Vensim PLE to create models for Water Management

Rui M. S. Pereira, Naim Haie and Gaspar J. Machado

Abstract— This paper intends to show how easy it can be to build a prototype that will help water resources managers to make their decisions not only based on politics or economics, but also with a scientific tool that will help them build different weather scenarios. First we present a very simple mathematical model that has all the potential to evolve from version to version. Its implementation is easy to do, using a platform to perform simulations, called Vensim PLE. The philosophy that Vensim PLE follows to build up models of simulation is very interesting and simple.

It is based in 3 main entities - container variables, auxiliary variables and fluxes. It is a pictorial based language, and therefore, it is quite easy to follow models. The details are hidden when you define these entities represented in a figure. We used a freeware version for students.

An example that shows a possible model of what happens in the vicinity of an Urban area is presented, showing it is possible, to use Vensim PLE to build rather complex models of simulation. Provided we have good data, we are able to create different scenarios with literally the click of the mouse in our PC.

This paper can help water managers to understand how to implement their own models using a freeware software that is easy to use and produces nice and easy graphs without a lot of effort.

Keywords— water scarcity, weather scenarios, mathematical modeling, Vensim PLE.

I. Introduction

Climate change is here with us. It can be evidenced in most regions of our planet and it will tend to intensify as mentioned in the last IPCC [1] report (see also [2]). In this report, it is also stated that most of the climate change is MAN responsibility. Some examples stated are the increase of lakes in polar regions, changes in polar ecosystems, among others.

Predictions for the Southern Europe are a bit less than catastrophic.

In the same IPCC report, which has recently been awarded the Nobel Peace Prize, one can read there will be temperature rise in Southern Europe, especially in the summer. There will also be a significant drop of raining in this region.

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Longer and more frequent drought periods are expected. Iberia, all Southern Europe and North of Africa, Southern Africa, and Australia are some of the most affected places in the world [3], [4].

This means we have to build up good mathematical models and implement it, in such a way, that any responsible water manager can use it, and, be able to make scientific decisions, rather than political or strictly economical ones.

If we take a look at Figure 1, we can see that the many other regions will be severely affected by climate change. This causes multiple stresses on water resources of a region, making the situation of various world regions even further from sustainable development. This obviously leads us to impose on people a more efficient way to use their water [5],[6],[7],[8].

Various world governments started to implement plans to deal with climate change. The 10 year efficiency improvement program of the Portuguese government [9], launched in 2009 together with the plan of building 10 more dams, costs hundreds of millions of euros, hence the importance of having good mathematical models to simulate different scenarios is crucial, as well as to be able to monitor the environmental quality [10].

Our attention is focused on Portugal [11], although since this is basically a theoretical paper, the study area is not yet an issue. In future papers, based on real data, rather than on mathematical functions to model variables like rain or consumption, the area of study will be one important issue.

For the Portuguese case, we may read in [12], there are some interesting figures to retain: the agriculture sector spends 87% of the water, the urban centers about 8% of the water and industry the remaining 5%. It seems obvious that one has to address the efficiency of water used specially in agriculture and cities, but one also has to have good tools to estimate the actual state of our reserves at each instant. It is also important to develop an easy to use informatics tool that will instantly build scenarios in terms of water availability in all sectors depending on the consumption or weather conditions and efficiency of the entities that use the water. In this paper, we will develop a rather crude version of this tool, but that with improvements, based on stronger mathematical models, via more data availability, will soon be a good friend for decision makers. The software platform used to implement the mathematical model was taken from the site [12].

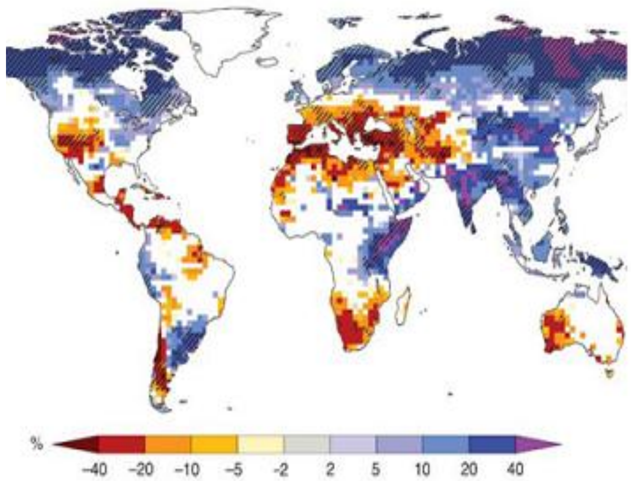

Fig.1 Large-scale relative changes in annual runoff for the period 2090-2099, relative to 1980-1999 ([1]). Blue regions mean that there will be more rain. Red regions mean exactly the opposite.

II. Problem Formulation using Vensim PLE

We will start by presenting Vensim PLE. This will make it easier to understand the mathematical model we followed.

A. *The use of Vensim PLE*

From Vensim PLE home page, we can read the statement: "Vensim PLE is free for academic use because the firm believe it easier for more people to learn system dynamics. It is also expected that people who learn with Vensim PLE will start to use the modeling approach seriously in their work and therefore pay the shareware license fee, or choose to purchase a more advanced version of Vensim PLE Ventana publishes Vensim PLE which is used for constructing models of business, scientific, environmental, and social systems" [13].
Some of the most famous systems used to predict climate change like C-ROADS used Vensim PLE as working environment [14],[15],[16]. Here, we will present Vensim PLE main features, and how to use it in a limited climate change.

In Vensim PLE, there are essentially 3 types of entities: Containers, Fluxes, and Variables. Anything can be thought trough from here. The necessary art we have to have here, is to write a mathematical model, that sometimes as we know may have a high degree of complexity with just these entities.
Note there must be consistency in terms of physical units used. It means that a special effort has to be made in the mathematical model so you could not be trapped in a so called situation where you are adding up potatoes and oranges in the same container. In order to understand how Vensim PLE works, let us start with a simple example.

B. *Example 1*

Suppose we have a dam that has as input, the water that rained in the region for a period of time, and that has also to release water to keep a minimum level (that has to be non-negative), and, at the same time be useful for different purposes. We will also consider we may have some water losses not specifying of what kind.
In this case, we have a very simple model where you have a container (the dam) and 3 fluxes - influx of water due to rain, outflux of water due to consumption of water, and outflux due to losses (for instance evaporation, infiltration, or poor distribution efficiency). See Figure 2.

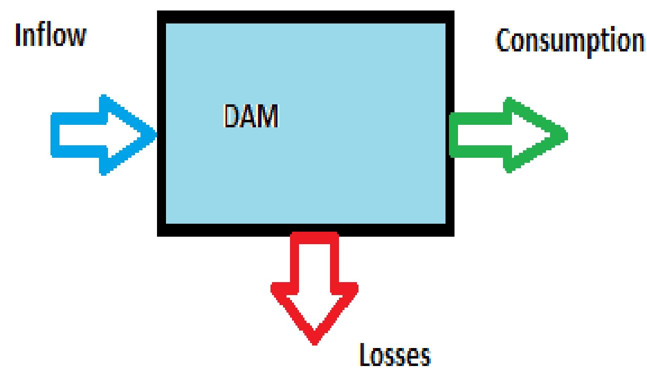

Fig. 2 Example for Vensim PLE methodology.

For us to model the water in the dam, we will consider the equation,

$$DAM = w_0 + \int_{ti}^{tf} inflow(t) - flowlosses(t) - consumptiontdt \quad (1)$$

where w_0 is the initial amount of water in volume, t_i and t_f are the initial and final times of the study, $inflow(t)$ is a function that has the influx of water in volume of water per unit time, $consumption(t)$ has the outflux of water in volume of water per unit time, and $flowlosses(t)$ has the outflux of water in volume of water per unit time that is lost. The way we model $inflow(t)$, $consumption(t)$, and $flowlosses(t)$ is another matter, that we will explain below. Vensim PLE, allows us to do this very easily. It is a software that uses pictorial language, easy to read, and that latter on we associate the semantics, with a set of rules.

Just looking at Figure 2, it is easy to see that the dam keeps the same amount of water if the sum of the outflow with losses is the same as the inflow. The level of water in the dam will change otherwise. Let us consider the following scenario. Our dam is described as in equation (1), where we consider for the inflow flux the rain, that is,

$$inflow(t) = rain(t) \quad (2)$$

Note that inflow is a flux of water going inside the dam over time. Its physical units are (volume/time). We have two outflows. One due to losses of water over time which we define as,

$$outflow1(t) = losses(t) \quad (3)$$

and the other, we could say is the consumption of water over time, given by,

$$outflow2(t) = consumption(t) \quad (4)$$

The way we define equations (1) to (4) will result in the amount of available water in the dam. Using Vensim PLE, we define a flux or rate with the symbol represented in Figure 3.

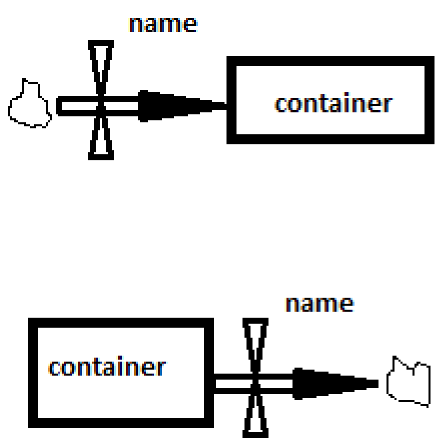

Fig. 3 Representation of inflow from a container and outflow to a container.

Variables are very easily graphically introduced using the ruler Vensim PLE offers. Then you give it a name and by pressing the $y = x^2$ button on the ruler you may define how the variable varies. These variables are either container variables or auxiliary variable that you can also easily find in the ruler. Time is as an internally defined variable.
Vensim PLE also offers a help/manual option with all its main features properly defined just by pushing the help button.

In Figure 4 you can see the first example as we implemented using Vensim PLE. Note that container variables (dam) are rectangles, fluxes are the “weird” arrows as we see in Figure 3 (inflow, outflow, and losses), and auxiliary variables appear as names (rain). You also have arrows that indicate the interdependency of the variables present in the model.

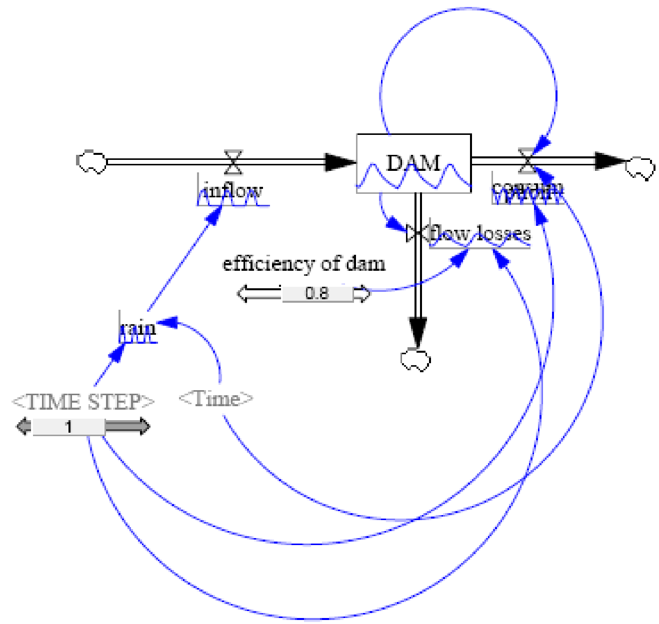

Fig. 4 Vensim implementation of the considered example.

Still in Figure 4, you can see small graphs over the variables. This happens when you launch a simulation in Vensim PLE. However in order to see the graphs properly, you should click with the mouse over the variable you wish to see the graph and then click over the graphs button that appear in the left ruler of Vensim PLE. In this case we modeled rain as,

$$rain(t) = \max\left(0{,}750 \sin \frac{2\pi t}{12T_s}\right) \quad (5)$$

where T_s is the time step. It values 1 *Month*. We have to include this, so that $rain(t)$ has units *water/Month*. This means that we are trying to simulate the rain over the period of a year, with 6 months of rain and 6 months of drought. This is obviously unrealistic. However, rain could also be read from a file. Provided we have good data, the model with respect to rain could work better.

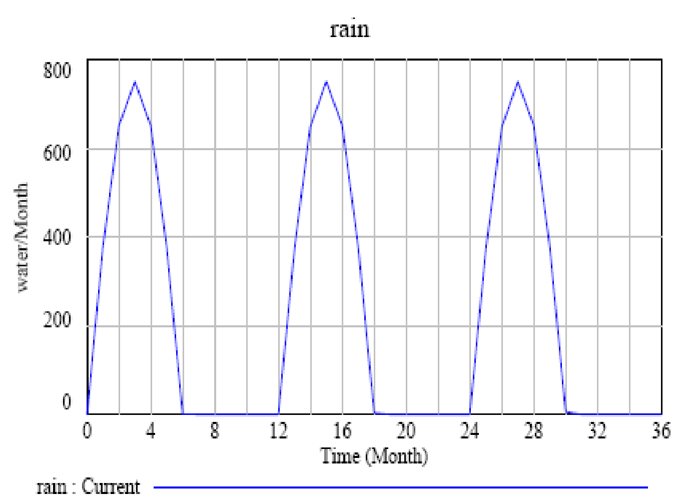

Fig. 5 Rain over time.

The variable inflow was simply equal to rain. Regarding the initial amount of water in the dam we considered $w_o = 0.507$.

In order to define DAM, we still need to define the efficiency of dam which will influence the result in flow losses and the also the outflow. The way to measure efficiency in water management is a difficult issue. It depends from sector to sector, and, for instance in agriculture, you have the classic way to deal with it given by [17] where efficiency is defined as useful water used by the plant over water used and a more robust way where you consider that there is water you use that is not useful to the plant itself but is not lost since it goes back to the river downstream defended by for instance in [18][19]. However, in the present context, all that matters is to attribute a value for the efficiency. We defined as a constant with the value 0.8. Note that this value can be easily altered just by moving the bar to left (decrease efficiency) or right (increase efficiency) when you run your simulation. You should check if units are correct and if the model is feasible mathematically. This is done by choosing *Model* in the ruler of Vensim PLE, and then choose *Units Check* and *Check Model*. If all is fine then you may run your simulation, which will work fine, provided the model is realistic. Coming back to our model, let us just describe what equation we included in order to define the flow losses. Once again we used an *if then else structure*. That is, if there is water in the dam, a certain amount of it is lost. This could be due to evaporation, infiltration or other phenomena. In this case we considered it to be 20% of the amount of water in the dam at that moment. To model the consumption, once again we used an *if then else* structure. If there is water in the dam, we will assume consumption as a function of a cosine. Otherwise the consumption is zero. In the case the dam is not empty we considered,

$$consumption(t) = 35 \,|\cos \frac{2\pi t}{12T_s}| \qquad (6)$$

This expression has no real physical meaning. As said before, we may use real data read from a file and this way, the results would probably make more sense. Anyway, for this model the results obtained in the dam along time are presented in Figure 6.

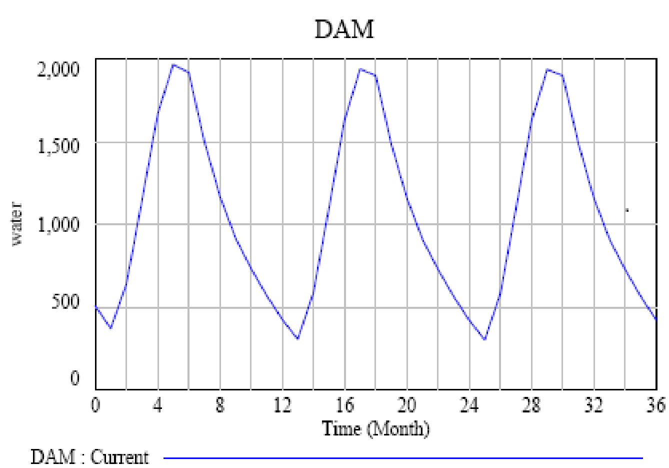

Fig. 6 Water in DAM over time.

From Figures 5, 6, 7 and 8, it is easily seen that the model certainly is very unrealistic. This is due to the data we feed it and other features not included. Still, since Vensim PLE gives the possibility to build and speedily execute such models, we think it is a good tool to simulate scenarios in the context of water management.

We are able to conclude the model works fine accordingly to what we intended. However, being an academic model it hardly has anything to do with reality in any place we know. That is easily seen in the simple fact that we allow the consumption to be zero, or to have 6 months of rain followed by 6 months without any rain in a year.

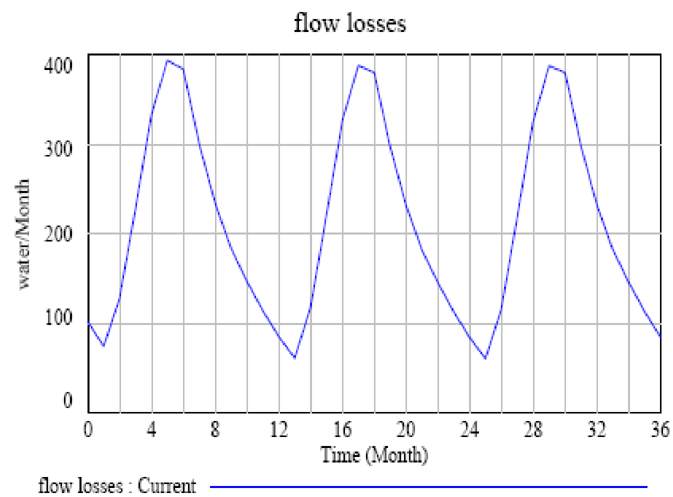

Fig.7 Flow losses over time.

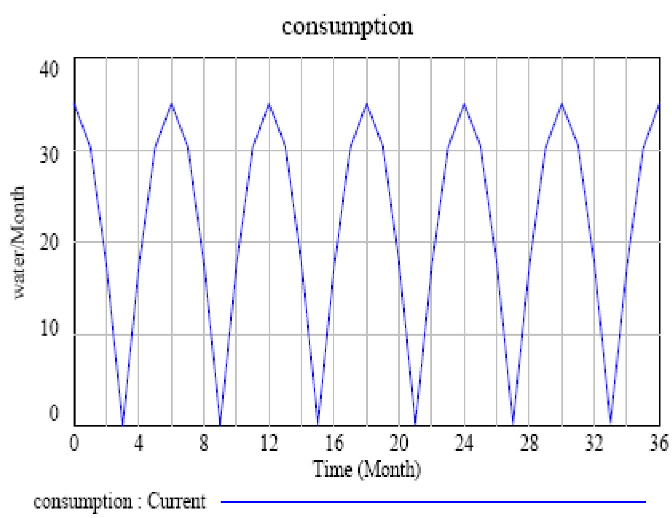

Fig 8 Consumption over time.

C. *Example 2*

The area of study will be centered in a vicinity of a small urban area, where we assume so far that agriculture takes no place in here, and that industry is included in the Urban area block. In Figure 9, we represent the container variables, which are the dam (*DAM*), the treatment station before water distribution in the city (*TWS*), and the cleaning water station that will return the consumable water back to the river (*CSW*).

We will also define as a container the urban area (*CITY*) to simplify our model.
The main flows are rain, losses in the dam (losses dam), river flow, entry treatment water station (*entryTWS*), inflow in the city (*consumption*), losses in the TWS (*lossesTWS*), losses in the city (*lossescity*), entry in the cleaning water station (*entryCWS*), losses in the cleaning water station (*lossesCWS*), recovered water, and the mouth of the river.
The mathematical models and its implementation is similar to the previous one. This was a purely academic exercise. We did not use any real data to simulate any of the fluxes. This could be done provided we have statistically significant data files that could be imported to Vensim PLE. Anyway the point is to show that these models can be constructed easily with a powerful tool like Vensim PLE, plus some ingenuity, good and enough credible data.
Without giving detail you can see in the next figure how the pictorial implementation of this model in Vensim PLE looks like.

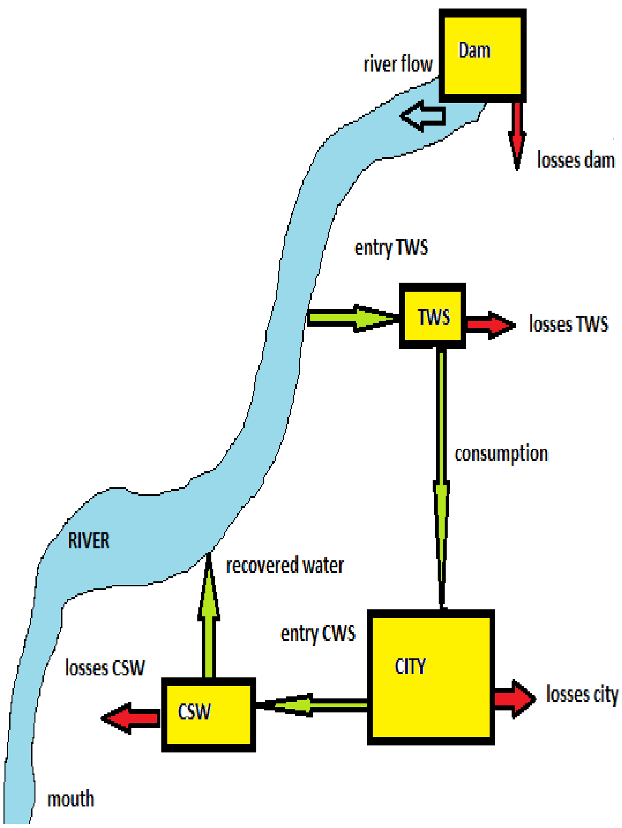

Fig. 9 Schematic representation of example 2.

We will not explain all the variables, or formulas used in here, as it would be tedious, but, for this implementation we intend to show it makes sense mathematically speaking. We will show some results obtained for variable containers, as well as *rain*, *losses of dam*, *entry TWS*, *river flow*, *recovered water*, and *mouth of the river*.
So in the conditions we considered the amount of water in the dam defined pretty much as in the same example, but here our simulation took 100 TIME STEPS, in this case, this means 100 months.

The dam receives water from the rain. We defined rain as *an if then else* function similar to the one defined in equations (5) and (6).

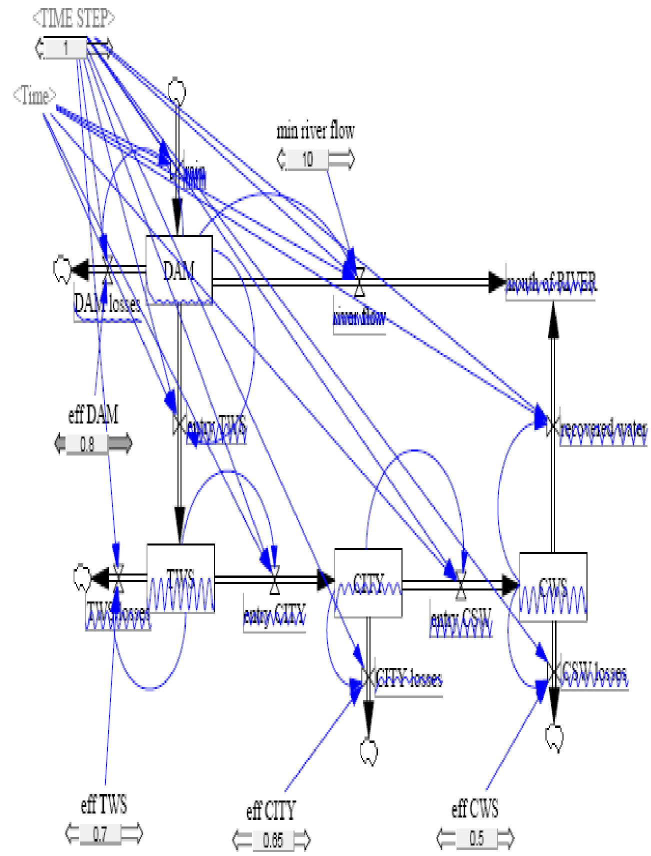

Fig. 10 Vensim implementation for example 2.

In this model, we considered,

$$rain(t) = 150\left|\sin\frac{\pi t}{12T_s}\right| \quad (7)$$

where T_s is the TIME STEP. In order to define *entryTWS* which represents the amount of water received by the treating water station upstream of the CITY, we have,

$$entryTWS(t) = 100\left|\sin\frac{\pi t}{12T_s}\right| \quad (8)$$

The losses in the DAM were defined via the efficiency of the DAM, the same way as in the first example. The water that is not captured for the *TWS* or is lost, continues to the river. In this case we considered,

$$riverflow(t) = \min\ river\ flow + 10\left|sin\frac{\pi t}{12T_s}\right| \quad (9)$$

Finally, the water balance is achieved via the definition of water in the dam,

$$DAM = w_0 + \int_{ti}^{tf} rain(t) - flowlosses(t) - entryTWS(t) - riverflow(t)\, dt \quad (10)$$

The reasoning of the model is very similar to treat all the other container variables. We define an efficiency of the container, the losses are dependent on that efficiency (just as we defined in the first example), we then define a function of time both for the inflow variables and for the outflow variables, and finally, we impose the water balance in the container variable.

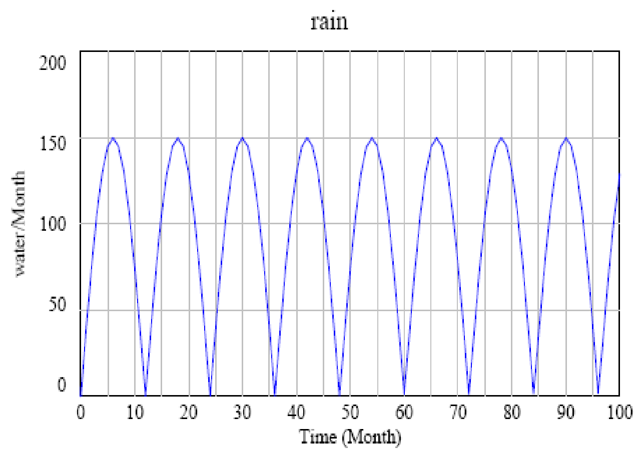

Fig. 11 Rain over time for second example.

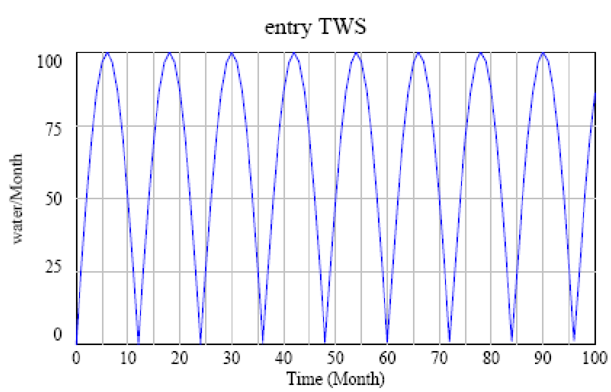

Fig. 12 Entry in the treating water station over time.

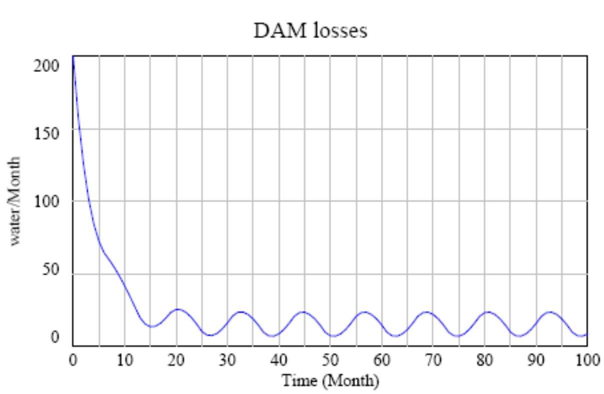

Fig. 13 Dam losses over time.

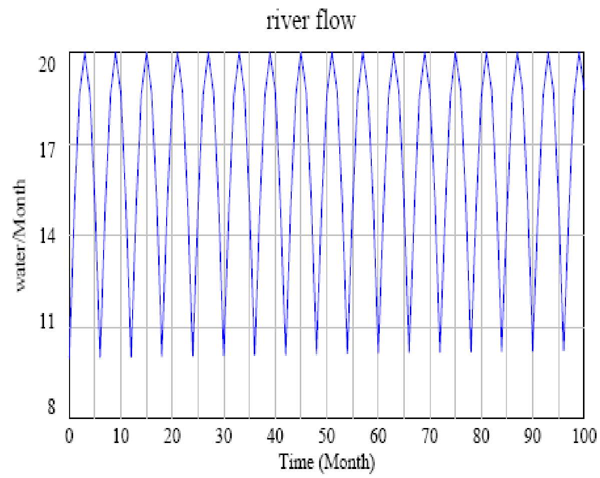

Fig. 14 River flow over time.

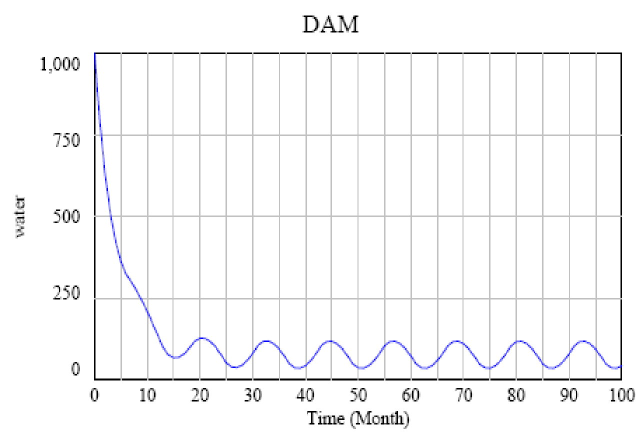

Fig. 15 Water in the Dam over time for second example.

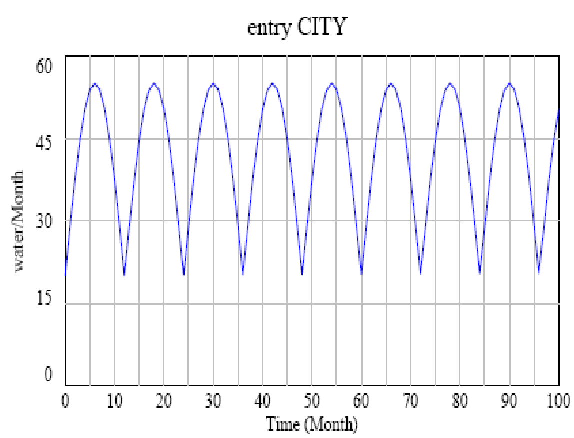

Fig. 16 Water entering the city over time.

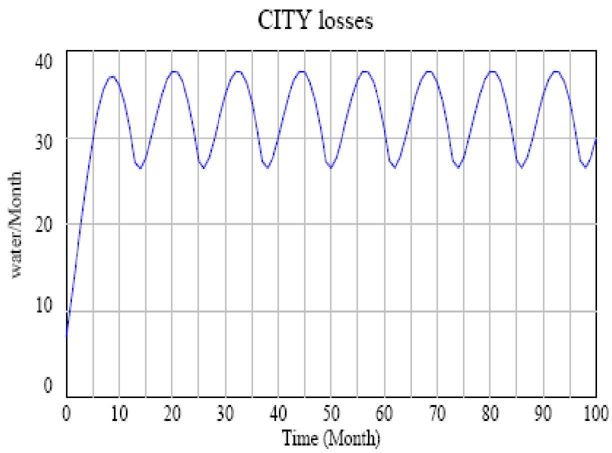

Fig. 17 Water losses in the city over time.

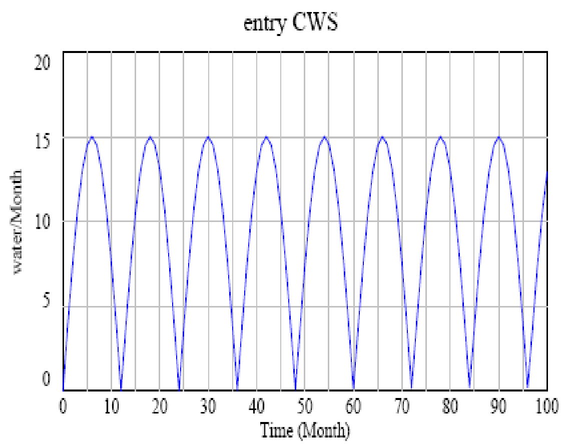

Fig. 18 Water entering CWS over time.

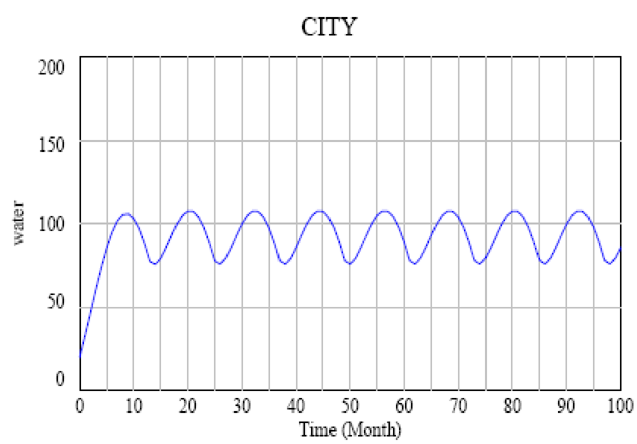

Fig. 19 Water in the city over time.

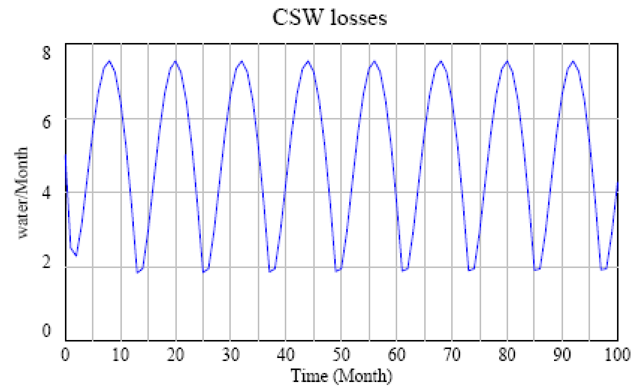

Fig. 20 CSW losses over time.

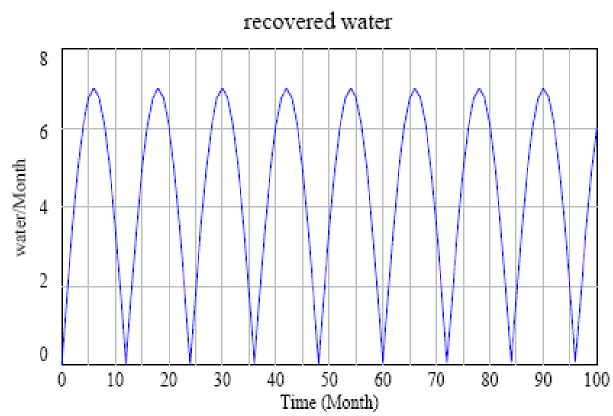

Fig. 21 Recovered water by CSW over time.

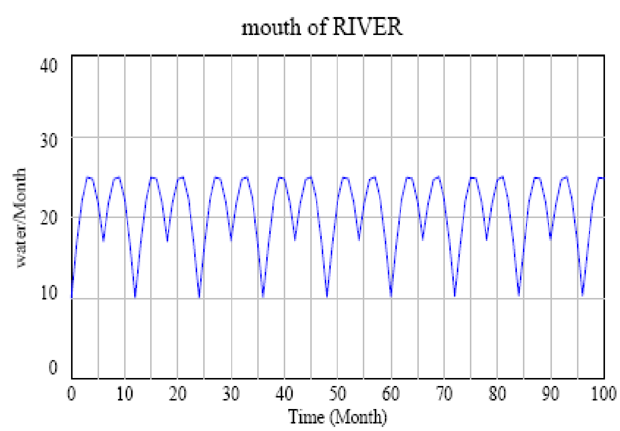

Fig. 22 Water at the mouth of the river over time.

III. CONCLUSION

The first conclusion we take is that the philosophy that Vensim PLE follows to build up models of simulation is very interesting and simple. For one it has 3 main entities - container variables, auxiliary variables and fluxes.

Second since it is a pictorial based language, it is quite easy to follow models. The details are hidden when you define these entities represented in a figure.

Some variables that we defined here using a mathematical formulas, like rain or consumption can be defined via real data read from files. We still did not use real data because our aim was to prove we are able to build up mathematical models with some complexity just by using Vensim PLE. This is a freeware software for students.

A lot of work has to be done to make all of this presented here a useful tool. The work will be focused on how to implement a more reasonable mathematical model to perform water management, and on choosing a location where we have enough available data.

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