WATER SECURITY IN THE SAN PEDRO RIVER VALLEY, AGUASCALIENTES, MEXICO

Background

UN-Water, the United Nations' inter-agency for water-related issues defines **Water Security** as: *The capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability*.

When confronting water scarcity, as many regions of the World do today, oftentimes the most difficult aspect of *Water Security* is the shortage of *adequate quantities of water*. This situation compels to safeguarding the sustainability of whatever volume is available in each case, by means of the **water supply and demand balance that must exist in the continuum of time**.

The present project deals with a real life *Water Security* case. The watershed selected for the project was the San Pedro River Valley in the State of Aguascalientes, México located some 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. The San Pedro River Valley dissects a rectangular shaped-region 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 supply with well water from the *Aguascalientes aquifer* that lies almost exactly under the San Pedro River Valley footprint and also supplies water for urban and industrial uses in the Valley.

Description of the water situation in the San Pedro River Valley

Although it is known that the Valley's water resources are dwindling, its growth has continued unabated. In light of this situation, two pressing concerns were presented to water authorities by a group of agricultural, urban and industrial users:

1. Taking into account the climate variability in the basin, *<u>is the Calles Reservoir-DR001 system sustainable?</u>*

2. What policies can be designed and implemented *to reduce the continuous extractions from the overexploited Aguascalientes Aquifer?*

Addressing the water sustainability queries in the San Pedro River Valley

The reply to these two queries requires the *balancing of water supply and demand flows over the continuum* of time to ensure *quantitative sustainability*. The process of *building the balancing mechanism* becomes a Control Engineering Problem (CEP). An explanation of what is a CEP and how it works is presented by mean of a pseudo-model:

1. The *supply* and the *demand flows* show time-varying behaviors (are dynamic) and thus, cannot be examined statically;
2. It is then necessary to know what *causes the water resources balance (or imbalance)* as a time function, since that provides the knowledge to write the differential equations of *supply* and *demand flows* to build the requisite dynamic model;
3. Structurally, the *supply* and *demand flows* differential equations have:
   - **i.** A Process Mechanism (*Plant*) that when solving numerically the model's equations generates time related numeric values of the variable it represents (e.g., population) in the form of a *Trajectory* (the variable values associated with time).
   - **ii.** A Process Control (*Controller*) that guides the *Process Generator* to start/end running; to increase/decrease the intensity and to give shape to the *Trajectory* pattern (e.g., birth rate and death rate in the case of population).
4. For the CEP version of the San Pedro River Valley, all natural and human processes that are deemed necessary to fully represent the *Real Life System* (*Valley*) are to be included in the dynamic model. This ensures that the *Model* of the Valley, and the *Valley*, respond in an analogous manner when the same *Policy* is applied to both of them because the *Model* and the *Valley* mirror each other.
5. At the beginning of a *Model* run when the time $t=0$, both the *Valley* and the *Model* exhibit analogous *States* (*Model State* is the collection of all the values of the *Model* variables. Likewise the *Valley State* is the collection of the values of the Model homologous variables chosen in the *Valley* to solve the problem), since the values of the variables measured in the *Valley* and the corresponding variables computed by the *Model* in accordance to 4 above must be equal within a very small error.
6. When the *Model* run starts, the clock of the algorithm that solves the differential equations increases its time from t to $t+\Delta t$, where $t< t+\Delta t$ and in general, given a $t_{initial}$ and a t_{final}, then $t_{initial} \leq t \leq t_{final}$.

7. If we enter a *Control History*$_1$ (a time series of controlled values) in the *Controller* of the *Model,* the *Plant* of the *Model* generates a trajectory in response to the *Control History*$_1$, that transfers the *Model* from a State($t_{initial}$) at t_{inital} to a State(t_{final})$_1$, at t_{final}.
8. Using 7, the *Control History** transfer the model from the same initial state to State(t_{final})*,that is not equal to State(t_{final})$_1$.
9. It becomes clear that the CEP has the means of transferring the *Model* from a State($t_{initial}$) to a *Sustainable_State (t)*^, where $t_{initial} \le t \le t_{final}$ when the *Control History*^ is applied. In accordance to 4 above, the *Control History*^ becomes the best *Policy*^ that transfer the *Valley* to a *Sustainable Water State.*

WATER SECURITY SCENARIOS: The MAUA/San Pedro DYNAMIC MODEL

MAUA/San Pedro was the *Model* selected to generate the *Water Security Scenarios*. MAUA/San Pedro was built from ProEstado-MAUA® (a detailed description of the MAUA model can be found in the section Models) and is a bottom-up representation that fully captures the coupling natural and human processes acting up in the *Valley*.

MAUA/san Pedro was customized for the *Valley* utilizing the diagram of Figure 1 that show on its left hand side the catchment area that feeds runoff to 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 of the *Aguascalientes aquifer* for urban and industrial uses and to supply the agricultural production of the three sub-watersheds of the San Pedro River basin.

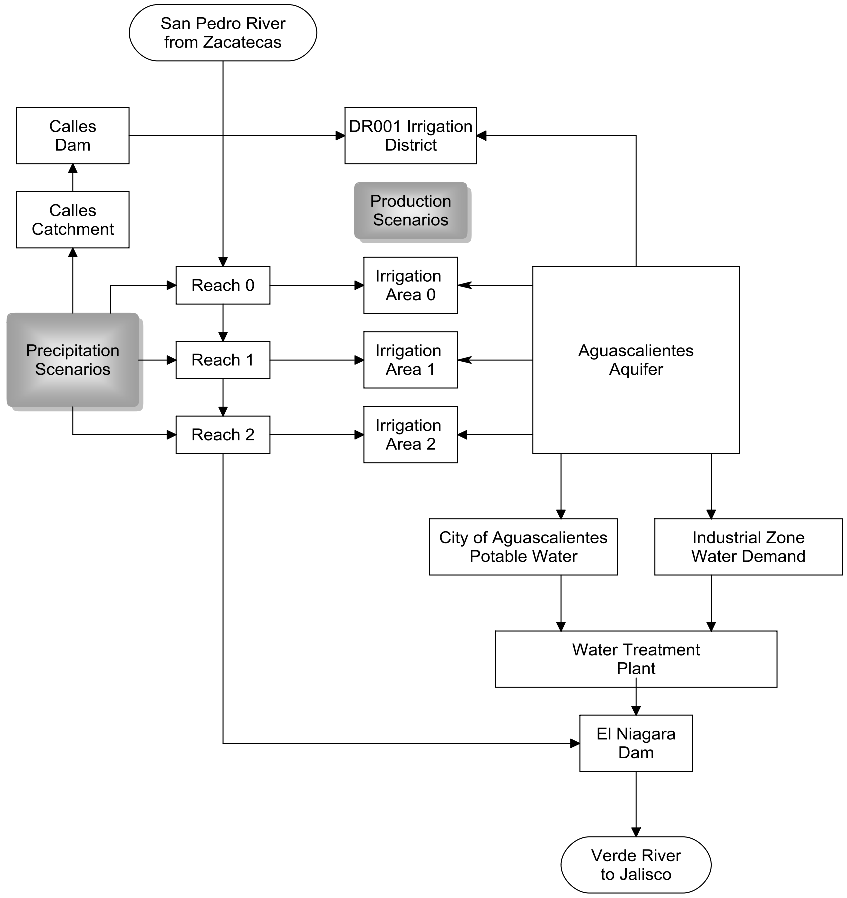

Figure 1. Functional Diagram of the San Pedro River Valley

WATER SECURITY SCENARIO FORMULATION AND TESTING

The purpose of the present exercise was to find **two *Control Histories*** that could guide the *Calles Reservoir-DR001*, on the one hand, and the *Aguascalientes aquifer* on the other, to two respective *Sustainable Water States*. The scenario specifications for this application are next:

Scenario Parameters

Model run length: From January 1 of 2005 to December 21 of 2035
Integration step: one-day
Length of the simulation: 11,315 days
Calibration phase: 3,926 days, from January 1, 2005 to October 15, 2015, last date for which the following data required to calibrate the model was available:
Scenario phase: 7,389 from October 16, 2015 to December 31, 2035
Dynamic Simulation Platform: Stella Research Version 9.1.4®

Scenario Formulation

Control Histories

The Scenario Formulation starts by selecting the *Control Histories*, which are exogenous variables that are inputted into the MAUA/San Pedro as time series that have the same length and integration step than the *Model*. Table 1 depicts the Sub-models or Scenarios of MAUA/San Pedro and the *Control Histories* associated in each case, which were involved in the *Model's* calibrating phase.

Sub-model or Scenario	Control Histories
Region's Precipitation and Evaporation	**-Daily rain volumes** (for seven stations distribute in the Calles Reservoir runoff catchment region) from January 1, 2005 to August 20, 2015
Calles Reservoir	**-Historical Daily Data for Input, Storage, Precipitation and Extractions** from January 1, 2005 to August 20, 2015
DR001 Agricultural Production	**-Drip Irrigation Surface** planted of several crops by Production Cycle of for Spring-Summer; Fall-Winter: Perennials from January 1, 2005 to August 20, 2015 **-Flood Irrigation Surface** planted of several crops by Production Cycle of for Spring-Summer; Fall-Winter: Perennials from January 1, 2005 to August 20, 2015
Sub-watershed 0, 1, 2 Agricultural Production of	**-Drip Irrigation Surface** planted of several crops by Production Cycle of for Spring-Summer; Fall-Winter: Perennials from January 1, 2005 to August 20, 2015 **-Flood Irrigation Surface** planted of several crops by Production Cycle of for Spring-Summer; Fall-Winter: Perennials from January 1, 2005 to August 20, 2015
Population	**-National Council on Population (CONAPO)** annual birth and deaths rates by gender and age from January 1, 2005 to August 20, 2015
Industry	-**National Institute of Economics and Geography (INEGI)** Annual growth rates for 12 economic sectors from January 1, 2005 to August 20, 2015 INEGI Annual employment in 2015 for 12

	economic sectors from January 1, 2005 to August 20, 2015

Table 1. Sub-models or Scenarios of MAUA/Pedro and the *Control Histories* associated in each case for the calibrating phase.

CALIBRATION PHASE

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 of conduits, filters and valves had been finalized but the main water distribution feeder that borders the district was only 70% completed. To keep the *DR001* producing at that time, a dual irrigation system had to be engineered 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 *Calles Reservoir* questioning if in the long-term it could be sustainable.

Utilizing the *Control Histories* of Table 1, for Regional Precipitation and Evaporation, the Calles Reservoir and the DR001 Agricultural Production, the simulated values generated by MAUA/San Pedro and the observed values of the corresponding variables from the *Valley* were compared to adjust the parameters of MAUA/San Pedro and to evaluate the accuracy of its results. This procedure ensured that the MAUA/San Pedro structure was adequate to simulate future values of the model variables based on the initial *Watershed State* and the *Control Histories* inputs by decision makers.

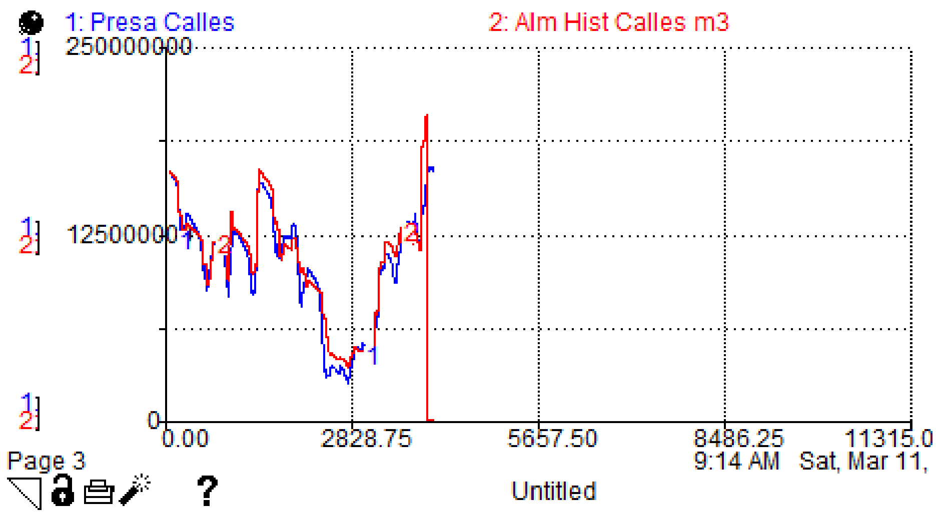

Figure 2. Calibrations run of MAUA/San Pedro for the Calles Reservoir (*1-Blue*, *Presa Calles; 2-Red, Alm Hist Calles m3*)

Figure 2 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 of only 9%.

Aguascalientes Aquifer

The historical data of the functioning of the *Aguascalientes aquifer* was not available in a suitable, complete and homogeneous form and could not be utilized to calibrate the aquifer model. Only general knowledge of the 'condition of the acquirer' and its annual recharge volume were available. It is certainly puzzling that such incredibly important source water for the *Valley*, from which the life of the *Valley* itself depends, has not been more thoroughly examined over the years.

What it is known is that the Aguascalientes Aquifer overexploited since it supplies 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.

On a daily basis the city of Aguascalientes extracts from the Aguascalientes Aquifer three cubic meters per second for city uses and the city's wastewater is collected by the sewage system that conveys it to a city operated 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 1), that also receives the inflow of the San Pedro River. The El Niagara spillover when the dam is full becomes the Verde River that flows downstream into the neighboring State of Jalisco.

With the sparse information available over the *Aguascalientes aquifer* but knowing that with MAUA/San Pedro the daily demands for the various uses can be calculated, and the extracted from the 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, a small volume of water remains stored in the aquifer.

Figure 3, is a Stella diagram of the Calibration Run, with the Control Histories of Table 1 that are homologues to the Policies implemented for the various components of the Model today. The horizontal axis measures time in days while the vertical axis measures the volume stored in the *Aguascalientes aquifer*, in cubic meters. As it can be seen in the diagram over the 36 years of simulation the volume drops from 4,000 Mcm to 93 Mcm, a staggering loss of 98% of its volume.

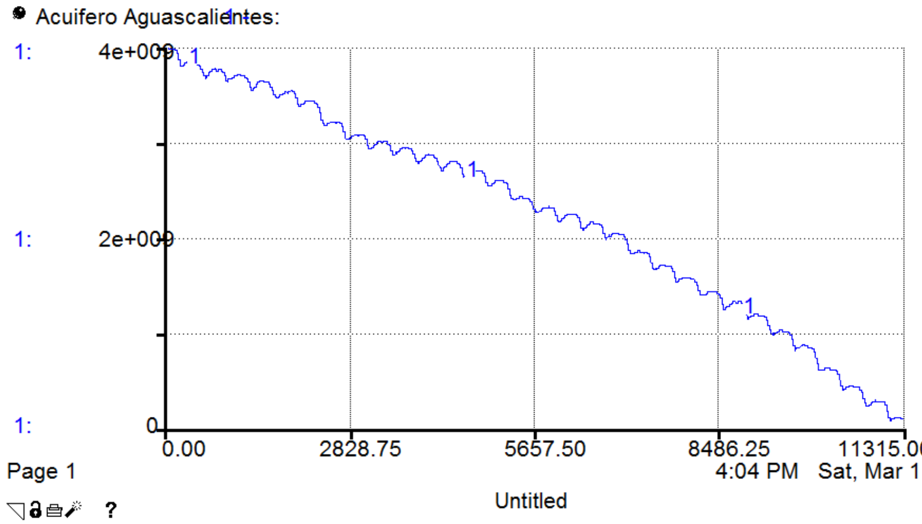

Figure 3. Aguascalientes aquifer from 2005 to 2035 in cubic meters

SUSTAINABILITY SCENARIOS

Q1: Is the Calles Reservoir – Irrigation District DR001 sustainable?

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 run for the Calles Reservoir are displayed in Figure 5.

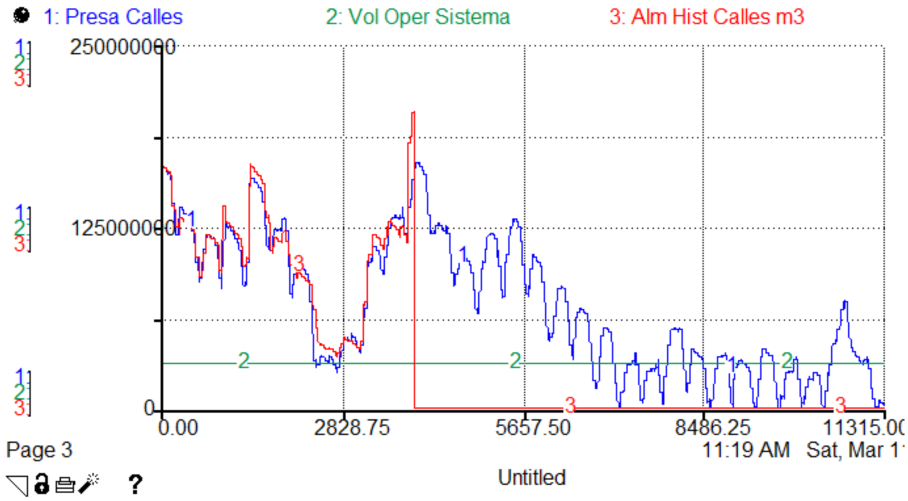

Figure 4. Scenario Dual Irrigation Modality, with Minimum Operating Volume (*1-Blue*, *Presa Calles; 2-Green. Vol Oper Sistema; 3-Red, Alm Hist Calles m3*)

Figure 4 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 Calles 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 5.

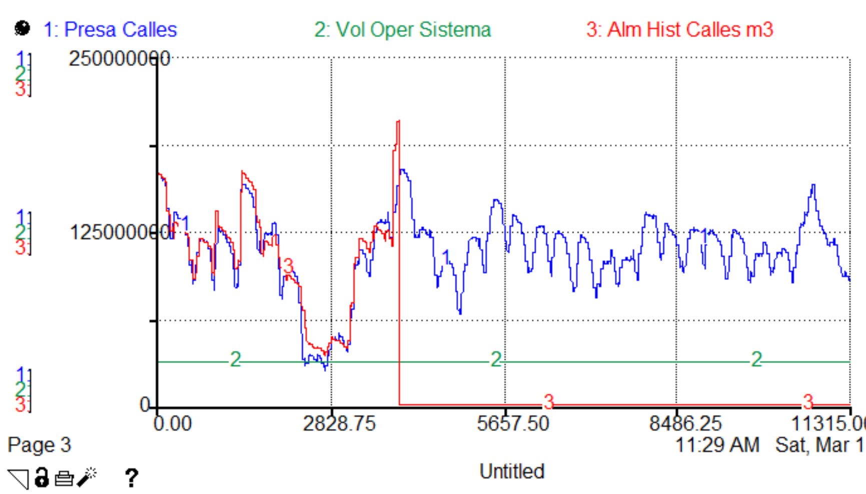

Figure 5. Scenario Main Feeder Completed, Drip Irrigation Only
(*1-Blue*, *Presa Calles; 2-Green. Vol Oper Sistema; 3-Red, Alm Hist Calles m3*)

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.

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 6 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.

The Figure 6 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.

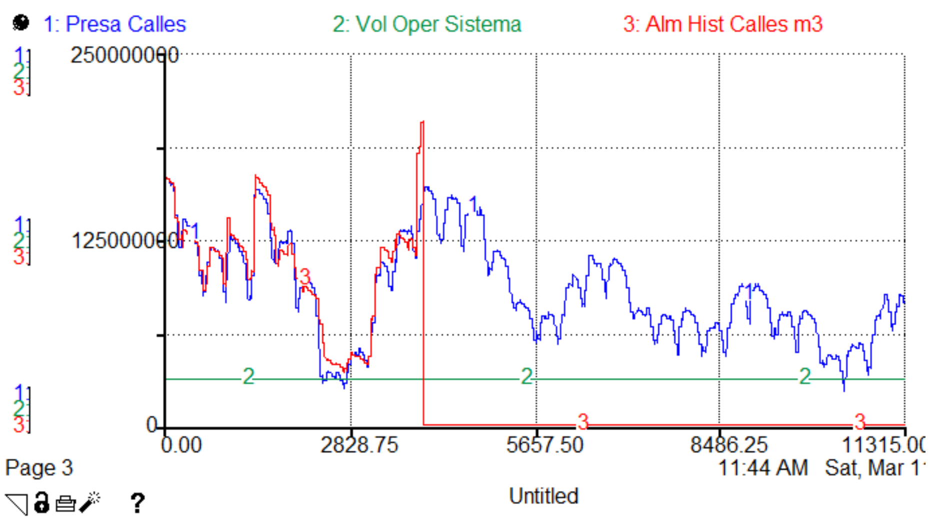

Figure 6. Scenario Main Feeder completed, Drip Irrigation only, severe climate
(*1-Blue*, *Presa Calles; 2-Green. Vol Oper Sistema; 3-Red, Alm Hist Calles m3*)

Figure 7 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.

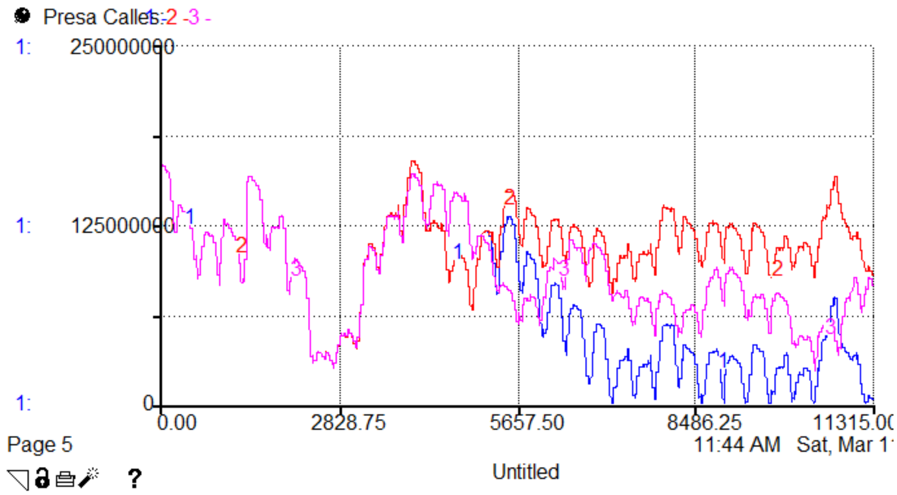

Figure 7. Comparison among three scenarios: (*1-Blue, Dual Irrigation; 2-Red, Drip Irrigation Fair Weather; 3-Magenta Drip Irrigation Severe Weather)*

Q2: Is there a policy that can balance the Aguascalientes Aquifer?

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.

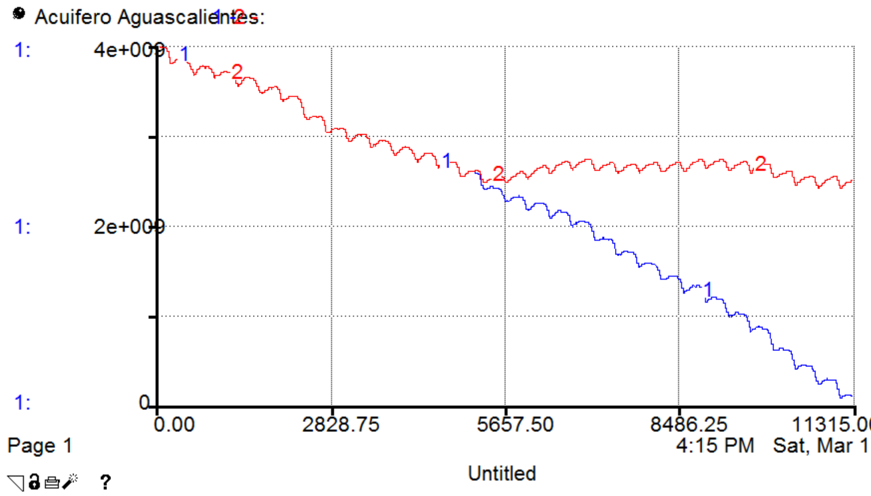

Figure 10. Aguascalientes' aquifer when treated water is reuse for industrial use. (*1-Blue*, *No Reuse; 2- Red, Treated Wastewater*)

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.