Dynamic modeling assessment of Water and Food Security: the San Pedro River Valley, Aguascalientes, México

Juan M. Huerta-Tolis, PhD.
Prospective Decision Models, Inc.
3461 Tallywood Circle, Sarasota, FL 34237
941-240-1440
juan.huerta@usa.net

Amós Antonio Pérez-Hernández
Independent Scholar
Abelardo L. Rodríguez 117-35, Misión de San Gerónimo
Aguascalientes, Aguascalientes, México 20326
52+1449.898.0307
amos_perez58@yahoo.com.mx

ABSTRACT: *For life to continue and prosper, a balance between supply and demand of key resources – water, food, energy, ecosystem functions and human health - must exist in the continuum of time. To assess this proposition in a real life situation, a project was undertaken for Water and Food Security in the San Pedro River Valley, in the State of Aguascalientes, México. We show that contemporary systemic assessment approaches such as Dynamic Coupled Natural-Human Systems and the Nexus Food-Water-Energy are in the domain of the Systems and Control Theory and can be solved with Control Engineering models like ProEstado-MAUA®, an integrated dynamic model that represents natural and human processes in a watershed to simulate its long-term behavior. A quantitative improvement in the understanding of Water and Food Security in the Valley was achieved and results are presented.*

Keywords: Water Security, Food Security, Dynamics of Coupled Natural-Human Systems, Nexus Food-Water-Energy, Climate Change, Population Growth, Regional Sustainability, Dynamic Modeling, ProEstado-MAUA

1. BACKGROUND

For life to continue and prosper, a balance between supply and demand of key resources – water, food, energy, ecosystem functions and human health – must exist in the continuum of time. The project on Water and Food Security in the San Pedro River Valley, located in the state of Aguascalientes, México, was undertaken to evaluate this proposition in a real life situation.

The basin under study is located about 560 kilometers northwest of Mexico City in the southern part of the Mexican Altiplano, a large arid-to-semiarid plateau that occupies much of northern and central Mexico. It extends from the United States border in the north to the Trans-Mexican Volcanic Belt in the south, and is bounded by the Sierra Madre Occidental and Sierra Madre Oriental to the west and east, respectively. The San

Pedro River Valley dissects the rectangular shaped-area with a north to south orientation and 930 square miles of surface.

The city of Aguascalientes, capital of the State, with close to one million inhabitants is within the San Pedro River Valley limits. The Valley also encompasses the majority of the State's industry and important agricultural producing land. The system formed by the catchment that feeds the Calles Reservoir, which supplies the 7,000 hectares of the irrigation district DR001, is also part of this region. The DR001 supplements its surface water from the reservoir with well water from the Aguascalientes Aquifer that lies almost exactly under the San Pedro River Valley footprint; the aquifer also supplies water for urban and industrial uses in the Valley.

2. ADDRESSING WATER SECURITY IN THE SAN PEDRO RIVER VALLEY

Although it is known that the region's water resources are dwindling, its growth has continued unabated. In light of this situation, two pressing concerns related to *Water Security* were posed by a group of agricultural, urban and industrial users of water in the Valley to water authorities: (1) taking into account the climate variability in the basin, "is the Calles Reservoir-DR001 system sustainable?", and (2) "what policies can be designed and implemented to control the continuous extractions from the Aguascalientes Aquifer?".

2.1 Conventional Assessment Methodology

Water authorities in the Valley have approached these two concerns with traditional hydraulic engineering methodology, calculating a static water balance for the region's present conditions and then determining an end point (e.g. 20 years into the future). The point chosen is arrived at by projecting forward water historical supply time-series and water historical demand time-series. It is important to observe that the two time series are statistically independent since the method employed does not provide any kind of feedback between the two of them.

When both projections reach the specified point in time, the difference in volume between the supply and demand defines the "breach". This volume is the main objective of the methodology from which action plans to close the *breach* can be derived. But the *breach methodology* does not indicate the "path" that should be taken from the present to the end point to ensure that no shortages of water will occur along the way. Shortages are the result of volume fluctuations driven by natural and human processes acting upon the demand or supply of water.

The *breach methodology* assumes that the volume of water necessary to close the *breach* can be obtained at the end point. This assumption was perhaps justified in the past when shortages of water resources were rare but now, when there is the certainty that water resources are decreasing, as is the case in the San Pedro River Valley, this assumption does not hold any longer. This is an excellent reason for which the *breach methodology* ought to be replaced by one that represents the complete supply and demand processes.

2.2 Contemporary Assessment Methodology: Dynamics of Coupled Natural-Human Systems

Recognizing that the San Pedro River Valley and many other World regions are experiencing water shortages, alternatives to the *breach methodology* are being developed. These methodologies are focused on water supply and demand but also fully represent the processes that shape their behaviors which can be of both natural and human origin. *Climate change* is a natural stress factor which is widely recognized. The most important human stress factor is the continuous growth of *Population* resulting in increasing demand for water resources for personal use, food and energy production.

In the San Pedro River Valley, the management of the supply and demand of water resources falls squarely in the hands of the watershed decision-makers who confront daily situations for which they must determine what to do and how to do it. Although they may have the tools to make appropriate decisions for the present, they lack the tools to show them how to conserve these resources for the future. By not looking at the long-term, decisions continue to be made in a "business-as-usual" way which often leads to the wrong solution of a problem both for the present and for the future.

The general objective of the present study is to improve the water resources decision-making process of the San Pedro River Valley; two specific objectives have been selected: (1) to determine whether the system Calles Reservoir-Irrigation District DR001 is sustainable and (2) to identify and test strategies that would extend the life of the Aguascalientes aquifer which is of vital importance for the region.

The methodology used here to model the San Pedro River Valley can be classified as *Dynamics of Coupled Natural and Human System* [NSF, 2007] since it includes the four different components that satisfy this definition: (1) the dynamics of a natural system; (2) the dynamics of a human system; (3) the processes through which the natural system affects the human system; and (4) the processes through which the human system affects the natural system. The resulting model has the capacity to generate long-term, quantitative scenarios that represent as closely as possible the regional reality which decision-makers encounter.

The modeling of *Dynamics of Coupled Natural Systems* utilizes the Systems and Control Theory representation as a linear, time-varying vector differential equation:

$$\dot{\boldsymbol{X}}(t) = \boldsymbol{A}(t)\boldsymbol{X}(t) + \boldsymbol{B}(t)\boldsymbol{U}(t)$$

Where:

$\boldsymbol{X}(t)$: the state vector variable that defines the status of the system at time t

$\dot{\boldsymbol{X}}(t)$: the rate of change of the "status" of the system in the time interval $t+\Delta t$

$\boldsymbol{A}(t)$: a vector variable of parameters used to specify the reality of the modeled system

$\boldsymbol{B}(t)$: vector variable of coupling parameters for the policies implemented in the modeled system

$\boldsymbol{U}(t)$: a vector variable that contains the policy being tested

For example, by modifying the values in $\boldsymbol{U(t)}$, the decision makers can control the outcome of the model represented by the vector differential equation above to build a feasible (non-vanishing) path to the future that provides the time-continues positive balance of the water resources in the region.

To portray the interacting population, economics, water resources, technology, etc., realities in the Valley, the corresponding models -population, economics, water resources, technology, etc. - are necessary. Traditionally, each of these models originates from a different discipline (e.g. demographics, economics, hydrology, etc.) and differs from the others in many of its characteristics such as the time and space scales it uses, the handling of uncertainty and in general in the mathematics it employs [Kling, 2015]. This usually makes the interconnections required by the integration process cumbersome and in many cases unworkable, leading to computational unfeasibility of the model being developed.

To circumvent this difficulty, we have focused on a *systems interdisciplinary methodology* that is based on the Mathematical Foundation of the General System Theory, [Mesarovic, 1975] for which the object of study is the "system itself," regardless of its finality (economics, environment, communications, etc.). The theory develops the most fundamental concepts of the system such as stability; controllability; observability; minimal realization; and decomposition of larger, complex systems into subsystems. It utilizes ***time*** as the index that synchronizes the resolution and feedback of all subsystems that create a larger-scale, complex systems; and ***dynamics*** as the generating function of the time variable behavior of the system. By applying Control and System Theory mathematics the interconnected natural and human systems that represent the realities observed in a region a single model can be created.

For the construction of the model empirical dynamic submodels for which a close correspondence exists between the behavior of the model and that of its referent are utilized. Such are the cases of the Penman-Monteith model for crop growth [Chapter 2-FAO]; the continuous simulation of rain-runoff processes model [Crawford, 1966]; a differential equation dynamic demographic model [García-López, 2016]; dynamic production functions, etc. The models deployed offer clear results of the status of the region making them suitable for use by the regional decision-makers.

To finalize the modeling building process, historical time series of variables for the region examined are utilized for calibration, comparing simulated and observed variables to adjust the model parameters and evaluate the accuracy of results. The watershed dynamics models built can then simulate the future values of the model variables based on the initial watershed state and the controls inputs by decision-makers.

3. MAUA/San Pedro, A WATERSHED DYNAMIC MODEL

MAUA/San Pedro is an adaptation to the San Pedro River Valley of ProEstado-MAUA®, a dynamic model built on theory, information, knowledge and data [Huerta, 2001]. MAUA/San Pedro has been adjusted by first-hand field visits to establish the "Ground Truth", that indicates which systemic elements on the terrain ought to be represented – whether natural or human.

For each watershed a bottom-up, dynamic model is made available that fully captures the relevant natural and human processes in order to generate and analyze long-term related behavior at three interconnected spatial levels:

1. *Atmospheric Level*: Simulates the meteorological variables of precipitation, temperature and evaporation.
2. *Surface Level*: With the following components:

   a. <u>Human processes</u>:

      i. **Social**. Considers the dynamics of the population pyramid, education, labor force and employment.
      ii. **Productive Activities**. Utilizes production functions inputs including labor capital and natural resource for industries that are germane of the particular watershed: automotive, clothing manufacturing, chemicals, metals, machinery, petroleum, power and water, financial services, etc.
      iii. **Agricultural Production**. A detailed representation of the crop growing dynamics for the spring-summer, fall-winter and perennial cycles is built into the model.
      iv. **Land Use**. Represents the dynamic behavior of all land uses for human settlements, agricultural production, industrial production, etc.

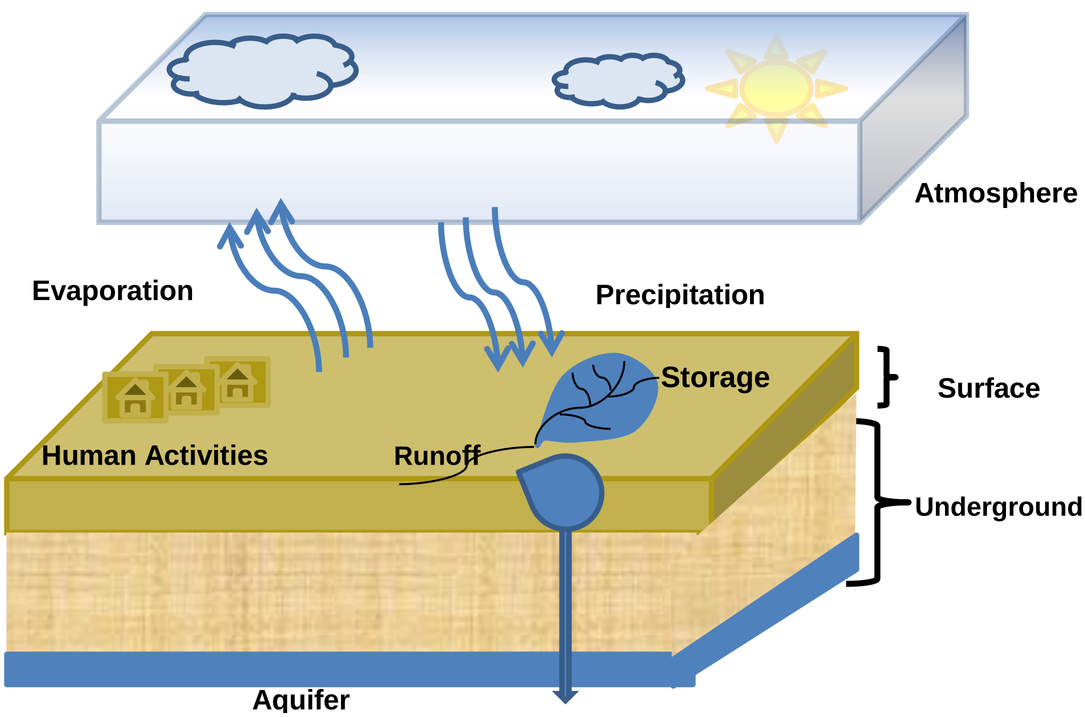

Figure 1. MAUA/San Pedro three level view of a watershed

   b. <u>Land Components of the Water Cycle:</u>

      i. Represents rain-runoff, infiltration, evaporation, rivers flows and lakes.
      ii. Captures the human component of the water use; reservoirs, impoundments, canals and water extractions from wells for agricultural, urban use and industry.

3. *Underground Level*: Represents the dynamics of the volume stored in aquifers as well as the extractions for the various human uses and the recharges as consequence of the runoff in the region.

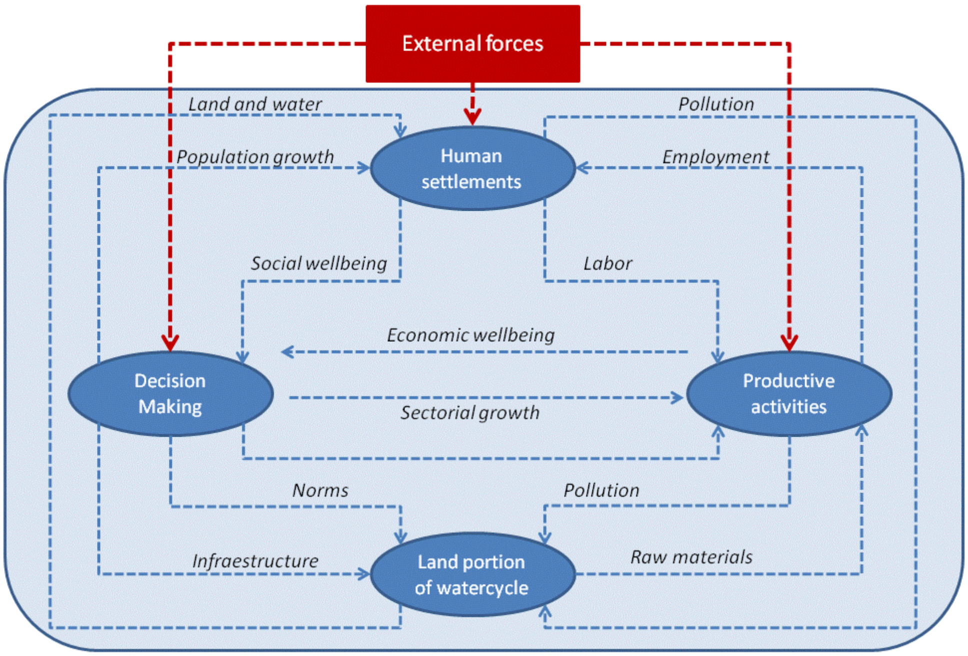

Figure 2. Human Processes

3.1 Adapting MAUA/San Pedro to the San Pedro River Valley

MAUA/San Pedro was adapted to the San Pedro River Valley utilizing the diagram of Figure 3. The diagram shows on its left hand side the catchment area that feeds the Calles Reservoir and its connection with the DR001 irrigation district. Under drought conditions water is also extracted from the Aguascalientes aquifer to "supplement" the irrigation of the DR001. In addition, the diagram shows the extractions from the Aguascalientes aquifer for urban and industrial water uses, and to supply the agricultural production of the three sub-watersheds of the San Pedro River basin.

The "scenario" for this project runs from the 1 of January of 2005 to the 31 of December of 2035 with the following working assumptions:

1. The time step is one day, which means that the model system of equations is solved 11,315 times.
2. The one-day time step was selected since a great deal of the model data base is recorded daily.
3. The population in the region will grow at the rate estimated by the federal commission of population of Mexico for the period of analysis. There no assumptions of migratory flows that can be later enter as scenario variables.
4. The rates of expansion of human settlements and potable water demand would be proportional to the population growth.

5. The policies that guide the development of the industrial sectors *we*re designed by the state's industrial chambers and by government planners and are currently in effect.

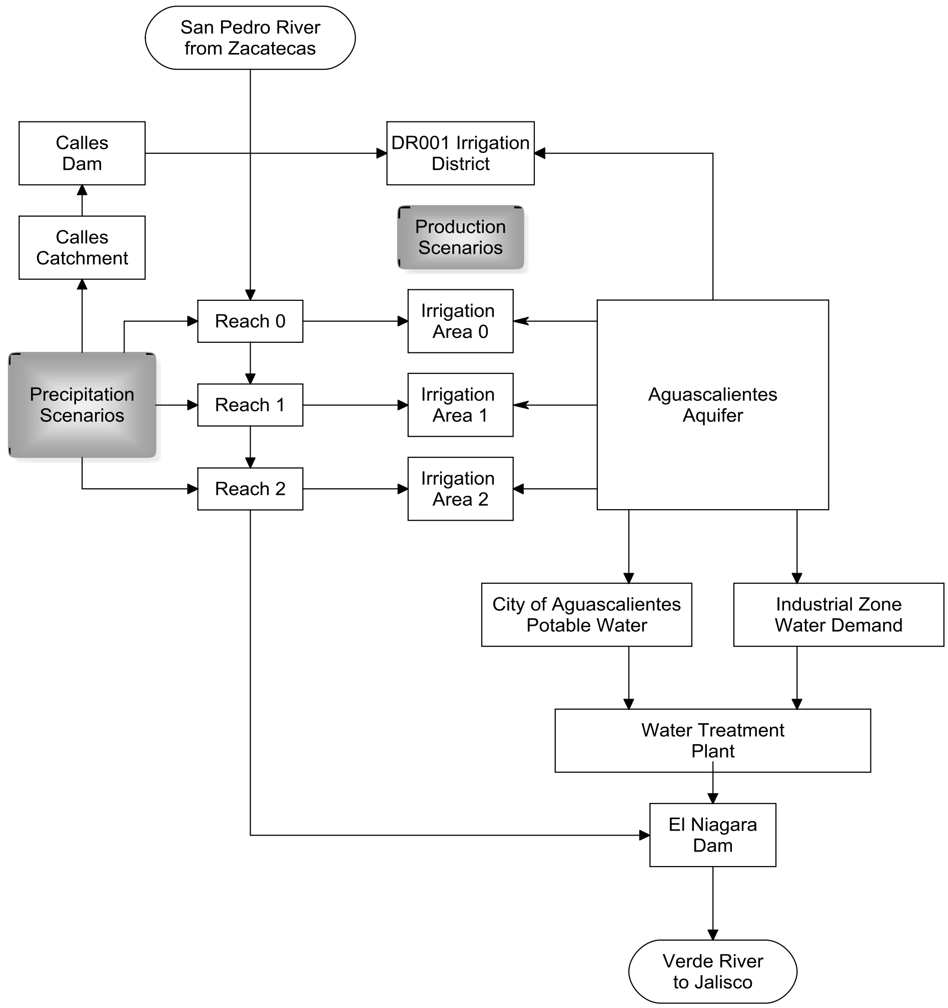

Figure 3. Functional Diagram of the San Pedro River Valley

4. WATER SECURITY ASSESSMENT OF THE SAN PEDRO RIVER VALLEY

4.1 Sustainability of Surface Water: the Calles Reservoir – Irrigation District DR001

In 2010 a project was undertaken to convey water utilizing a system of pipes for approximately eight miles from the Calles Reservoir to the DR001 in a way different than the traditional open channels and impoundments: the pressure due to the difference in altitude between the level of the water in the reservoir and the floor of the district causes the water to flow through the pipes. At the irrigation district, flood irrigation was replaced by drip irrigation. The price of this modernization project was staggering but the concept was that upon completion of the project, the irrigation volume could be reduced by more than 60%, an absolute necessity in an arid region like the San Pedro River Valley.

By 2013, the water conveyance system made-up pipes, filters and valves had been finalized but the main water distribution feeder that surrounds the district was only 70% completed. To keep the DR001 producing, a dual irrigation system had to be rigged with 5,952 hectares under drip irrigation and 1,241 hectares under flood irrigation. Obviously, this dual irrigation modality increased considerably the volume extracted from the reservoir questioning the long-term sustainability of Calles Reservoir and the Irrigation District.

Given the volume of water stored in the Calles Reservoir at that moment, the opinion of some water specialists was that the Reservoir could be sustainable while other argued the opposite although neither camp could put forward a clear and quantitative definition of "sustainability of the Reservoir." Consensus was not possible and the methodologies offered by the water specialists based on static reasoning did not provide the means for breaking the impasse. It was then we were asked to model this problem.

Given the erratic behavior of the meteorological variables in the Valley a climate variability scenario for rain, temperature and evaporation was designed and constructed utilizing methodologies recommended by the UNFCCC for regional, bottom-up models like MAUA/San Pedro. In particular two methodologies were employed: (1) Historical Weather Analogies and (2) Historical Weather Analogies perturbed by long- term regional trends to take into account the effects of El Niño and la Niña in the region.

A data base with daily historical values of the operation of the Calles Reservoir was built from January 1 of 2005 to August 20 of 2015, the latest available historical data. For the same time period another data base was built for the crops by irrigation source (reservoir or well) that had been planted in the DR001 district. The climate variability was prepared to drive the meteorological variables of the scenario. With the data available and the configuration of the reservoir and its catchment area included, the aquifer and the irrigation district, MAUA/Bravo was adapted, tested and validated.

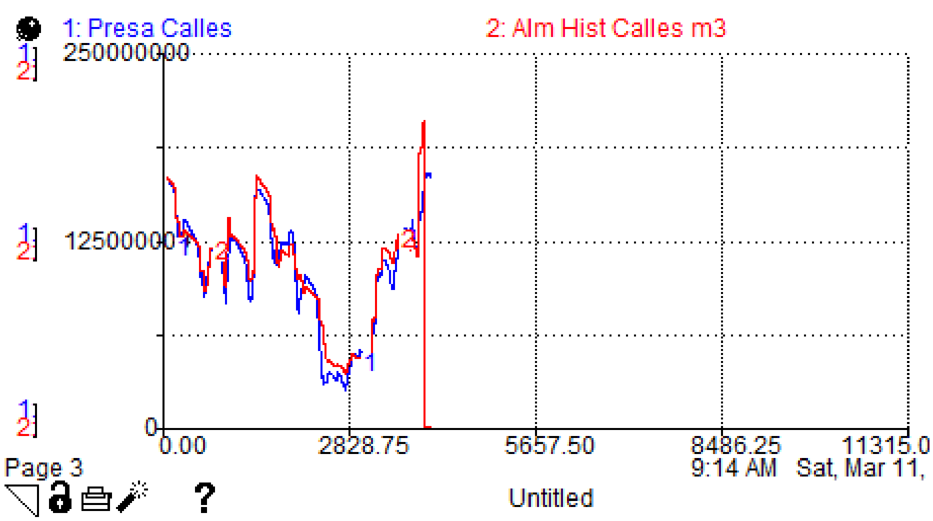

Figure 4. Calibrations run of MAUA/San Pedro for the Calles Reservoir (*1-Blue, Presa Calles; 2-Red, Alm Hist Calles m3*)

Figure 4 shows the volume computed by MAUA/San Pedro for the Calles Reservoir (*1-Blue*, *Presa Calles*) and the Historical volume values (*2-Red, Alm Hist Calles m3*) from January 1 of 2005 to August 20 of 2015, with an error computed of only 9%. The integration step utilized was one=day and the total length of the simulation is 11,315 days from which 3,926 days correspond to the calibration phase of the model and 7,389 to the scenario.

Scenario 1. Distribution Main Feeder Unfinished; Dual Irrigation Modality

For this scenario the situation in DR001 continues as it is today, with flood irrigation in one sector of the district and drip irrigation in the rest of it. The climate variability scenario utilized is the mildest one, assuming a historical analogy for precipitation, temperature and evaporation. The results of MAUA/San Pedro for the Calles Reservoir are displayed in Figure 5.

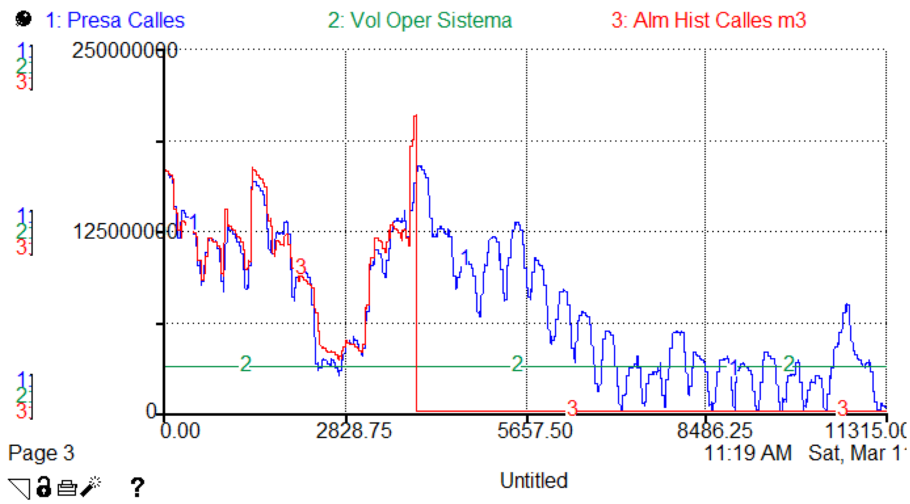

Figure 5. Scenario Dual Irrigation Modality, with Minimum Operating Volume (*1-Blue*, *Presa Calles; 2-Green. Vol Oper Sistema; 3-Red, Alm Hist Calles m3*)

Figure 5 shows a steady drop of the volume stored in the Calles Reservoir over time. Accordingly, the Volume Trajectory (*1-Blue*, *Presa Calles,*) crosses the operating level set at 30 million cubic meter of water (*2-Green*, *Vol Oper Sistema*) that corresponds with the minimum height required for the pressurized conveyance system to function, around 2023-2024. **After this period the Reservoir and DR001 become inoperative with very high losses of product and money**.

Scenario 2. Distribution Main Feeder completed; Drip Irrigation only; benign climate

What happens if the Main Feeder in the DR001 is completed and there is only dripping irrigation in DR001? For this scenario the assumption is that the Main Feeder in completed at the beginning of 2019. Also, the climate scenario is benign. The result of this scenario is displayed in Figure 6.

The Figure 6 shows that this scenario is "quantitatively sustainable" until the end of the period and perhaps beyond.

Scenario 3. Distribution Main Feeder completed; Drip Irrigation only; severe climate scenario

But, what can happen if the climate scenario is harsher that the one utilized for this run? Would the Calles Reservoir still be sustainable? The Figure 7 displays the volume stored in the Calles Reservoir (*1-Blue, Presa Calles*) under a severe weather scenario for which rain patterns in the Valley become more erratic and the yearly accumulated volumes of rain are diminished.

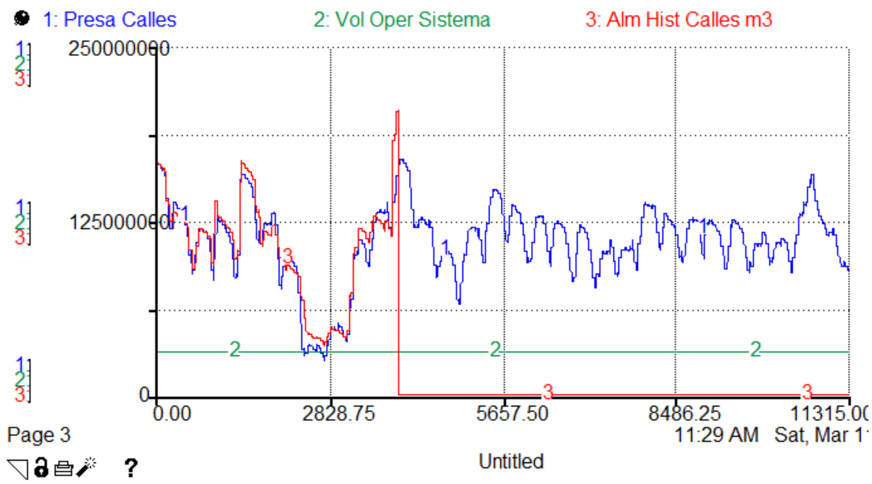

Figure 6. Scenario Main Feeder Completed, Drip Irrigation Only
(*1-Blue, Presa Calles; 2-Green. Vol Oper Sistema; 3-Red, Alm Hist Calles m3*)

The Figure 7 shows that even under severe weather conditions for the duration of the scenario, the volume on the Calles Reservoir is yearly above the operating minimum with the exception of one occasion and only for a short period of time.

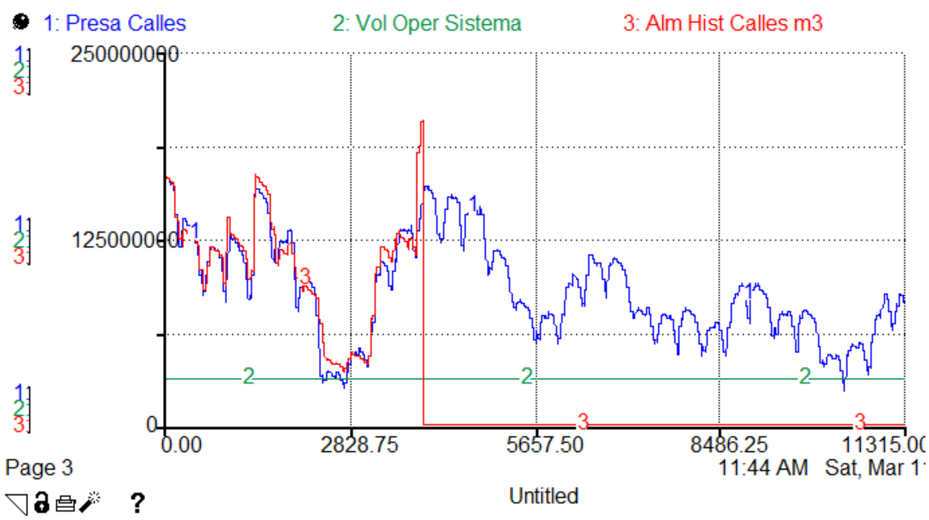

Figure 7. Scenario Main Feeder completed, Drip Irrigation only, severe climate
(*1-Blue, Presa Calles; 2-Green. Vol Oper Sistema; 3-Red, Alm Hist Calles m3*)

Figure 8 compares the trajectories of the three scenarios presented above. It is clear from the diagram, that **the wise strategy to be followed by the Valley water authorities is to complete the Main Feeder of the DR001 at a cost of about 40 million US dollars. To keep operating the dual irrigation modality of today, will have enormous economic costs- the loss of the modernization investment that is well over 150 million of USD, plus the agricultural production of the irrigation district permanently after 2024-2025 and production estimated at a yearly value of 200-300 millions of USD. The loss of agricultural output is also considerable and fluctuates between 70,000 and 100,000 tons of products per year.**

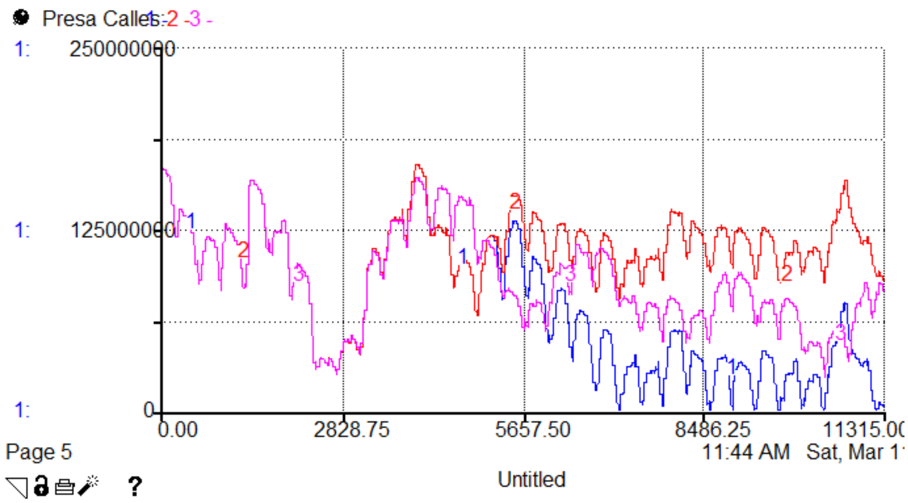

Figure 8. Comparison among three scenarios: (*1-Blue, Dual Irrigation; 2-Red, Drip Irrigation Fair Weather; 3-Magenta Drip Irrigation Severe Weather)*

4.2 Sustainability of Groundwater: An Assessment of the Aguascalientes Aquifer

The sustainability assessment of the Calles Reservoir – Irrigation District DR001 provided convincing evidence that using MAUA/San Pedro to design high value policies was the right way of assessing the situation although its impact in the whole Valley was relatively small when compared to the situation of the Aguascalientes Aquifer. This overexploited Aquifer provides irrigation water to portions of the DR001; the agricultural production in the three reaches of the San Pedro River basin located inside of the Valley; the city of Aguascalientes for human and commercial uses; and the industrial zone that surrounds the city. Needless to say that a drastic reduction of the volume stored in the aquifer could have catastrophic repercussions in the Valley.

On a daily basis the city of Aguascalientes extracts from the Aguascalientes Aquifer three cubic meters per second for city uses. This volume is distributed to the city by a private utility through a federal government concession. The city's wastewater is collected by the public works through a sewage system that conveys it to a city owned wastewater treatment plant that has an outflow of about three cubic meters per second. The discharged of the plant becomes one of inputs to the El Niagara Reservoir (see Figure 3), that also receives the inflow of the San Pedro River. The El Niagara spillover when the reservoir is full becomes the Verde River that flows downstream into the neighboring State of Jalisco.

Scenario 1. Baseline

Figure 9, is a Stella diagram of the Base Scenario run, without modifying operating policies. The horizontal axis measures time in days while the vertical axis measures the volume stored in the Aguascalientes Aquifer in cubic meters. Since there are no accurate government estimates of the volume stored in the Aguascalientes Aquifer, a very large volume of 4,000 million cubic meters (Mcm) was assumed at the beginning of the scenario with the purpose of showing that at the end of the 36-year run, this initial volume would have dropped to 93 Mcm, for an accumulated deficit of 4,007 Mcm, a staggering loss of 98% of its volume.

The differential equation for the Aguascalientes aquifer is:

$$Volume\ (t+1) = Volume\ (t) + \Delta t\ *(Recharge\ (t) - Extractions\ (t))$$

t: is time *Δt: is the time step, equal to one day*

Recharge (t): 294 Mm/years, a constant estimate provided by CONAGUA, with no periodical updates.

Extractions (t))=f(urban_use(t); agricultural_use(t); industrial_use(t);(t))

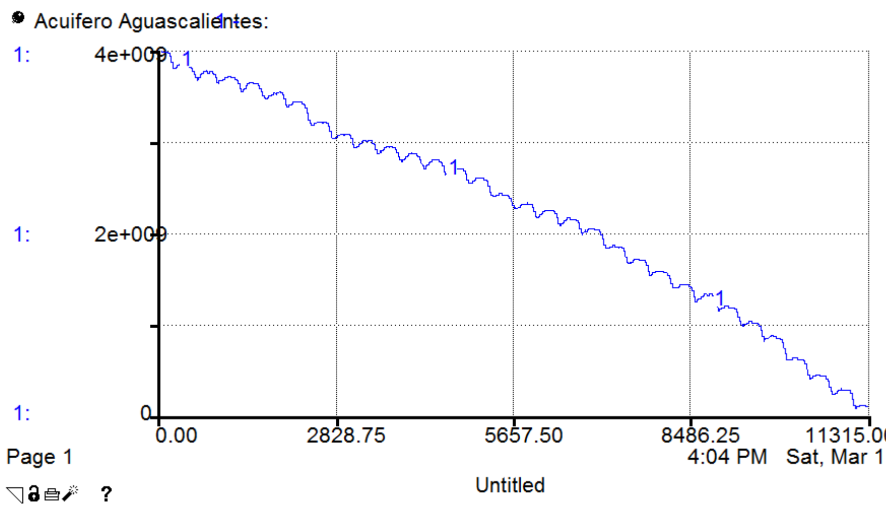

Figure 9. Aguascalientes aquifer from 2005 to 2035 in cubic meters

Scenario 2. Reuse of wastewater treated to supply Industry

The decision-makers participating in this project are aware that without immediate policy changes the aquifer volume will continue to shrink rapidly until, either by cost or exhaustion it will no longer be able to supply water. In light of this, **a policy of reusing the outflow of the wastewater treatment plant to supply the industrial non-consumptive demand of the Valley was formulated and tested**. This policy is allowed by Mexican Water Law that established that as long as the volumes utilized by cities are not discharged to “a federal channels or reservoirs” (e.g. El Niagara Reservoir), they can be used repeatedly. So, given this recycling policy, what would be the change of the aquifer volume?

To test this scenario a simulated treated water outflow impoundment was built in MAUA/San Pedro model so that the discharge of the treatment plant could go to this impoundment and not to El Niagara. Also, water intakes for every industry in

MAUA/San Pedro were connected to the simulated impoundment. The results of this policy test are displayed in Figure 10.

The Volume Trajectory 2 (*in red*) in Figure 10 shows that when treated wastewater is reused by industry for non-consumptive demand**,** the volume of the Aguascalientes Aquifer increases from an initial value of 2,606 Mcm on day 5,145 (February 1 of 2019) when this policy is implemented to a small increase by day 8,480 (March 20 of 2028), but mostly remaining balanced.

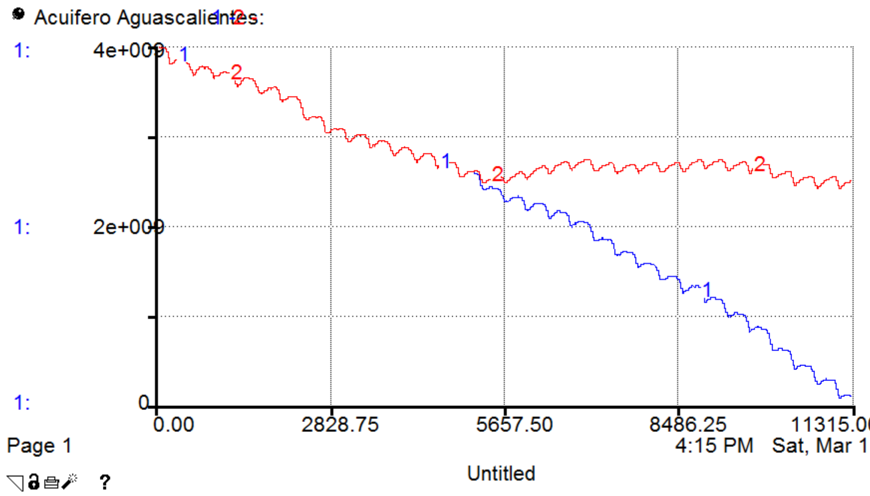

Figure 10. Aguascalientes' aquifer when treated water is reuse for industrial use. (*1-Blue, No Reuse; 2- Red, Treated Wastewater*)

The evaluation of this policy is that it should be implemented by the water authorities immediately since any time delay means a lower volume of the aquifer.

5. FOOD SECURITY ASSESSMENT OF THE SAN PEDRO RIVER VALLEY

5.1 Equivalence of the Nexus Food-Water and an appropriate Dynamics of Coupled Natural and Human Systems model

The deployment of MAUA/San Pedro to assess the sustainability of the Calles Reservoir, the Water district DR001 and the Aguascalientes Aquifer provided a cogent assessment of *Water Security* in the San Pedro River Valley; resulting in both a clear policy to make the Calles Reservoir-DR001 sustainable and a promising policy to stabilize the level of the aquifer. This section is dedicated to the subject of *Food Security* for the same Valley. The *Nexus Food-Water* approach is utilized for the assessment. The requisite Energy Model to complete the Nexus in our model will be built in the next phase of development of this project.

The contemporary literature on sustainability [FAO, 2015, U.S. Chamber of Commerce Foundation, 2015] frequently focuses on the Nexus Food-Water-Energy, a concept stemming from the fact that the World population is approaching eight billion and the stewardship of vital resources has become more uncompromising. In this context it has been observed that water, energy and food are inextricably linked. "*Water is an input for* *producing agricultural goods in the fields and along the entire agro-food supply chain. Energy is required to produce and distribute water and food: to pump water from groundwater or surface water sources, to power tractors and irrigation machinery, and to process and transport agricultural goods.*" [UN Water, 2010]

This description of the Nexus shares in common with the *Dynamics of Coupled Natural and Human Systems Methodology* three basic characteristics of a complex system: (1) *Numerical Complexity*, due to the great number of elements that can make up the system; (2) *Connectivity* among the system components in accordance to their specific configuration and (3) *Time Variable Behavior* (dynamics) of the system components and the system overall. It can be said that the *Dynamics of Coupled Natural and Human Systems approach* provides suitable mathematical constructs to represent the Nexus internal workings for which, in the majority of the articles, one can only find written descriptions but, without the corresponding equations that formalize the structure of the Nexus.

In contrast with written descriptions found in the literature, we have built dynamic models like MAUA/San Pedro that consider the interaction of Natural and Human System and utilize the robust and extensive mathematics of Control Engineering to obtain quantitative results. This is of the highest importance, since they *"provide some measure that distinguishes this [Nexus] system from an infinite number of other possibilities — you are beginning to know it deeply. You comprehend some of its beauty and you gain access to its power and the understanding it provides"* [Sagan, 1997].

5.2 Food Security Regional Assessment Methodology

Food Security has been defined as: "*A situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life."* [FAO,2002]. The Mexican government has embraced the UN definition and has made *Food Security* a high priority national objective. However, it has been argued that it is difficult to assess *Food Security* at the level of a region since in the process of converting agricultural crops into food products the inputs to this process can cross the border of the agricultural producing region, in and out, several times blurring what each region contributed to the final product.

But, there is a different argument that can be made to assess the *Regional Food Security*. Agreeing that *Food Security* is a <u>*country-wide objective not a regional objective*</u>, in Mexico where there is a large number of regions similar to the San Pedro River Valley, a *ratio* can be computed dividing the *region's agricultural production of crops but converted into food products*, by the *region's food products demand of its inhabitants*. In other words,

$$Regional\_Food\_Ratio_{i,t} = Food\_Production_{i,t} / Food\_Demand_{i,t}$$

for $i=1,2,3,\ldots\ldots,n$ *and* $0 \le t \le t_f$

Where:

i= region index

t: time

$Regional\_Food\_Ratio_{i,t}$*: Ratio of Food Production of the ith region at time t*

$Food\_Production_{i,t}$: *Agricultural Production of the ith region at time t, converted to food*

$Food\_Demand_{i,t}$: *Daily_per_capita_food_consumption of the ith region (a constant) X* $Population_{i,t}$ *(computed by MAUA/San Pedro)*

Note: The crop-to-food conversion can be accomplished utilizing, the *Plato del Bien Comer* [Secretaría de Salud, Mexico, 2006], a Mexican norm that provides a guide of the daily portions (in grams) of legumes, vegetables, carbohydrates and fruits that ought to be consumed by an individual for a healthy diet.

Now, if

$$Regional\_Food\_Ratio_{k,t}<1, \text{ for the kth region and t such that } 0\leq t\leq t_f$$

Then, the $Region_{k,t}$ has to import food to undo the deficit, from other regions in the country or from another country.

But, if

$$Regional\_Food\_Ratio_{p,t}\geq 1, \text{ for the pth region and some } 0\leq t\leq t_f$$

Then, the $Region_{p,t}$ has capacity to cover the demand and to export as well.

By applying this computation to all regions of Mexico and adding the ratios divided by the number of regions, a determination can be made of whether the country as a whole is exporter of food or conversely, importer of food.

From the above argument it is clear that the computation of *Food Security* for the entire country of Mexico is a lengthy but important undertaking that is beyond the scope of the present project. Nevertheless, since the San Pedro River Valley is considered an important agricultural and food producing region (although by many it is considered first and foremost a milk and dairy producing region), it was thought out that the computation of its *Regional_Food_Ratio* could give an **indication of present and future *Food Security* status of the Valley**. The findings were quite surprising.

Scenario 1: San Pedro River Valley Food Security Baseline

For the Baseline Scenario tested, the population of the San Pedro River Valley (Figure 11) increases its volume from 1,061,313 to 1,549,710, a growth of 46% in 19 years that yields an annual growth of 2%, which is considerable.

Figure 12, displays the yearly aggregate volume of legumes, vegetables, carbohydrates and fruits produced in the Valley (*2-Red, ProdAnualAgregada*) for local consumption as well as the aggregate volume of food (*1-Blue, DemAnualAgreg*), demanded by its inhabitants. In the formulation of the scenario a contemporary assumption was made that the agricultural land utilized for local consumption, represents only 30% of the total land available since current trends show that the other 70%, is dedicated to crops that become inputs to the value added chain for food exports that generate a higher income.

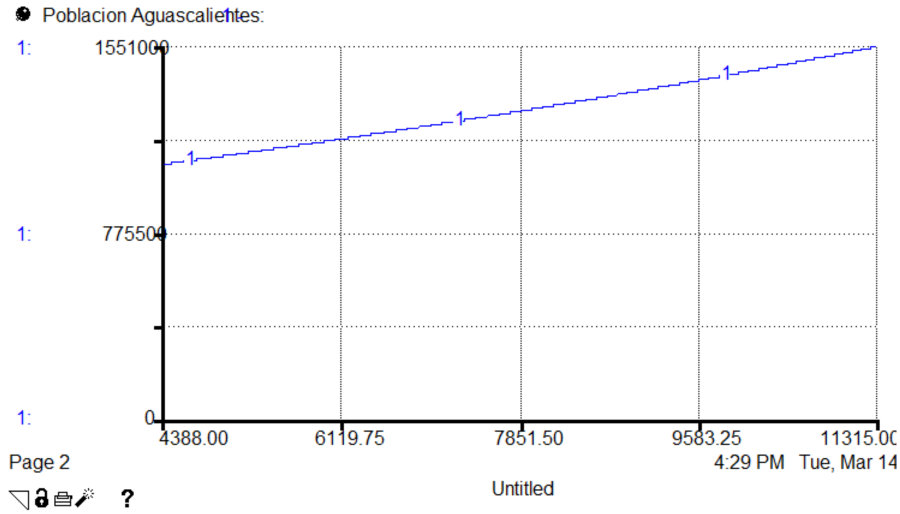

Figure 11. San Pedro River Valley Population (January 5, 2017 to December 31, 2035)

Figure 12, tells us a more interesting story that has to do with the differences in *Food Production* and *Demand* patterns. While the aggregate *Food Production* that is constant over time remains at 65,546 tons/year, the *Valley Population Demand* starts at 360,916 tons/year and ends at 550,354 tons/year. This means that the local aggregate production fills only 17.3% of the *Population Demand* in 2017 and 12% in 2035.

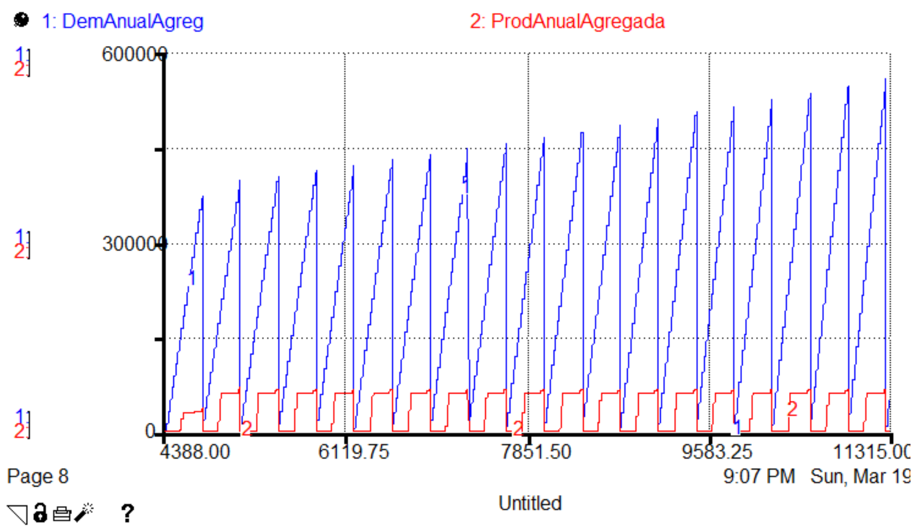

Figure 12. Yearly Aggregate Food Production and Food Local Demand
1-Blue, DemAnualAgreg; 2-Red, ProdAnualAgregada

Figure 13 shows that if one integrates the yearly difference of *Food Production minus Population Food Demand*, over the 19 year that goes from 2017 to 2035, the accumulation of *Food Imports* would have reached 7,702,065 tons that, over that period of time had to be imported into the San Pedro River Valley to keep its population fed.

But in 10 to 15 years from now, when the pressure on the World food market will most probably be quite strong, the *Food Breach* in the Valley probably would have to confront food shortage that would consequently bring social and economic upheaval in the region. Within this scenario however, not all the inhabitants of the Valley would be equally affected by the potential shortage. **The segment of the population in the Valley likely to suffer its effects would be the low income individuals who earn up to four Daily Salaries (a Daily Salary is the minimum wage in México and is about 5 USD per day), representing 60% of the inhabitants in this region. They would be affected because they do not have the buying power to purchase the "food for export" that is manufacture in the San Pedro Valley itself.**

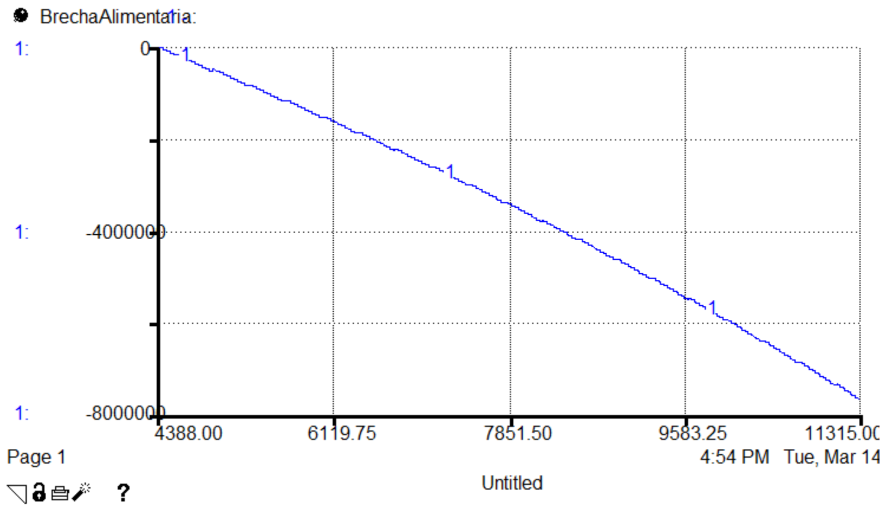

Figure 13. Food Breach
(1-Blue, BrechaAlimentaria)

While this San Pedro Valley regional *Food Security* analysis does not attempt to make a statement at the country level, it provides an indication of the probable behavior of a typical agricultural producing region where the *Food Security* issue, has not been appropriately framed in terms of the necessary balance between supply and demand. So, for the foreseeable future ***Food Security* in terms of the pillars that support this concept in México: (1) food availability; (2) food access and (3) stability of supply, [Salud Pública, 2014] cannot be ensured for the Valley.**

5.3 Future food supply research: A Small Agricultural Producer model

The results of the present project above, clearly indicated the need to develop, as soon as possible, programs aimed to increase the food production for local consumption. One of these programs designed for the current project is the Small Agricultural Producer model that aims at reducing the *Food Breach*. This program is supported by the FAO in its 2014 annual report that indicates that around the World, the small agricultural producers with 3 or fewer hectares satisfy 80% of the food demand.

For the Valley, this knowledge flies in the face of the fact that the **bulk of the federal and state government support to agriculture goes to the agroindustry that as a rule utilizes more than 3 hectares, that is well financed by private capital and whose goal is to export**. It is clear then that the government should channel its support to the Small Agricultural Producer model, if an increase *Food Security* is the goal.

The FAO also reports that family operated agricultural concerns are the basis for the Small Agricultural Producer initiative because they are crucially important to guarantee Food Security, and at the same time, to care and protect the environment and of course to help to eradicate poverty and malnourishment.

In anticipation of the continuation of the present project an inventory of agricultural producing land in the Valley was compiled with preliminary results displayed in Table 1.

area	No. of Plots	Hectares	% Plots	% Hectares
< 0.5	6,338	1,300	17.26	0.85
0.5 - 3	16,064	24,691	43.75	16.07
3.1 - 10	12,018	67,126	32.73	43.69
10.1 - 50	2,024	36,647	5.51	23.85
50.1 - 100	203	14,036	0.55	9.14
> 100	68	9,828	0.19	6.40

Table 1. Inventory of agricultural land in the San Pedro River Valley

From Table 1 it can be seen that for the group of 0 to 3 hectares, 17% of the total hectares corresponds to 61% of the total plots while in the 50 hectares group incorporates 18% of the total hectares but less than 1% of the plots. An analysis of these numbers indicates that if a policy were implemented for plots of less than 3 hectares, to plant bio-intensive crops, there would be a sizable improvement of the *Food Security* in the Valley.

6. FINDINGS AND CONCLUSIONS

In a World of diminishing resources and increasing population, international organizations and governments search for “new approaches” to improve the stewardship and management of key resources – water, food, energy, ecosystem functions and human health [Pielke, 2012]. But even when there is consensus that the regions of the world operate today within a “reduced resources” context, the approaches being developed still lean greatly towards a financial paradigm where the final deciders are monetary considerations such as profit, and not the scarcity of the resources. **This mind set seems to forget that the most expensive water is the one that does not exists.**

In an effort to replace the “business-as-usual” modus operandi, the *Systems Approach* has been unavoidably tapped because it enables one to find ways to internalize the proverbial “externalities.” Among them, the physical environment is number one, but from a wider perspective the complete set of social, economic and political realities must be fully considered.

Unquestionably the *Systems Approach* has the advantage of representing large-scale, complex problem as one construct, instead of the usual string of disconnected submodels that are difficult to build and cannot run simultaneously. The Food and Agricultural Organization of United Nations (FAO), the National Science Foundation (NSF), a number of European organizations that work on sustainability, several country governments, universities and research groups have all understood this message and are enthusiastically working on systemic concepts such as the Nexus Food-Energy-Water (NFEW).

NFEW has actively encouraged researchers with training in geography, natural resources, ecology and other disciplines to break into the Systems field so that they can be able to describe and explain how three interconnected systems –water, food, and energy-, interact with each other in time and space. But the results of these investigations are mostly written characterization of the Nexus, with scarce examples of mathematical models capable of producing the quantitative results that are critically needed by decision makers. The preference of written documents over working mathematical models may be due to the insufficient level of training on Systems and Control Engineering mathematics among the NFEW's researchers. The other reason could be that only a small number of Systems and Control Engineers participate in NFEW related research.

But in today's context there are truly pressing problems that need to be immediately resolved such as [Water Funder Initiative, 2016]:

1. Bringing a basin into balance for people and nature and
2. Strengthening the resilience of water systems.

We have recognized the existence of these problems; this is the reason that compels us to build dynamic models that fully represent the natural and human processes in watersheds. With them, we can provide decision makers the tools that will enable them to find and maintain the *requisite balance between supply and demand of key resources – water, food, energy, ecosystem functions and human health - in the continuum of time.*

The objective of the present project was to adapt our watershed dynamic model, ProEstado-MAUA®, to the San Pedro River Valley in Aguascalientes, México, to assess the supply and demand balance of Water and Food. The execution of this project gave us opportunity to do several things:

A. *Systems Methodology*. While this project was not focused primarily on methodology, it nevertheless provided an opening for developing a connection between Systems and Control Theory and the contemporary approaches being developed by organizations such as the National Science Foundation on topics like the Nexus Food-Energy-Water and the Dynamic of Coupled Natural and Human Systems.
   Considering that the regional systems that need to be assessed are large scale and complex, Systems and Control Engineering can provide the *interdisciplinary framework to represent these regional systems as differential equations that can be then numerically solved*. To reiterate: this approach avoids the drawbacks of attempting to interconnect models that arise from many different disciplines (i.e., economics, sociology, demography, engineering, etc.).
B. *Water Security*. The water shortage in the Valley is an acute problem with technical and political dimensions. The dynamic modeling of the Calles Reservoir and the Irrigation district DR001 system was the last recourse of water experts in the region had after a stalemate of how to assess the "sustainability" of that system. The analysis and subsequent recommendations provided by us with the employment of the MAUA/San Pedro, were credible for the politicians who are now in the process of adopting them as policy. The situation of the Aguascalientes Aquifer had been diagnose correctly before we intervened, but they did not have a tool that like MAUA/San Pedro, could provide them with the requisite quantitative analysis, that

could demonstrate the possibility of reaching the balance desired. The technical issue of building a “purple-line” to recycled treated water is now being approved.

C. *Food Security*. The Food Security assessment in the Valley provides a new vision for an old problem: not enough food production for local consumption. In spite of the fact that Food Security is a national and high visible goal, in practice, at least in the case of the San Pedro River Valley, the process to address this problem is just at the beginning. The scenario developed with MAUA/San Pedro showed that Food Security has not been properly framed since agricultural support from the various levels of the government favors agroindustry at the expense of the small agricultural producer. This lack of understanding is translated today into increasing volumes of food that need to be “imported” into the Valley. But, as the model pointed out, within the next 15 year period the food supply situation can become critical, generating a problem that can become extremely complex to handle, and may lead to shortages and price gauging. Famine and social unrest in the Valley are quite likely to occur. As an antidote to this possibility a powerful project to begin addressing an accelerated food production program was presented in this document.

D. Project participation by Stakeholders in the Valley. The execution of this project has included the participation of water and agriculture stakeholders; it has also included federal, state and local authorities. Against the back drop of a restricted water situation, the water stakeholders took the time to learn System Thinking concepts and enough Systems modeling to be able to interpret MAUA/San Pedro results. The change of paradigm from the traditional static water thinking to a continuous accounting of humidity in the watershed took some time to sink in, but it did. The food and agriculture stakeholders were very excited to have “a model” where policies and ideas could be tested and the results analyzed for potential implementation. The interest to continue has been heightened with the idea of combining the model with concepts such as a circular economy.

There are many other basins around the World whose pursuit of sustainability can be assessed and satisfied with adaptations of MAUA/San Pedro.

REFERENCES

National Science Foundation, “Dynamics of Coupled Natural-Human Systems,” 2007

Kling, C, Arritt, R., “Research needs and challenges in the FEW system: Coupling economic models with agronomic, hydrologic, and bioenergy models for sustainable food, energy and water systems,” NSF’s Food, Energy and Water Workshop, October 2015

Mesarovic, M., Takahara, Y., General Systems Theory: Mathematical Foundations, Academic Press, 1975

Food and Agriculture Organization, U.N., “Chapter 2-Penman-Monteith Equation,”.

Crawford, N, Linsley, R., Digital Simulation in Hydrology: Stanford Watershed Model IV, Technical Report 39, Civil Engineering, Stanford University, 1966

Garcia-Lopez, J. E., Huerta, J.M., “Demografía Dinámica de México: DemoDinMexico,” Reality, Data and Space International Journal of Statistics and Geography, INEGI, January 2016

Huerta, J.M., Serra M, Sandoval R., “ProEstado – MAUA, A Systems Dynamics Approach for the Design of Sustainable Water Use Strategy in the Middle Lerma – Chapala Basin”, a chapter in the book The Lerma – Chapala Watershed, Evaluation and Management, Editors Anne M. Hansen and Manfred van Afferden, Kluwer Academic / Plenum, 2001.

United Nations Framework Convention on Climate Change, “Chapter 6 Water Resources,” 2006.

Food and Agriculture Organization, U.N., “The Water-Energy-Food Nexus A new approach in support of food security and sustainable agriculture,” 2015

U.S. Chamber of Commerce Foundation, “The Energy-Water-Food Nexus,” 2015

U.N. Water, “Water, Food and Energy Nexus,” 2015

Secretaría de Salud, México, “El Plato de Bien Comer, NORMA Oficial Mexicana NOM-043-SSA2-2005, 2006

Sagan, C., Billions of Billions, 1997

Pielke, R., Hossain, F., “Dealing With Complexity and Extreme Events Using a Bottom-Up, Resource-Based Vulnerability Perspective, Extreme Events and Natural Hazards: The Complexity Perspective,” Geophysical Monograph Series 196, American Geophysical Union. 2012

The Water Funder Initiative, “Toward Water Sustainability: A Blue Print of Philanthropy,” 2016