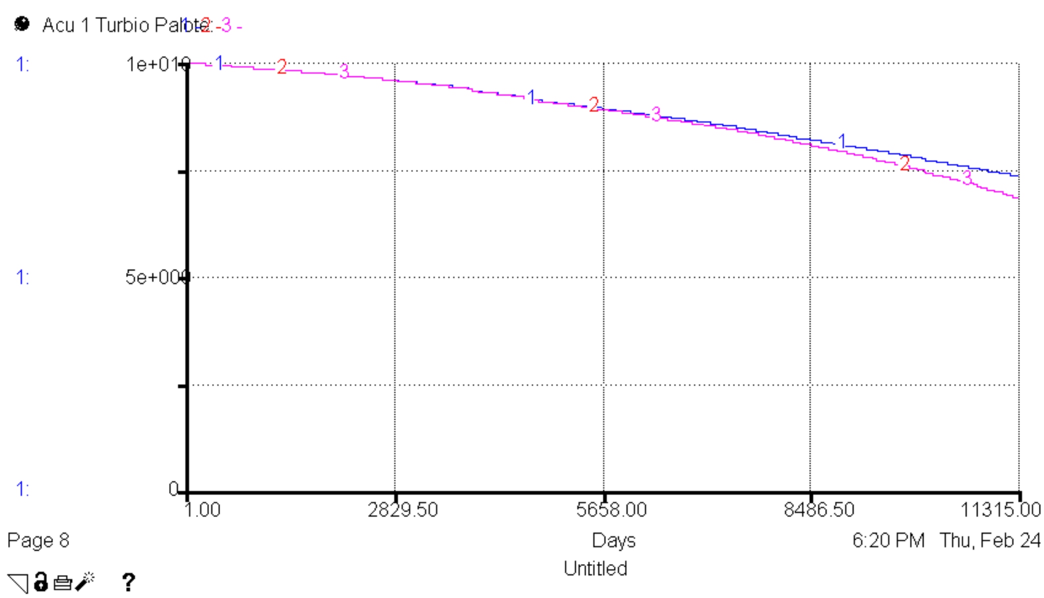


Figure16. Volume of the Turbio-Palote Aquifer in cubic meters

## Analysis of the Scenarios and Conclusions

The scenarios presented for the Lerma River basin and the Turbio-Palote watershed show two distinct methods of controlling water in Guanajuato. The surface water, the water that we see, that runs in the Lerma River and its affluents in Guanajuato is being tightly controlled by the national water authorities. In contrast, although it is also the national government responsibility to control the use of aquifers, since there are literally thousands of wells throughout Guanajuato it is practically impossible to exercise any kind of effective policing action.

Looking at the declining volume of the Turbio-Palote aquifer over time, it is apparent that its future depends almost exclusively on the people that live and work in this watershed. The laws and regulation in place are not adequate to protect the aquifer. Unfortunately many of the people of Guanajuato do not understand what it would take to preserve their aquifer for the future. That is why MAUA/Clima is so important.

It is clear that in scope and depth the climate change problem in Guanajuato falls squarely in a category of a Complex Problem (CP) characterized [Funke, 2001] by:

1. *Complexity*. *S*tructurally these problems have so many elements that interact with each other that they must be looked at as "systems."
2. *Connectivity*. An inherent characteristic of systems since its parts are connected and interacting.
3. *Dynamics*. Continuous variation over time (the opposite of static) a characteristic which is also inherent to systems
4. *Opacity /Lack of transparency*. Not an inherent characteristic of the system – the information, knowledge and data that the *modeler* has available to achieve the goal of properly representing the reality under analysis.
5. *Multiple Goals*. A system has the capacity to reach several goals in sequence or simultaneously and the way this is achieved will depend on the handling of the system itself

Since CPs have always eluded traditional approaches of solution, the field of psychology has been interested in studying human judgment in connection with this type of problems. With the advent of computers the research of CPs solving among psychologist has become enhanced by the use of dynamic systems and simulation.

In Europe at the end of 1970s, two distinct CPs approaches were developed, one by Donald Broadbent in England that emphasized the difference between conscious and unconscious knowledge. Broadbent used for his research simple computerized models of systems [Broadbent, 1986]. The other approach developed in Germany by Dietrich Dörner, focused on the interplay of knowledge, motivation and the social component, and for that, very complex computerized models that reflected with a good level of fidelity the "real world" were developed [Dörner, 1995].

Early in their research Dörner and his associates encountered a low predictive power of traditional IQ testing for problem solving of everyday situations. Then, instead of using tasks that might be seen as academic, they focused their attention on constructing complex everyday problems in the computer and simulating scenarios with which the subject of the experiment (experimenter) had to interact. These problems complied with the definition given above of CP and they called the methodology Complex Problem Solution (CPS).

The CPS methodology can be used for everybody, taking into account their normal behavior which includes emotional aspects in the decision making process. Accordingly, psychologists have built CPS models that are characterized by:

- the proper representation of all important details of a complex system to "locate" the experimenter inside a real complex system;
- a system construct with the capacity to represent the variations that can occur so that the influences that make its handling difficult can be identified;
- an improved capacity to compare systems utilizing a formalism where assumptions and structures are explicit and
- ability to derive performance indicators from the system construct

It was found that systems of Linear Systems which are the basis of System Dynamics satisfied the above characteristics of connectivity and dynamics and thus were suitable to represent CP and find quantitative solutions for them.

**MAUA/Clima as a Tool to Examine and Solve Climate Change Related Problems.**

In the sense described in the above, MAUA/Clima has been built to become a policy analysis and decision support tool for decision makers of Guanajuato in government and society. The scenarios generated with MAUA/Clima and discussed above depict the situation as it would develop over time if there were no interventions to try to ameliorate matters in the various watersheds. In the 19 years period between now and 2030 many alternatives could and should be tested on a watershed by watershed basis to improve the conditions depicted in the scenarios.

With the exception of Solis Dam where agricultural land was reduced no other policy variable in MAUA was utilized. We could have tried alternative policies in an effort to improve the situation of several watersheds but instead, we decided to defer this task for the user of MAUA since they are the ones that need to learn what is at stake here. Consistent with this, the next phase of this project ought to be dedicated to transfer MAUA/Clima to the users of Guanajuato and to teach them how to use this tool.

In Guanajuato there exist societal and governmental organizations whose concern is related to vulnerability of their state to climate change. These groups are being briefed about the capability of MAUA/Clima and the type of analysis it can produce. The current thinking is that

MAUA/Clima will become the keystone of a Climate Change Observatory whose analysis and tailored studies will be made available to these organizations.

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