

# **A RELATIONSHIP BETWEEN HYDROLOGY AND ECOLOGICAL ECONOMICS TO LONG TERM WATER SUPPLY AND DEMAND IN A WATERSHED**

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## **ABSTRACT**

This job shows a daily tank model that simulates the hydrological cycle in a watershed. An economic component is coupled to tank model for water valuation in the different variables of the hydrological cycle. In this case the exercise is done for groundwater and subsurface components. Each component is evaluated for both water storage and flow. Also this job includes the concept of rescaled adjusted range (RAR). This concept permits to compute the water regulation capacity through a reservoir which can deliver an output flow equals to the multi-annual average flow without incurring a deficit. RAR helps to value the three different components of simulated streamflows in a watershed: Groundwater flow, subsurface flow and direct-runoff flow. The water pricing model permits to obtain the resource demand curve and elasticity for allocation or demand management.

Keywords: Hydro-economic model, water market, water allocation, water valuation.

## **1. Introduction**

Water in a basin can be used as a source for drinking water, recreation, irrigation, electric energy, etc. Also, the water bodies can have the environmental function of receiving the sewage water. In both cases the water surface water and groundwater can be affected potentially. Water is transformed to a commercial use and the impact of economic use in the water availability and quantity has implications in the short and long term. This job focuses on establishing a hydro-economic model to assessment of water resource through the flow and storage variables of the hydrological cycle in a watershed. According to Browner and Höfke (2007), hydro-economic models can be divided into two kinds of models the first is the modular, which allow the effective transference of information from one module to another. These models operate independently. The second kind of models is based on a integrated holistic structure. In these models the exogenous variables of each module are solved through a system of equations. In general two important aspects of integrated hydro-economic models are: the hydrological models use simulation techniques and economic models use optimization techniques. Hydrological models are applied to physical units, which are defined with hydrological criteria and economic models are applied to units defined by administrative boundaries. The time scales in hydrology are days, months, years and in economics are years. In addition, there is a third category of models called general equilibrium computational models. These take into account the linkages between economic sectors and are useful for evaluating water pricing policies.

In the last decade the tendency has been to migrate from an environmental economics to an ecological economics. This change has taken into account the use and depletion of natural resources in both cases renewable and nonrenewable. Environmental economics and ecological economics help to understand the man-environment-economy relationship to take economy towards sustainability (Venkatachalam. 2008). Environmental Economics applies the concepts and relationships of neoclassical economics while ecological economics has developed through a pluralistic point of view: The first approach brings analytical rigor and this analysis is taken into account to define government policies. The approach of ecological economics touches different areas with a very broad spectrum that requires an interdisciplinary effort. Some questions for environmental economics are not yet resolved and the same questions for ecological economics will be even a major challenge.

Eco-hydrology is one of the areas that Ecological Economy must touch and it is essential to assess water and both ecosystem goods and services (Zaleswki, 2000). This science allows us to understand that water is an element that regulates and is regulated by the ecosystem. Human activity has altered the dynamics and the regulation component of the hydrological cycle in which the biota plays a fundamental role. In a watershed the water cycle is the result of biogeochemical evolution. Therefore, the Eco-hydrology is the study of functional relationships between hydrology and biota in a catchment scale to achieve sustainable resource management. It is very important to maintain the homeostasis of the ecosystem for the balance of the biota. Any alteration of freshwater ecosystems implies: pollution and changes in nutrient cycling and water. One of the most effective

ways to control the dynamics of the biota is to regulate the hydrological cycle, for example, increasing water retention in the soil through reforestation.

Ecological economics (Daly and Farley, 2004) has a different point of view. In this case, the economic system is part of the global ecological system, which allows that small-scale systems can be sustained and at the same time the systems are part of the global system by Ecological Economics. Raw materials are generated and consumed in an economic system. This requires an energy supply system that transforms raw materials. It is the case of oil, which can be used in many production processes and in everyday life, but it generates waste products that become in the system outputs and these must be considered as a part of integral solution. In the Ecological Economics an ecosystem has functions and structures that generate services that are valuable to people. In general the main role of ecological economics is to avoid over-exploiting an ecosystem, i.e., whether the costs are greater than benefits, both ecosystem goods and functions do not allow the sustainability of it when the natural resources are used with the time. This can be seen in the curves of benefits and costs of a system when production is increasing the benefits outweigh the costs, but there is an equilibrium point from which the benefits do not grow faster than costs and the system shows a diminishing returns until the costs are not compensated by the benefits. When the system analyzed has an ecological character and it is represented in both goods and services connected with a cycle of growth, productivity and recovery or well-established cycles for nature, ecological economics adapts our economic system to physical and ecological constraints on planet Earth.

An ecosystem develops relationships between all goods and services. These goods and services change in space and time and make that ecosystems do not have a single response to pressure or demands on it. Ecological economics seeks to accomplish three things for an appropriate enjoyment of an ecosystem: ecological sustainability, equity in distribution and efficient use of resources. Water valuation is now considered an important instrument in the community that seeks new methodologies to regulate water and to achieve a sustainable resource use. Water valuation can help the efficient allocation of resources, but it is not enough. The user reactions to changes in water demand and the price structure of the resource must be understood. Studies have shown that when marginal costs of water are high this behavior gives to water a character of an inelastic good. This happens for consumptive uses, specifically (Massarutto, 2003).

The appropriate pricing of a natural resources require for an adequate estimation of discount rate which permits the resource allocation within the parameters of optimality and sustainability and in this way takes into account the money value in time. The natural resources valuation and financial assets are subject to risk inherent in the markets. At present there are no developed water markets, but the environmental authorities can think that in the future. One of the challenges will be to have a regulated market system for allocation and water use in the future. When a resource becomes scarce this gains value. Because of water variability in space and time and having the climate change in mind, the price of water will be highly volatile. This will imply a risk hedging, i.e., negotiate the water price and that utility firms or large users can hedge against extreme hydrological events (La Niña or El Niño phenomena). Financial derivatives permits risk hedging in financial markets and natural resources would not be the exception (Kunsch, Ruttiens and Chevalier, 2006). The problem of water valuation is not trivial and government institutions to national or local level require methodologies and strategies to conserve resources and generate the wealth that society needs to preserve the balance in an ecosystem.

## 2. Methods

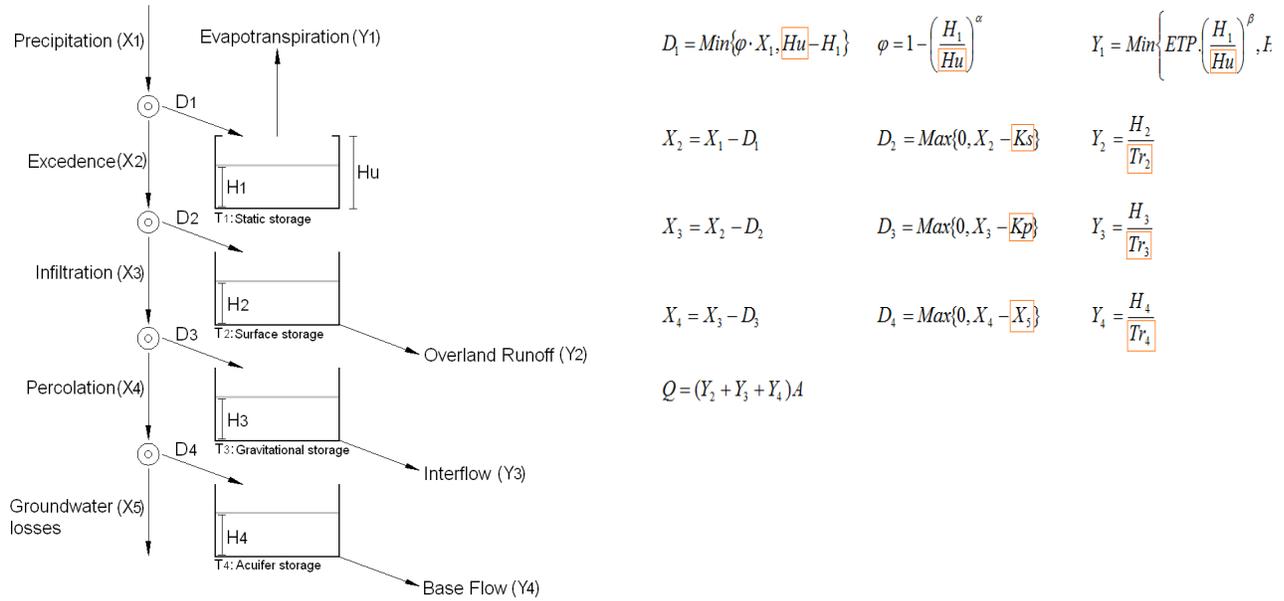
In this job we used a hydrological model and an economic model. The hydrological model is conceptual and it represents the hydrological cycle by accumulation and water flow between tanks. The physical processes of the hydrological cycle modeled and that the tank model works are: infiltration, direct water runoff, water storage in the unsaturated zone, sub-surface flow, water storage in the saturated zone, groundwater flow. The economic model assigns the water price taking a reference price and computes the water value in each component of the tank model along of time period required. In the next section both the hydrological and economic model are explained and how they are connected. Also what both economic calculations and analysis are possible to do by the hydro-economic model.

### 2.1 Daily tank model

The production of runoff is based on the simulation of the water balance in the basin, assuming that water is distributed in four levels of storage tanks which are interconnected (Vélez, 2001). At each time interval,

precipitation  $X_1$ , is distributed to the different tanks. This distribution depends on the volume stored in each one  $H_i$ . In turn, the storage levels determine its contribution to runoff  $Y_i$ . The model performs water balance in each tank.

The amount of water that results in each node  $D_i$  and that continues to lower levels through the distributor pipe  $X_i$  depends on the amount of water available, the state of the storage tank and the ability of the distributor pipe downstream node. This hydraulic capacity is related with the hydraulic conductivity of the soil and sub layers. Figure 1 illustrates the distribution and equations.



(a) Conceptual scheme (b) Daily tank model equations  
Figure 1. Daily tank model, from (Vélez, 2001)

The model parameters are: maximum capillary storage ( $H_u$ ), unsaturated hydraulic conductivity ( $K_s$ ), percolation saturated conductivity ( $K_p$ ) and the residence times of tanks 2, 3 and 4 ( $Tr_2$ ,  $Tr_3$ ,  $Tr_4$ ). To calibrate the model to a watershed the six parameters are fitted by a manual technique. The model input is the precipitation field on a daily basis and the output is a simulated streamflows which is compared with the observed discharges at the drainage point that defines the watershed output. To evaluate the fitting we used Nash criteria (Nash and Sutcliffe, 1970; Perrin *et al.*, 2001), the balance error (BE) and the Root mean square error (RMSE).

$$RMSE = \left[ \frac{\sum_{t=1}^n (\mathcal{Q}_{t,sim} - \mathcal{Q}_{t,obs})^2}{n} \right]^{1/2} \quad (1)$$

$$E1 = \text{Nash}(Q) = \left( 1 - \frac{\sum_{t=1}^T (\mathcal{Q}_{t,sim} - \mathcal{Q}_{t,obs})^2}{\sum_{t=1}^T (\mathcal{Q}_{t,obs} - \overline{\mathcal{Q}_{obs}})^2} \right) \quad (2)$$

$$E2 = \text{Nash}(\sqrt{Q}) = \left( 1 - \frac{\sum_{t=1}^T (\sqrt{\mathcal{Q}_{t,sim}} - \sqrt{\mathcal{Q}_{t,obs}})^2}{\sum_{t=1}^T (\sqrt{\mathcal{Q}_{t,obs}} - \sqrt{\overline{\mathcal{Q}_{obs}}})^2} \right) \quad (3)$$

$$BE = \frac{\overline{Q}_{sim} - \overline{Q}_{obs}}{\overline{Q}_{obs}} \quad (4)$$

Where:  $Q_{t,obs}$  and  $Q_{t,sim}$  are observed and simulated mean streamflow during month  $t$ , respectively.  $\overline{Q}_{obs}$  and  $\overline{Q}_{sim}$  are observed and simulated mean multiyear streamflow in the calibration period and  $T$  is the number of months of calibration period. The first criterion is based on the mean square error. The second criterion (E2) uses the square root of the discharges in order to minimize the amplifying effect of the square for high streamflow values. The third criterion refers to the long term water balance. The values of two first criteria are in the range  $[-\infty, 1]$ . The value of 1 means a perfect fitting between observed and simulated streamflow series. The third criterion is in the range  $[-\infty, \infty]$ . A value of 0 means a perfect long term water balance.

## 2.2 Economic model

The value of water must reflect the spatial and temporal variation of the resource. The value of water has different values and it depends on the use, place and moment in time. In this job, the water was assigned to different storages and flows of the hydrological model represented by the tanks and outputs. If we consider a system with  $n$  inputs,  $m$  outputs and a reservoir  $S$ . The input total value of water can be estimated from:

$$FVQ_{in,i}(t) = DVQ_{in,i}(t) + IVQ_{in,i}(t) \quad (5)$$

In equation 5,  $FVQ$  is the total value of input flow,  $DVQ$  is the direct value of input flow and  $IVQ$  is the indirect value of input flow according to the input  $i$  at time  $t$ . In the system the input flow has an indirect value if it contributes to the direct value of the output. Seyam et al (2002 and 2003) shows three models to estimate the value of water based on whether the system has delays and/or multiple inputs and outputs. In this case a delay is equivalent to having a reservoir. For the hydrological model the four storage tanks are considered reservoirs and therefore they represent delays of the flow. One of the Seyam's model is to consider  $n$  inputs,  $m$  outputs and one delay and it is coupled to the economic model. Whose name is A dynamic model based on hydrological properties.

The indirect value of an input can be considered as the product of the inflow and the unit value of water in the reservoir,

$$FVQ_{in,i}(t) = DVQ_{in,i}(t) + \frac{FVS(t)}{S(t)} Q_{in,i}(t) \quad (6)$$

In equation 6,  $FVS(t)$  is the full value of storage in the time  $t$  and  $S(t)$  is the storage. In this case the unit value of the input flow and water in the reservoir are considered equal. The  $DVD$  is considered in this case zero. To compute the  $FVS$  in the storages and  $FVQ$  before and after storages use the following expressions.

$$FVQ_{out}(t) = UVQ_{out}(t) * Q_{out}(t) \quad (7)$$

$$UVQ_{in}(t) = \frac{FSQ_{out}(t)}{Q_{in}(t)} \quad (8)$$

$$FVS(t) = UVQ_{in}(t) * S(t) \quad (9)$$

$$FVQ_{in}(t) = FVS(t) * \frac{Q_{in}(t)}{S(t)} \quad (10)$$

The above equations help to estimate the total value of water before, after and in the tanks.  $UVQ_{out}(t)$  is considered as an input value and this reflects the value of water in its best alternative use, for example, irrigation, drinking water, power generation, etc. The calculation sense of the water value is backward in comparison with sense of the hydrological cycle.

## 2.3 Long-term storage capacity in reservoirs

Hurst (1951) was interested in studying the storage capacity of reservoirs in the long term to regulate the flow of the Nile River in the Victoria and Alberta Lakes (Poveda, 1988). The objective was to determine the regulatory capacity or volume of a reservoir to meet a demand equals to annual mean discharge without deficits during the time length considered and safe economically. The procedure is as follows: consider a series of volumes of inflows entering a reservoir  $X(t)$ ,  $t = 1, 2, \dots, n$ . The net inflows are adjusted for a percentage  $\alpha$  of the annual mean discharge, which can be interpreted as the level of regulation of the reservoir. The cumulative sum of adjusted inputs  $S^*(t)$  is computed with the following expression:

$$S^*(t) = S^*(t-1) + (X(t) - \alpha \bar{X}_n), \text{ para } t = 1, \dots, n \quad (11)$$

Where:  $\bar{X}_n$  is the mean value of the input flows, equations 11 and 12 are the same if  $\alpha=1$ .

$$S^*(t) = \sum_{i=1}^t X(i) - \frac{t}{n} \sum_{i=1}^n X(i) \quad (12)$$

Expressions 9 and 10 represent the mass curve with the changes proposed by Hurst. In the previous series determines the maximum and minimum,  $M_n^*$  and  $m_n^*$ , respectively. Then the adjusted range is defined as  $R_n^* = M_n^* - m_n^*$ . The adjusted range can be interpreted as the minimum value that may have an ideal reservoir for:

- To regulate the annual mean discharge without deficits.
- During reservoir operation have no flows by spillway.
- The final volume stored at the end of  $n$  periods and the start volume at the period  $n=1$  are the same.

From adjusted range is possible to define the rescaled adjusted range (RAR),  $R_n^{**}$ :

$$R_n^{**} = \frac{R_n^*}{d_n} \quad (13)$$

Where:  $d_n$  is the estimated value of standard deviation,  $\sigma_n$ , of net inflows,  $X_t$ .

RAR is important because the water supply of watershed is represented by this reservoir and the demand equal to annual mean discharge is the maximum flow that can be met in the long term. This ensures that the demand is met with 100% reliability. Therefore this is the maximum demand that permits to have a use of water in a sustainable way in the long term.

Tank model decomposes the flow in three components, groundwater flow, subsurface flow and direct-runoff flow. RAR is computed to each component. According to regulation capacity of each component, groundwater flow RAR is greater than two other components and therefore the contribution to regulate the total flow is higher. This condition is important to estimate the water value of each component and assign a higher value to the component of groundwater flow.

## 2.4 Water demand function in a watershed

From Hydro-economic model can estimate the water demand curve in the period of time analyzed. Tank model permits to obtain the groundwater, subsurface and direct-runoff flows and their respective economic values. Also this model estimates the water value in the different storages (Figure 1), groundwater storage (tank 4), gravitational water in the unsaturated zone (tanks 2 and 3) and static storage (tank 1). And finally you can estimate the economic value for precipitation and evapo-transpiration.

Ecological economics uses the same concepts of classical economics applied to natural resources renewable and non renewable with criterion of sustainability, equity and efficiency in the long term. The great difficulty in assessing the water lies in the lack of markets in which the supply and demand price can be set by market conditions. The physical transportation between both sources and demand sites do not make possible to develop a water market, on the contrary this is not the case of electric power. Establish the supply and demand curves are not a trivial case when there is no base market. The concepts of production and utility functions depend on the spatial and time of nature. The production function of water in a watershed depends on the

precipitation cycle (droughts, normal periods and floods), soil cover, soil type and structure, as well as physical parameters of the watershed such as basin slope, drainage, etc. This is not a trivial function for all possible consideration in a watershed. The factors that primarily determine the production of water in a basin are rainfall and storage capacity of the basin. The utility function reflects the satisfaction or utility that a good or service produces, in this case would be water. There is no doubt about the importance of water to the cycle of human life and the planet. The welfare level that water generates is subject to spatial and temporal variability too. The welfare is different in the summer or drought months than flood months. The welfare function depends on the human beings and their needs (drinking water, recreation, power generation, irrigation, recreation, landscape, fishery) meanwhile the production function depends on watershed natural conditions. These conditions can be changed by the user trends of water and the climate change. The hydrological cycle would be affected and in consequence the production function will change too. Therefore the hydrological cycle shows a high dynamics with strong feedbacks.

As an approximation this job establish a relationship between the hydrological tank model and the economy in the long term, if we consider that there is a reservoir that meets a demand equals to the annual mean discharge. In hydrology the regulation of a river is never higher than the annual mean flow. The other part considers that the hydro-economic model can generate the information necessary to obtain the water demand curve in the basin and the elasticity of the resource.

The model permits to obtain the resource price-supply series in each flow and tank, axe  $X$  (mm/day) for the flows in the watershed, axe  $Y$  (\$ USD/day) is the value assigned by the economic model. In this case the demand curve is determined for both groundwater and sub-surface flows. These two flows are very important for the water production and they reflect the regulation capacity in the watershed by physical processes that explain hydrological cycle. From the price-supply curve of water can set the resource demand curve, axe  $X$  (mm/day) and axe  $Y$  (\$ USD/mm) and also the elasticity of the resource is estimated for the entire range of variation in the water supply. Also the exercise is made for gravitational and groundwater storages (tanks 3 and 4).

### 3. Findings and discussion

Results are presented following the methodology in the previous section. The hydro-economic model was applied in the Las Palmas watershed. It is located near Medellin city, in the northwest part of Colombia. This watershed has an area of 27.33 km<sup>2</sup> and a daily precipitation and discharge record from 28/03/2003 to 31/12/2005. The annual mean discharge is 3.06 mm/day. In this case the discharge series (m<sup>3</sup>/s) was scaled by watershed area (m<sup>2</sup>) and the discharge were converted to mm/day. This watershed can be considered natural or without human intervention.

#### 3.1 Daily tank model

Tables 1 and 2 show the calibration parameters of the tank model and the performance errors, expressions 1, 2, 3, and 4.

Table 1. Calibration parameters of the tank model, Las Palmas watershed

Parameters	Value
Maximum capillary storage	160 mm
Hydraulic conductivity $K_s$	25 mm/day
Percolation hydraulic conductivity $K_p$	4 mm/day
Residence time $Tr_1$	2 days
Residence time $Tr_2$	4 days
Residence time $Tr_3$	30 days

No water groundwater importation and exportation is considered in the tank model. The start values in each tank are: capillary storage 100 mm (tank 1), sub-surface flow 1 mm (tank 2), gravitational water storage 4 mm (tank 3) and groundwater storage 50 mm (tank 4).

Table 2. Performance errors of tank model calibration, Las Palmas watershed

Error	Valor
RMSE(mm/día)	1.68
Balance (%)	1
Nash01 (%)	68
Nash02 (%)	83

Figure 3 shows the observed discharges and the simulated discharges by the tank model for the time period analyzed. Rainfall-runoff has a good performance to simulate minimum and mean flows. The physical dynamics to model maximum flows are not adequately represented in these models because of high variability of rainfall in the time and space and the rainfall that causes these peaks has short duration. This is a typical behavior from the tropical Andes zone. According to the results of the calibration, this is considered good and the tank model represents properly the water cycle in the watershed. Figure 4 shows the three components of flow and Figure 5 shows the evolution of storage in the groundwater tank (tank 4) and gravitational water tank (tank 3).

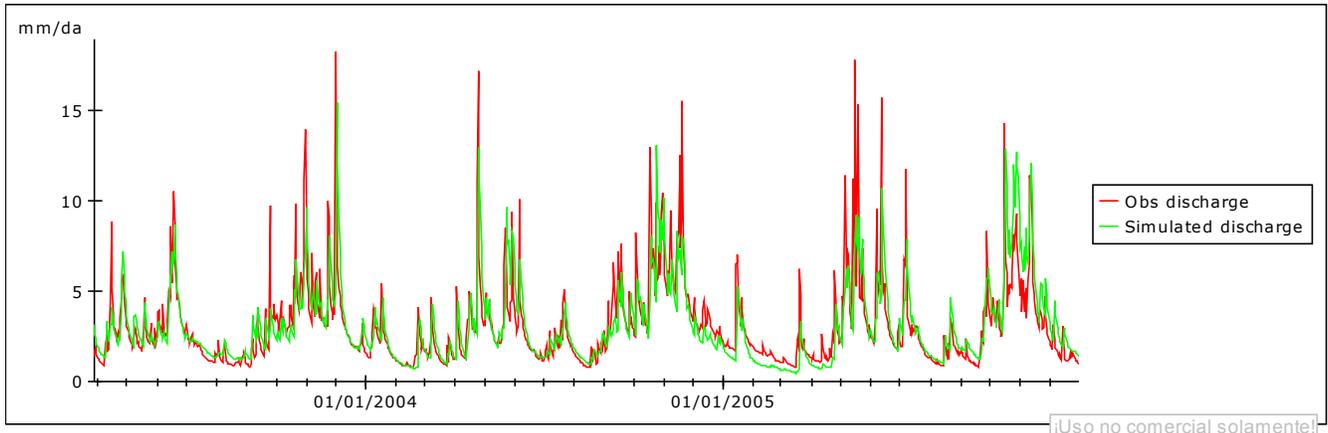


Figure 3. Observed discharges and simulated discharges in the tank model

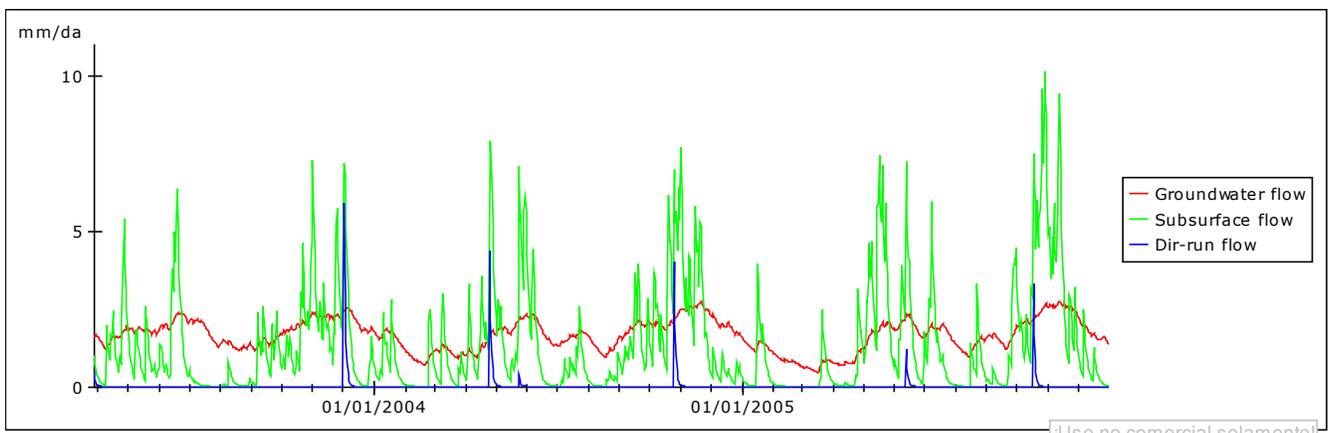


Figure 4. Simulated flow components: Groundwater flow, sub-surface flow and run-off direct flow

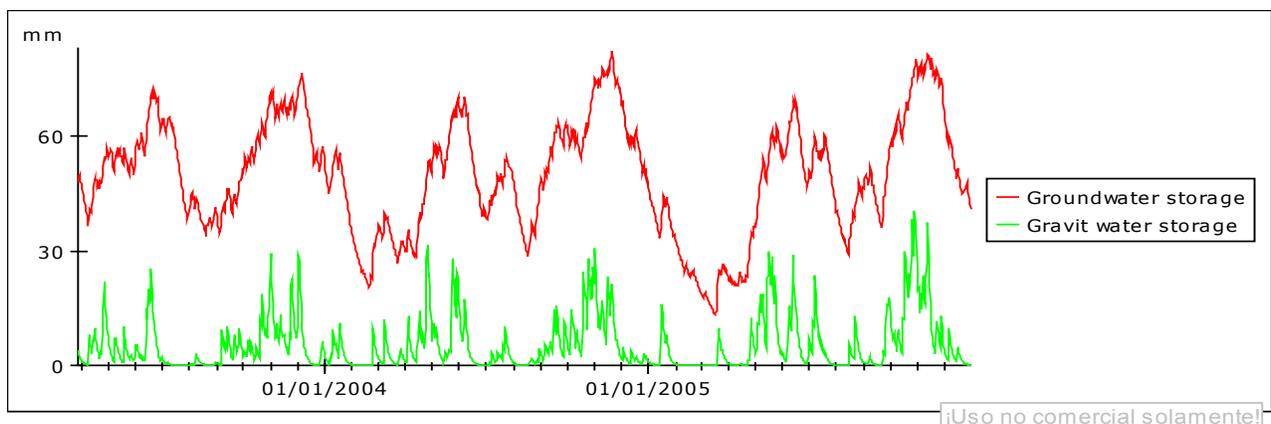


Figure 5. Evolution of groundwater and gravitational water storages in the tank model

### 3.2 Economic model for water valuation

Once the tank model has been calibrated in the study watershed the following step is estimating the value of water in different components of the tank model and taking into account the assumptions presented in section 2. It must calculate the rescaled adjusted range of simulated streamflows to estimate the volume of the fictitious reservoir that should permit to meet a demand equals to the annual mean discharge without deficit. RAR for observed discharge is 238.86 mm. The reservoir demand is equal to 3.06 mm/day which corresponds to the annual mean discharge. Figure 6 shows the storage evolution in the reservoir and Figure 7 show the simulated streamflows and the monthly deliveries for the time period analyzed.

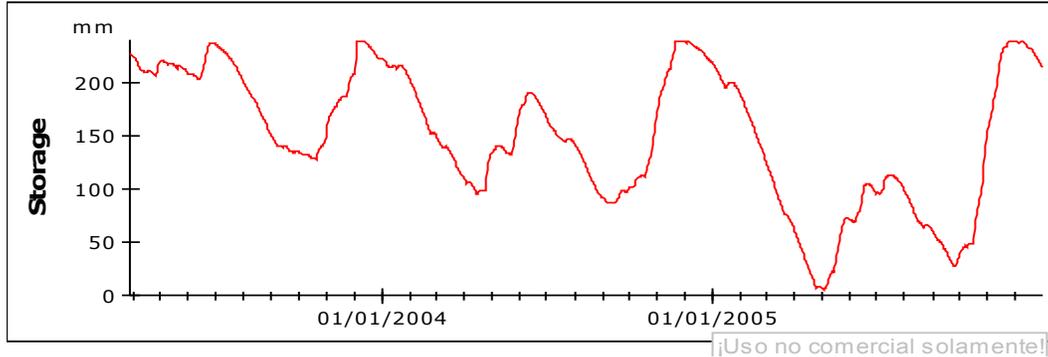


Figure 6. Evolution of fictitious reservoir

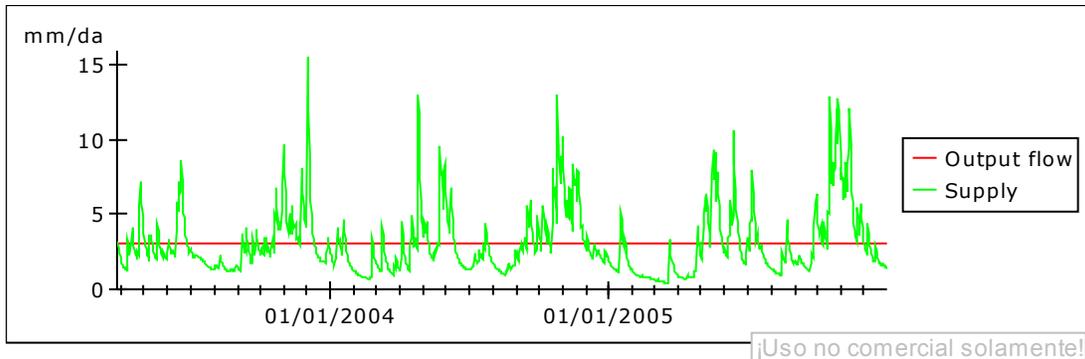


Figure 7. Monthly input streamflows and monthly deliveries in the reservoir,  $S_{max} = 238,86 \text{ mm}$ .

To apply the economic model requires a final value of water at the watershed output point. This is considered as the equivalent value of water consumed by a population of 278790 inhabitants with a per-capita consumption of 300 liters/inhabitant-day and a water unit value of 1 USD/mm. Therefore the value of water for population is of 27330 \$ USD/mm. Figure 8 shows the value of stored water in the time. Figure 9 shows the value of water on a daily basis for groundwater and subsurface flows, respectively. Figure 10 shows the value of water for underground storage (tank 4) and sub-surface storage (tank 3).

The output flow value is calculated according to expression 6. The value of water of groundwater flow, subsurface flow and direct runoff flow is proportional to the contribution to the simulated streamflows and to RAR of each flow component (equation 14).

$$FVQ_i(t) = \frac{R_{n,i}^{**}}{R_{n,Total}^{**}} * \frac{Q_{in,i}(t)}{Q_i(t)} \quad (14)$$

$$R_{n,Total}^{**} = R_{n,GW}^{**} + R_{n,subsurf}^{**} + R_{n,dir-runoff}^{**}$$

The  $R_n^{**}$  values of flow components are:  $R_{n,GW}^{**} = 197,97$ ;  $R_{n,subsurf}^{**} = 96,10$ ;  $R_{n,dir-runoff}^{**} = 42,65$ .

The value of stored water in the reservoir is obtained by the following expression:

$$FVS(t) = FVQ_{out}(t) - FVQ_{GWflow}(t) - FVQ_{Subsurf}(t) - FVQ_{dir-runoff}(t) \quad (15)$$

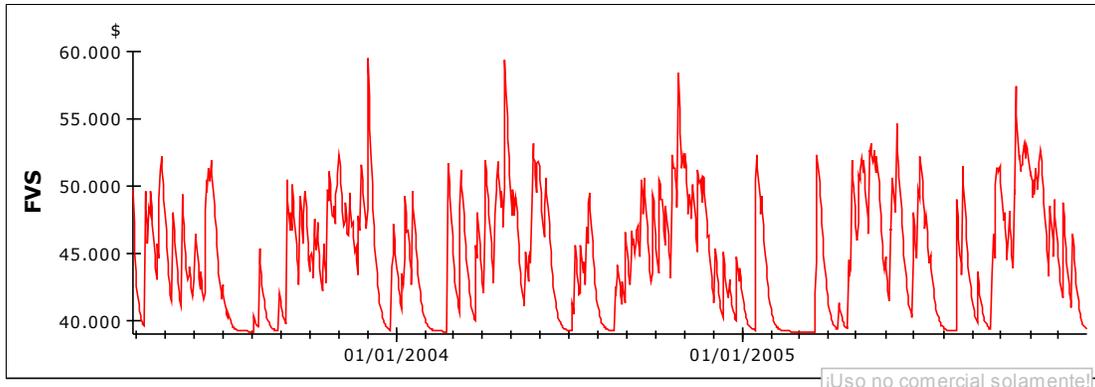


Figure 8. Value of stored water in the timer period analyzed

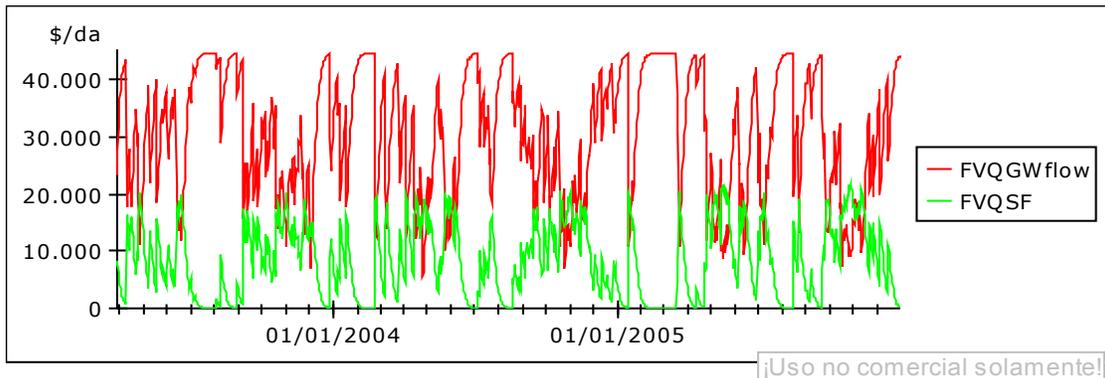


Figure 9. Daily values of groundwater and sub-surface flows in the time period analyzed

The value of stored water in the groundwater and gravitational water tanks is computed using expressions 5 to 9. Figures 10 and 11 show results for storage.

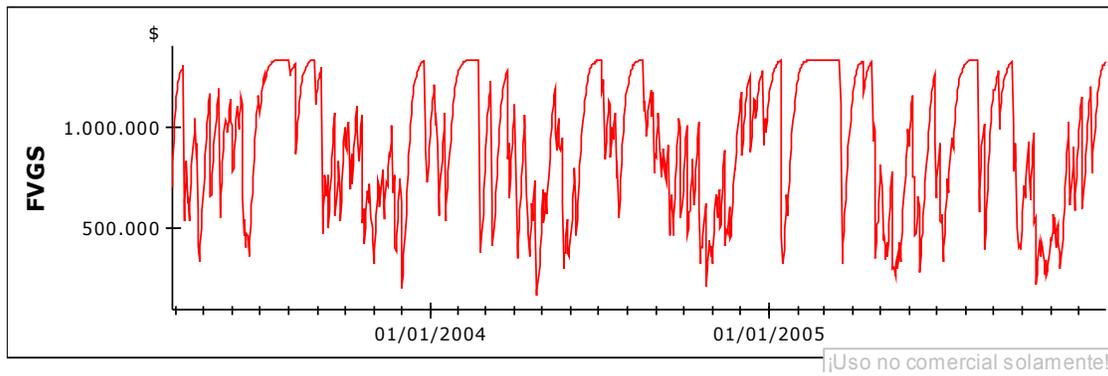


Figure 10. Daily water values of groundwater storage in the time period analyzed

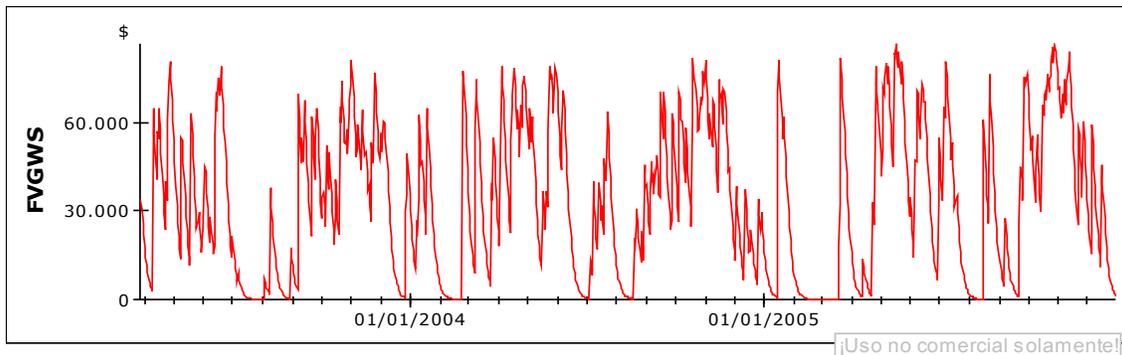


Figure 11 Daily water values of gravitational storage in the time period analyzed

### 3.3 Water demand curve and water elasticity in Las Palmas watershed

From the value series of water (Figures 8, 9, 10 and 11) estimate the water demand curves. The flow demand curves has in the axe X (mm/day), the water quantity and in the axe Y (\$ USD/mm), the water value. The groundwater and gravitational water flows series are ranked from lowest to highest flow value. These series are matched with the value series of water. The relationship between price and water supply is that highest prices correspond to lowest water supply and vice versa. The variability of flows and storages give variability to water prices, therefore the axe X values are computed in intervals of 0.5 mm/day of wide. The number of intervals is determined by difference between the highest and lowest value in each case. After that the demand elasticity computes according to expression 16.

$$Elasticity = \left| \frac{\frac{\Delta Q}{\bar{Q}}}{\frac{\Delta P}{\bar{P}}} \right| \quad (16)$$

Where:  $\Delta Q$  is the water supply interval,  $\bar{Q}$  is the class mark of interval,  $\Delta P$  is the water price interval and  $\bar{P}$  is the class mark of interval. Figures 12 to 15 show demand curves in each case.

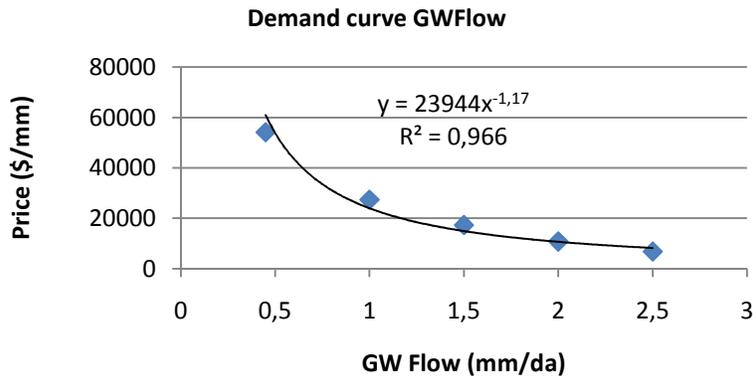


Figure 12. Demand curve for groundwater flow

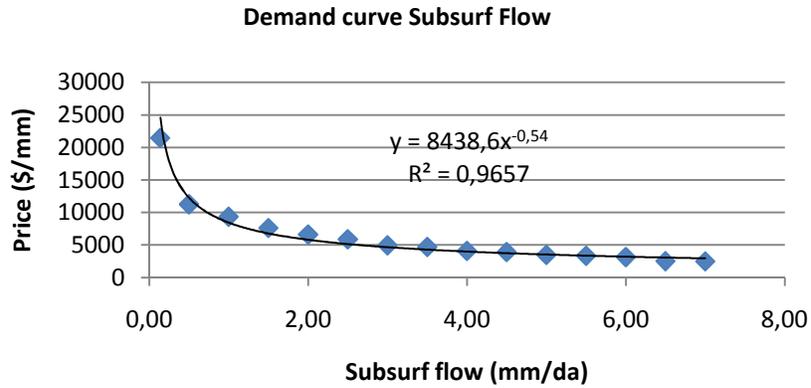


Figure 13. Demand curve for sub-surface flow

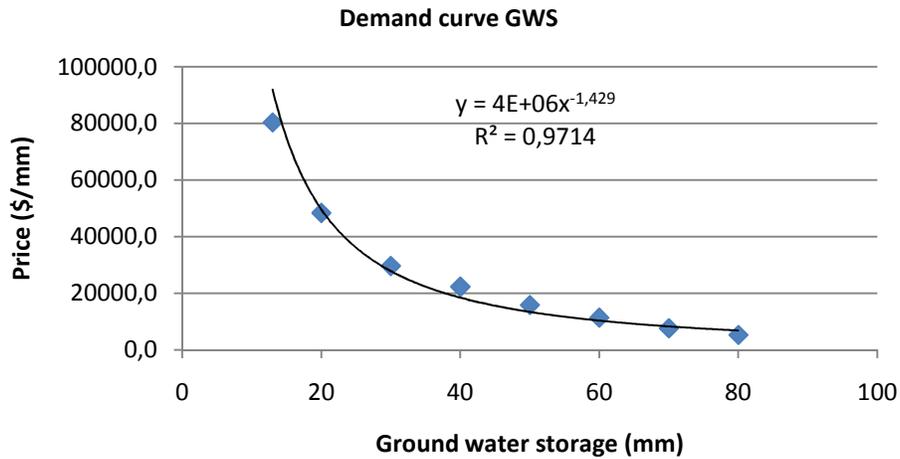


Figure 14. Demand curve for groundwater storage (tank 4)

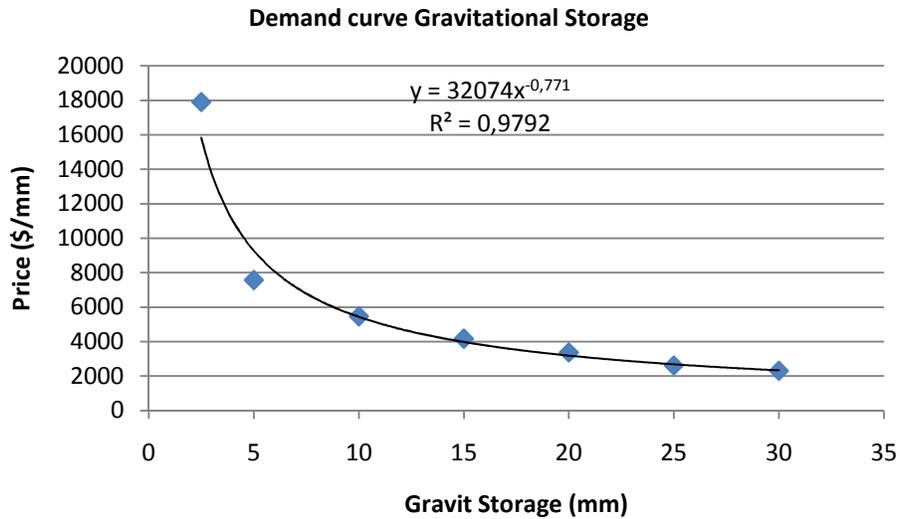


Figure 15. Demand curve for gravitational water storage (tank 3)

Table 3 shows the elasticity of demand curve for groundwater and sub-surface flows and Table 4 shows the elasticity of demand curve for the gravitational water and groundwater storages (tanks 3 y 4)

Table 3. Elasticity of demand curve (GW flow and Subsurf flow)

GW flow		Subsurf flow	
Q(mm/da)	Elasticity	Q(mm/da)	Elasticity
0,45	0,578	0,16	1,820
1,0	1,555	0,5	3,606
1,5	2,469	1,0	1,934
2,0	3,575	1,5	2,042
		2,0	1,894
		2,5	1,057
		3,0	2,994
		3,5	0,948
		4,0	2,603
		4,5	0,895
		5,0	2,367
		5,5	1,477
		6,0	0,351
		6,5	7,656

Table 4. Elasticity of demand curve for the Gravitational water and groundwater storages (tanks 3 y 4)

GW Storage		Grav Water Storage	
GWS(mm)	Elasticity	Grav WS(mm)	Elasticity
16,5	0,854	3,75	0,823
25	0,831	7,5	2,066
35	1,014	12,5	1,490
45	0,655	17,5	1,355
55	0,553	22,5	0,882
65	0,392	27,5	1,446
75	0,365		

In addition demand curve and elasticity for stored water in the fictitious reservoir is computed and the results are shown in Figure 16 and Table 5

Table 5 Elasticity of demand curve for stored water

S(mm)	Elasticity
42	0,303
50	1,384
100	1,260
150	0,982
200	1,172

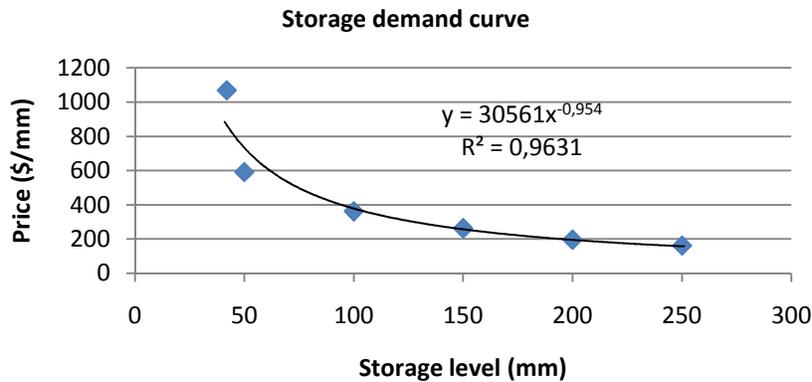


Figure 16. Demand curve for stored water at the watershed output point ( $S_{max} = 238,86$  mm)

### 3.4 Discussion

Tank model reproduces the observed discharges properly and the performance errors obtained are good for that kind of models and its application in the Andean zone. In this zone the hydrological regimen is strongly characterized by a bimodal behavior with two high steamflow periods, April-June and September-November and another two low streamflow periods, December to March and June to August. The rainfall-runoff models have shown their capacity modeling both low and mean streamflows. In contrast the high streamflows are not well simulated. The behavior of the precipitation that generates the maximum flows is very variable in space and time and this makes that physical processes are complex and highly nonlinear. Tank model reproduced in a good way storages and flows of water in the soil. Groundwater storage and flow show persistence, regulatory capacity and less variability, these are important characteristics of this resource and also these aspects give the most economic value to water in a watershed (see Figures 4 and 5). RAR of groundwater flow is 53% of the total RAR corresponding to three components of flow. The sub-surface flow is more variable than the other components and its RAR has a magnitude of 32%. This component has a lower capacity to regulate the water cycle in unsaturated zone and therefore it has less economic value. The direct-runoff component corresponds to flow peaks but it only occurs when there is excess runoff, which occurs in case of extreme events.

This job gives a methodology to link hydrologic modeling and the estimation of the value of water resources in the different variables that describe the water movement in the soil. The water drains into a basin is the product of land use, hydraulic properties of both water transportation and storage. The maximum flow that can regulate a reservoir is the annual mean discharge. RAR guaranties the minimum volume that ensures a steady discharge with 100% reliability (see Figures 6 and 7). The exercise can be done without reservoir, but in this case it was included as an additional element of analysis. Include this element links water supply and demand for a population of about 278,000 inhabitants and the reservoir volume of 238.86 mm meets always the demand with 100% reliability. Although that both observed precipitation and discharges have just 2,76 years of daily record, the assumption is that hydrology is repeated in a deterministic way for a long time period. In this case this assumption is representative of long term condition.

The economic valuation methodology allows for different components of the hydrological model to estimate the value of the resource. The value of water stored in the fictitious reservoir is the result of the assessment of water demand (final price) and assigning of this value to each one of flow components. Also from the prices series the demand curve is estimated in the fictitious reservoir (see Figure 16). The elasticity indicates that stored water for values less than 48 mm shows an inelastic good and it is elastic in the rest of the range from 48 to 238.86 mm.

The series of both groundwater and subsurface value have opposite values. The groundwater flow has higher economic value than subsurface flow, this is logical from the point of view of regulation and water storage in soil. Low groundwater flows are more valuable than the high or mean flows. Low subsurface flows are less valuable than high and mean flows. For the groundwater case this behavior is consistent with the basic theory of quantity-price of the resource and for sub-surface flows the behavior is the opposite. The water-price relationship for groundwater flows is determined by regulation capacity of groundwater tank (Tank 4). In the case of sub-surface flow the gravitational tank have no regulation therefore the water price depends on only of output magnitude. The elasticity of Groundwater flow shows that for values less than 0.76 mm/day, the resource is inelastic and

from 0.77 to 2.5 mm/day, it is elastic. The elasticity of subsurface flow indicates that this is an elastic good. Therefore there is a differentiation of water in the watershed and this is related with its source. Subsurface flow is an elastic good and groundwater is inelastic for recession or dry periods and it is elastic for both mean and excess flows.

Groundwater storage (tank 4) shows a higher economic value than gravitational storage (tank 3) because tank 4 or aquifer has a greater storage capacity. The tank 3 is the water stored in the soil unsaturated zone and this feeds the sub-surface flow, the storage capacity of this tank is much smaller than the tank 4. The resource value series of both groundwater and sub-surface storages reflect these hydrological characteristics. Table 4 shows the elasticity of water resource in both kinds of storage. Results show that the water stored in the aquifer is an inelastic good and the water stored in the unsaturated zone is an elastic good. This feature must be taken into account when someone wants to exploit or extract water from an aquifer to determine the price of water and define the extraction rate for managing of the resource.

#### 4. Conclusions

This job presents a Hydro-economic model in which tank model on a daily base is connected with an economic component. This model allows an analysis of demand and resource assessment to each one of the components of the hydrological model. The results show that there is consistency between the valuation of the resource and the characteristics of flow and storage of water in the watershed. The main results are:

- Tank model is suitable for decomposition and analysis of the hydrological cycle in the soil. The calibration obtained for the study watershed is good.
- The concept of re-scaled adjusted range allows taking into account in the assessment the regulatory capacity of the flow components, i.e., groundwater flow, subsurface flow and direct runoff-flow.
- Water demand meets is the annual mean flow, this is the maximum target that can be provided by available water at the drainage interest point. This target is sustainable and consistent with the water supply in the long term and with 100% reliability.
- The hydro-economic model gives more value to groundwater component (saturated zone) than sub-surface component (unsaturated zone).
- In this case the model gives water values opposite to both groundwater and sub-surface components.
- The price of groundwater shows more value for low flows and vice versa. The relationship is opposite for the sub-surface flow.
- The above behavior is explained by the ability to provide water in the long-term by aquifer. This happens in both dry and normal periods. The sub-surface water is produced by the tank 3, which have a low regulation capacity.
- Demand curves obtained have a logical behavior with respect to economic theory. The coefficients of determination are greater than 95% for all cases. The price of water to near zero becomes asymptotic to the axe Y, this indicates that the value of water is very high to extreme droughts.
- In the case of a watershed with ephemeral regime the demand curve will have a price for a water quantity of zero because the value of zero is physically feasible.
- The elasticity shows that the groundwater flow is an elastic good for low values and an elastic good for mean and high values. On the other hand the subsurface flow is an elastic good. For storages, the water of tank 4 is an inelastic good and the water of tank 3 is an elastic good.
- A discount rate must be included in the analysis. This is important to take the value of money over time. The application of an appropriate discount rate is an important aspect in the natural resources valuation.

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