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# A Proposal for Reservoir Volume Calculation in Rainwater Harvesting Systems

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**Abstract:** This paper introduces a proposal for reservoir volume calculation in rainwater harvesting systems. The proposed method can be used for reservoir volume design in rainwater harvesting systems and is based on three important variables. These variables are water demand, system efficiency and repayment time. Several simulations were carried out in different scenarios considering typical values of both catchment area (for low-income and medium-income households) and water demand, with fixed water and tank costs. Results showed that the integrated analysis of demand, efficiency and repayment time may assist designers to determine a more adequate reservoir volume.

**Keywords:** Rainwater use, reservoir volume, design criteria.

## 1. Introduction

An appropriate storage volume is essential for reservoir design of rainwater harvesting systems. It is crucial to maximize tank use as well as to minimize repayment time, especially in developing countries where the initial cost can be extremely high.

Several methods with their different fundamentals for tank volume calculation are described on the Brazilian Standard Norm [1]. Some of them are essentially empirical and based on international experiences. Others are based on supplying full demand, which suggests the need of high volume tanks, resulting in high investment costs. The volume of reservoirs can substantially vary from one method to another for the same input [2], making it difficult for designers to choose a method. Here, we performed a rational analysis for tank volume calculation based on efficiencies (attending and harvesting), water demand and repayment time for several scenarios.

In addition, our presented analysis covers a relatively wide range of roof areas, from low-income and medium-income households to warehouses. It is important to point out that small areas are critical for designing rainwater harvesting systems that will contribute partially to the water supply in urban areas.

## 2. Methods

The analysis of the main system variables was conduct based on the daily mass balance in the reservoir, for one year only, considering that the tank is fully emptied for maintenance, as recommended by NBR15527/07:

$$S_{(i)} = Vp_{(i)} + S_{(i\text{-}1)} - D_{(i)},\ i = 1,2\ldots365 \text{ dias} \quad (1)$$

where, $S_{(i)}, S_{(i\text{-}1)}$ = volume of water in reservoir, $Vp_{(i)}$ = rainwater volume, $D_{(i)}$ = daily demand.

The pluviometric data from 1961 to 1990, for the city of São Paulo, were downloaded from HIDROWEB [3]. The daily rainwater availability was estimated

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through Eq. (2), as recommended by NBR15527/07, subtracting the first-flush (*ff*).

$$Vp_{(i)} = (C \ x \ P_{(i)} x A \ x \ \eta) - ff \qquad (2)$$

where, $P_{(i)}$ = average precipitation, $A$ = catchment area, $C$ = runoff, and $\eta$ = catchment efficiency.

Additionally, the following variables were defined:

Attending efficiency ($Ea$, $0 < Ea < 1$):

$$Ea = \sum_{i=1}^{365} Va(i) \Big/ \sum_{i=1}^{365} D(i)$$

$$Va(i) = \begin{cases} D(i) & if\, Vp(i) + S(i-1) \geq D(i) \\ S(i-1) + Vp(i) & if\, 0 < S(i-1) + Vp(i) < D(i) \end{cases}$$

where, $Va_{(i)}$ = used volume

Harvesting efficiency ($Eh$, $0 < Eh < 1$)

$$Eh = \sum_{i=1}^{365} Va(i) \Big/ \sum_{i=1}^{365} Vp(i) \quad for \quad ff = 0$$

The *Eh* parameter indicates the harvesting potential and may fix the reservoir maximum use.

The assumptions used in the simulations were: (1) constant daily demand, (2) the demand is lower than or equal to the total rainwater availability, (3) the maximum demand is equal to the rainwater availability, which implies $Ea = Eh$, and (4) rainwater supply is equal to the maximum demand for studying different cost scenarios.

The investment return was calculated considering the prices of fiberglass tanks in PINI [4], 7% of interest tax [5] (Table 1), and government subsidy of 2%. Drinking water cost was estimated to be R\$2.02·m$^{-3}$ according to SNIS [6]. The adopted values of $C$, $ff$ and $\eta$ were 0.8, 2 mm and 0.9, respectively.

Based on the tank prices presented in PINI [4], a non-linear regression was performed to correlate reservoir unit cost with volume values within ranging from 6 to 15 m$^3$. This procedure was adopted because prices for this volume range were not available.

$$y = 0.1776 + 0.1486 \exp(-x / 755.4285) \qquad (3)$$

where, $y$ = unit cost (R\$/dm$^3$), $x$ = tank volume (dm$^3$)

All simulations were carried out according to the algorithm shown in the Fig. 1. The simulated scenarios take into account variations in some parameters, such as: roof areas, rainwater demand, drinking water cost,

**Table 1 Tank size, cost and interest tax.**

| Tank (m$^3$) | Tank Cost (R\$)[1] | Tank Cost (US\$)[2] | Interest tax (%)[3] |
|---|---|---|---|
| 0.5 | 127.19 | 70.82 | |
| 1 | 217.23 | 120.96 | 7.0 |
| 3 | 544.53 | 303.21 | |
| 6 | 1,065.50 | 593.3 | |
| 15 | 2,654.89 | 1,478.31 | |

[1]PINI[4], [2]1.7959 R\$/US\$ reference dez/2007, [3]Brazil-Central Bank [5].

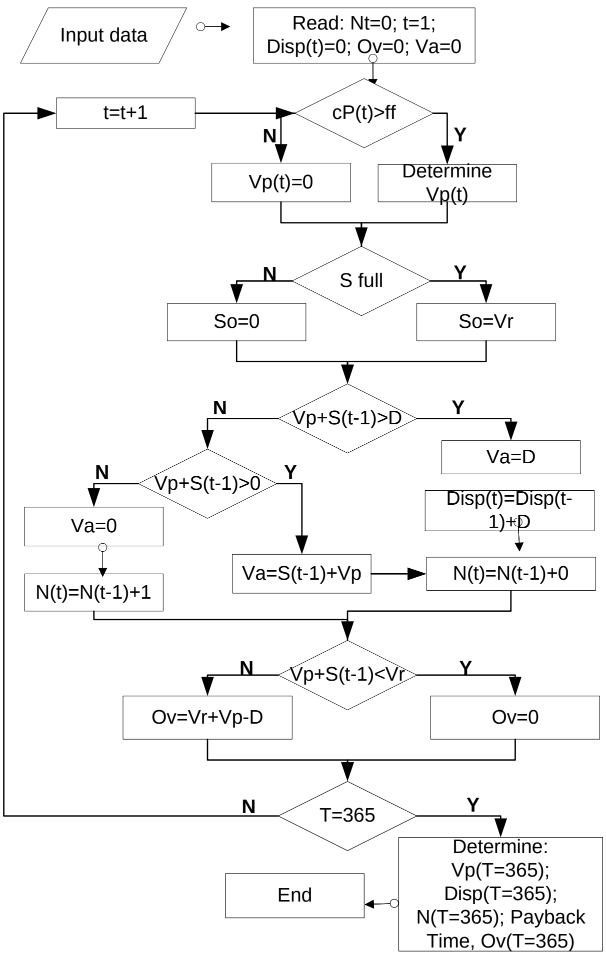


**Fig. 1 Flow chart of the algorithm utilized for simulations.** ***Vp*= rainwater volume; *Va* = used volume; *P* = precipitation; *c* = runoff coefficient; *Vr* = assumed (or adopted) tank volume; $Disp_{(t)}$ = delivered volume (correspondent to the sum of used volumes); $N_{(t)}$ = fail counter (computes the number of times that the tank is empty); *ff* = first flush; *Ov* = overflow; *t* = time (days).**

reservoir volume, reservoir cost and repayment time. For simulations of group 1, five different roof areas were adopted, while for group 2 and 3 both water and reservoir costs were varied (Table 2).

## 3. Results and Discussion

Our first simulation was performed utilizing a 0.5 $m^3$ tank and a 60 $m^2$ roof area with a water charge of U$1.12 $m^{-3}$. It is clear that both the *Ea* and the repayment time decrease with increasing the demand (Fig. 2). On the other hand, as the demand increases, the *Eh* parameter also increases (Fig. 2). The *Ea* and *Eh* parameters converge to the same value in the maximum demand, which is in this case 0.2 $m^3 \cdot day^{-1}$ (Figs. 2–3). A systematic behavior can be observed when simulating different reservoir volumes for different demands (Fig. 3). Indeed, it is noted that the lowest payment times occur at the maximum demand values (*Ea* = *Eh*), for all reservoir volumes (Figs. 3–5).

In the Figs. 3–5 the horizontal dashed lines indicate the maximum attending demand, according to previously adopted hypotheses. Biased conclusions can be taken by analyzing only the parameter *Ea*, because it suggests high efficiencies for low demands. That is, the water level in the reservoir will always be much greater than zero, indicating low use of the installed capacity or simply overestimated tank volume.

On the other hand, it is observed that the *Ea* and *Eh* curves tend to converge as the demand increases (Figs. 3–5), resulting in the same value on the maximum demand point (for fixed tank volumes). This suggests that the reservoir optimization should beconsidered

**Table 2 Variable and fixed parameters on the simulated scenarios.**

| Simulations | Rainwater demand | Reservoir volume | Drinking water cost | Reservoir cost | Repayment time |
|---|---|---|---|---|---|
| Group 1 | V | V | F | V | V |
| Group 2 | F | V | V | V | F |
| Group 3 | F | V | F | V | F |

*V* = variable, *F* = fixed.

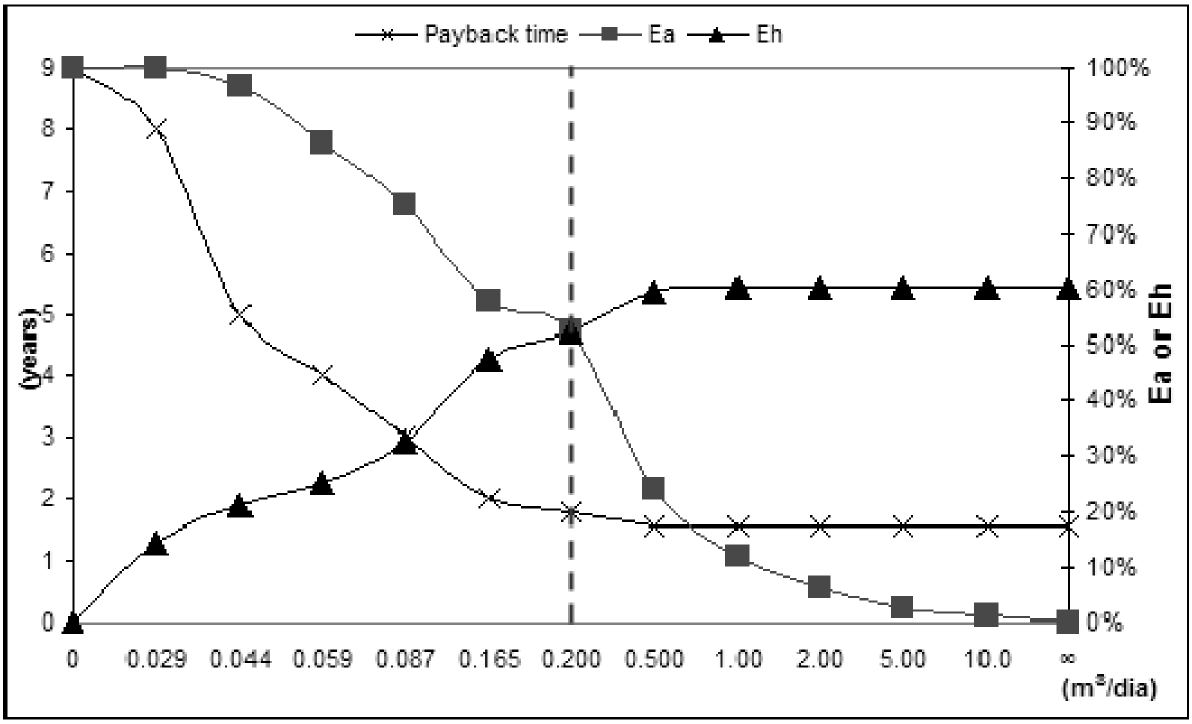


**Fig. 2 Efficiencies, payback time and demand relationship, data: roof area = 60 $m^2$, *ff* = 2 mm, *C* = 0.85, $\eta$ = 0.9, tank cost (Table 1), 0.5 $m^3$ tank and drinking water of R$2.02/$m^3$(US$1.12/$m^3$).**

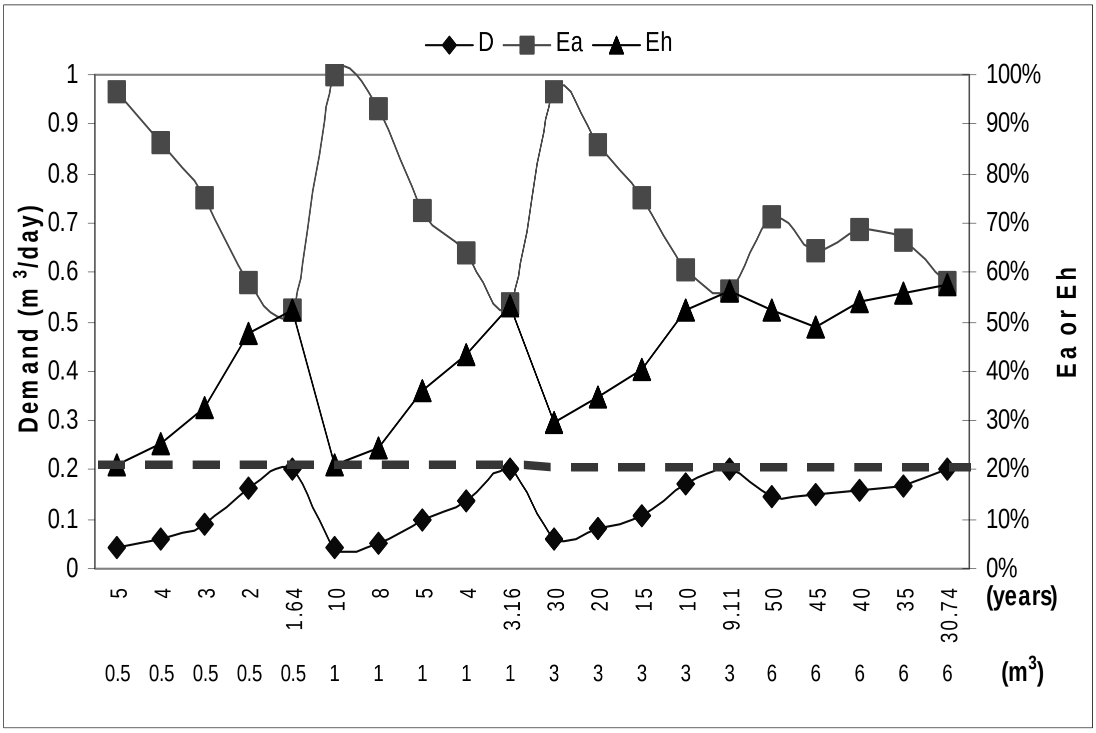


**Fig. 3 Efficiencies, payback time and demand relationship for several reservoir volumes, data: roof area = 60 m$^2$, *ff* = 2 mm, *C* = 0.85, $\eta$ = 0.9, tank cost (Table 1), and drinking water = R\$2.02/m$^3$.**

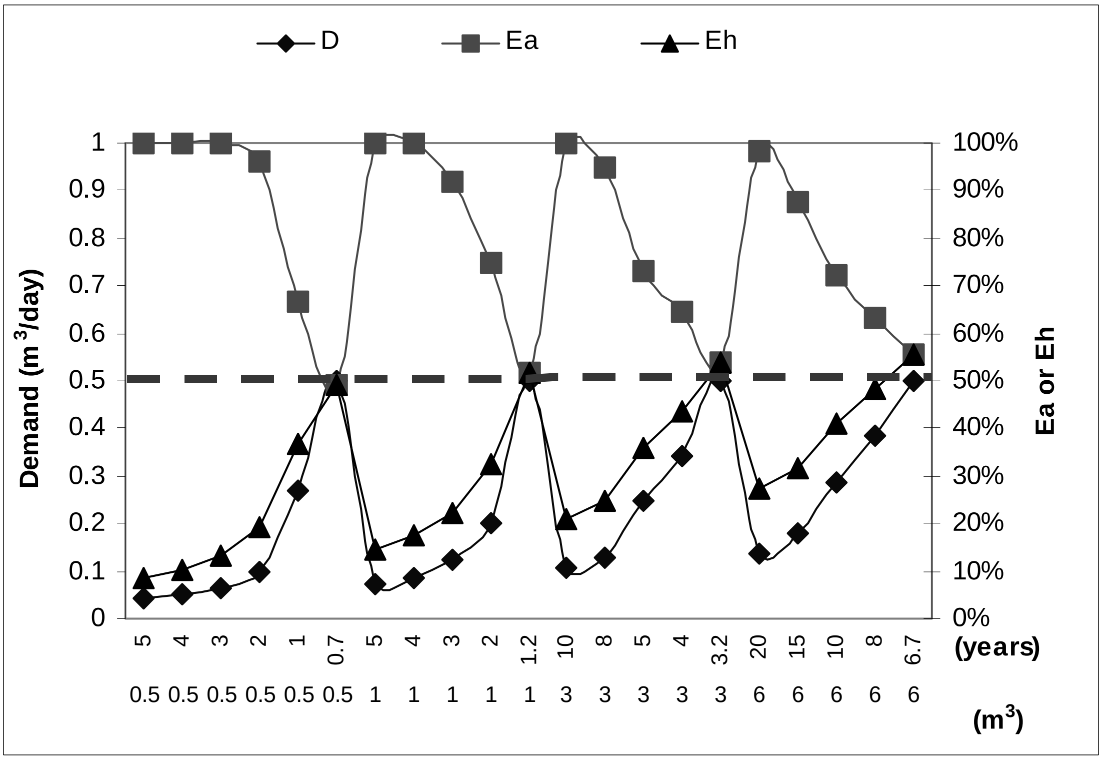


**Fig. 4 Efficiencies, payback time and demand relationship for several reservoir volumes, data: roof area = 150 m$^2$, *ff* =2 mm, *C* = 0.85, $\eta$ = 0.9, tank cost (Table 1), and drinking water = R\$2.02/m$^3$.**

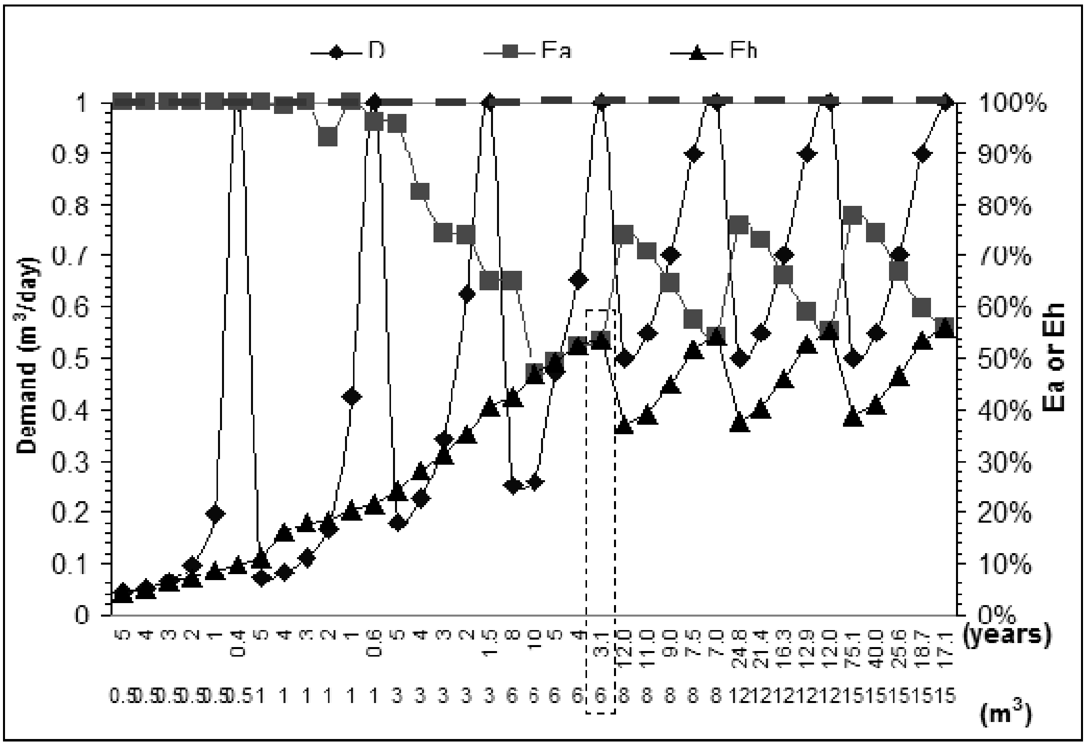


**Fig. 5 Efficiencies, payback time and demand relationship for several reservoir volumes, data: roof area = 300 m$^2$, *ff*= 2 mm, *C* = 0.85, $\eta$ = 0.9, tank cost (Table 1), and drinking water = R$2.02/m$^3$.**

by maximizing its use, which is characterized by attending the highest possible demand. In these conditions, one has the smallest investment return period, which can again be verified on the intersection of *Ea* and *Eh* curves (Figs. 3–5). Additionally, it is noted that an increment on the reservoir volume, for the maximum demand, does not result in a significative increase of *Eh*, but it does increase the investment return time.

Fig. 5 shows the simulations for 300 m$^2$ roof area. The best result is obtained on the first convergence point of *Ea* and *Eh*, meaning relatively high efficiencies and optimum reservoir use, as highlighted on the graph (dashed box) (6 m$^{-3}$, 3.1 years for repayment). Note that *Ea* and *Eh* values did not encounter each other for the reservoirs volumes of 0.5, 1.0 and 3.0 m$^3$. It is important to point out that all simulated cases were made considering partial attending demand, i.e., the collected rainwater is used as a complement of the municipal drinking water distribution system and so there is an alternative water source. In the case in which rainwater is the only water source, flow equalization must be considered.

Figs. 6–7 show the results of simulations for extreme values (lowest and highest) of roof areas (40 and 1,000 m$^2$). The same discussion presented above for the Figs. 3–5 can be used for the Figs. 6–7, since the variables behave alike, showing the same tendencies. This may validate the presented proposal for a wide range of roof areas and demands, thus allowing the designer to choose a proper reservoir volume for each particular condition.

The lowest RT (repayment times) were obtained for the highest demands, i.e., when $V_{ap}$ = $D$. Optimized systems, meaning short payback periods, are found when the maximum installed capacity is approached, for all reservoir volumes and roof areas.

Based on these findings, other simulations were carried out to answer the following question: How expensive should the reservoir (or the drinking water cost) be so that the desired repayment periods could be reached?

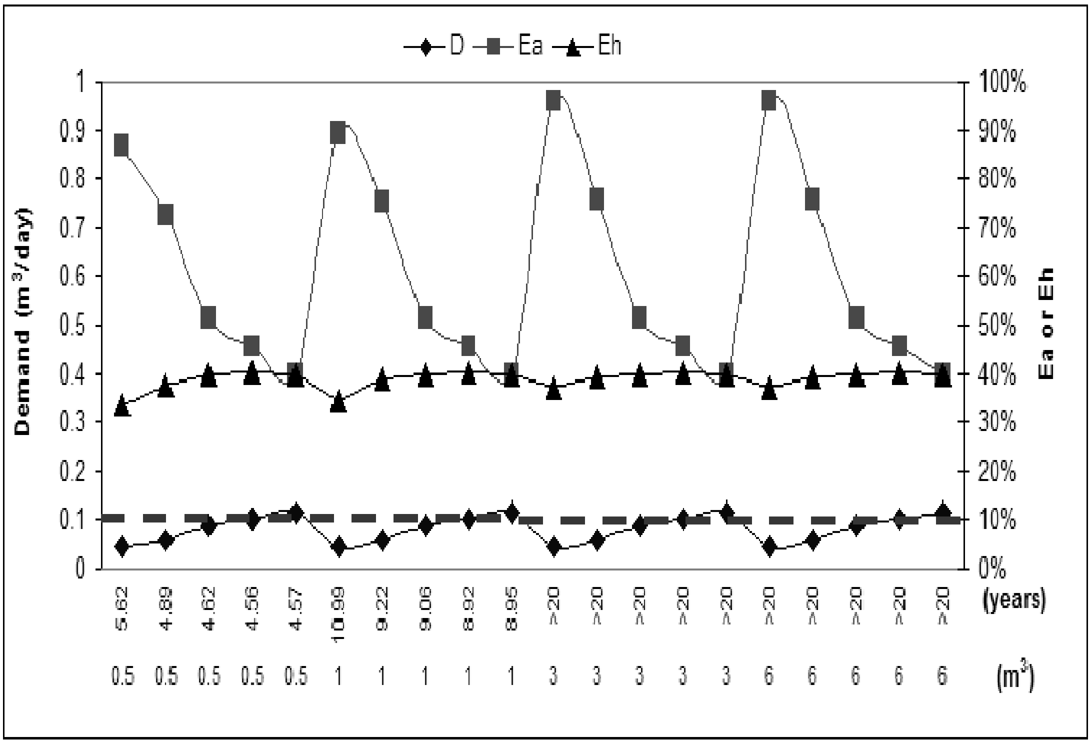


**Fig. 6 Efficiencies, payback time and demand relationship for several reservoir volumes, data: roof area = 40 m$^2$, *ff* = 2 mm, *C* = 0.85, η = 0.9, tank cost (Table 1), and drinking water = R$2.02/m$^3$.**

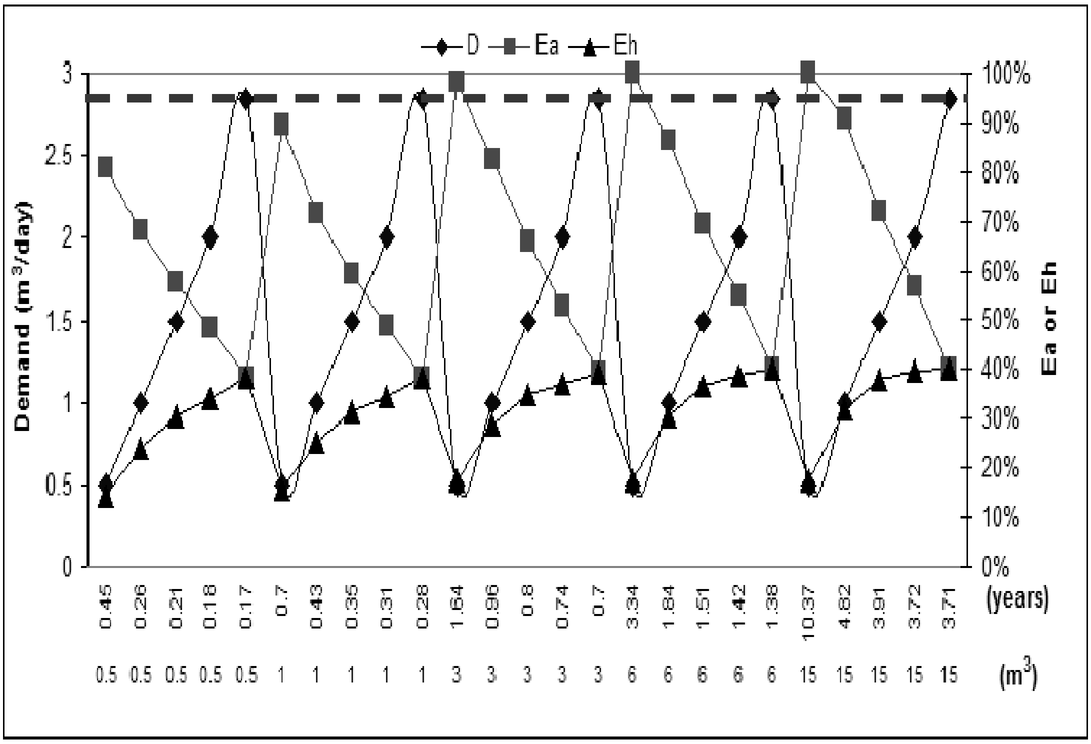


**Fig. 7 Efficiencies, payback time and demand relationship for several reservoir volumes. Data: roof area = 1000 m$^2$, *ff* = 2 mm, *C* = 0.85, *η* = 0.9, tank cost (Table 1), and drinking water = R$2.02/m$^3$.**

Figs. 8–9 presentdrinking water supply price and tank cost simulations, respectively, for roof areas of 60, 150 and 300 m$^2$ and fixed RT, represented by the flat line of repayment time curve. Firstly, reservoir cost was kept fixed (according to Table 1) and drinking water cost was calculated for determined values of repayment time and reservoir volume (Fig. 8). Secondly, drinking water supply cost was fixed to obtain reservoir cost at desired values of repayment times (Fig. 9). The demand was kept constant and equal to the maximum one in these simulations (*Ea* = *Eh* condition).

These results show that the water supply and reservoir prices need to be higher for the roofs with lower area in order to the investment pay itself off. The values of projected water cost (per m$^3$) were R$3.5 and 26.6 for volume tanks of 0.5 and 6 m$^3$, respectively, a catchment area of 60 m$^2$ and an investment return period of one year (Fig. 8). The actual market price is R$ 2.02 m$^{-3}$. These water prices reduce with increasing catchment area values (150 e 300 m$^2$). If the water price is kept at R$2.02 m$^{-3}$ and the desired investment return period is between one and two years, it is observed that there is a need of reservoir cost reduction for few low-income household cases from the prices that are practiced in the market, whereas a positive scenario can be obtained for households with larger roof areas (Fig. 9 and Table 1). The projected values obtained in Fig. 9 show the reservoir prices that would have to be fixed in the real market in order to make the rainwater use viable economically. For example, the reservoir of 0.5 m$^3$ would have to cost around R$80, 150 and 320 for roof area households of 60, 150 and 300 m$^2$ (Fig. 9), respectively, and for a repayment time of one year. The market price for this case is R$ 127.19. Thus, Fig. 9 shows the limit from which the costs will not be paid.

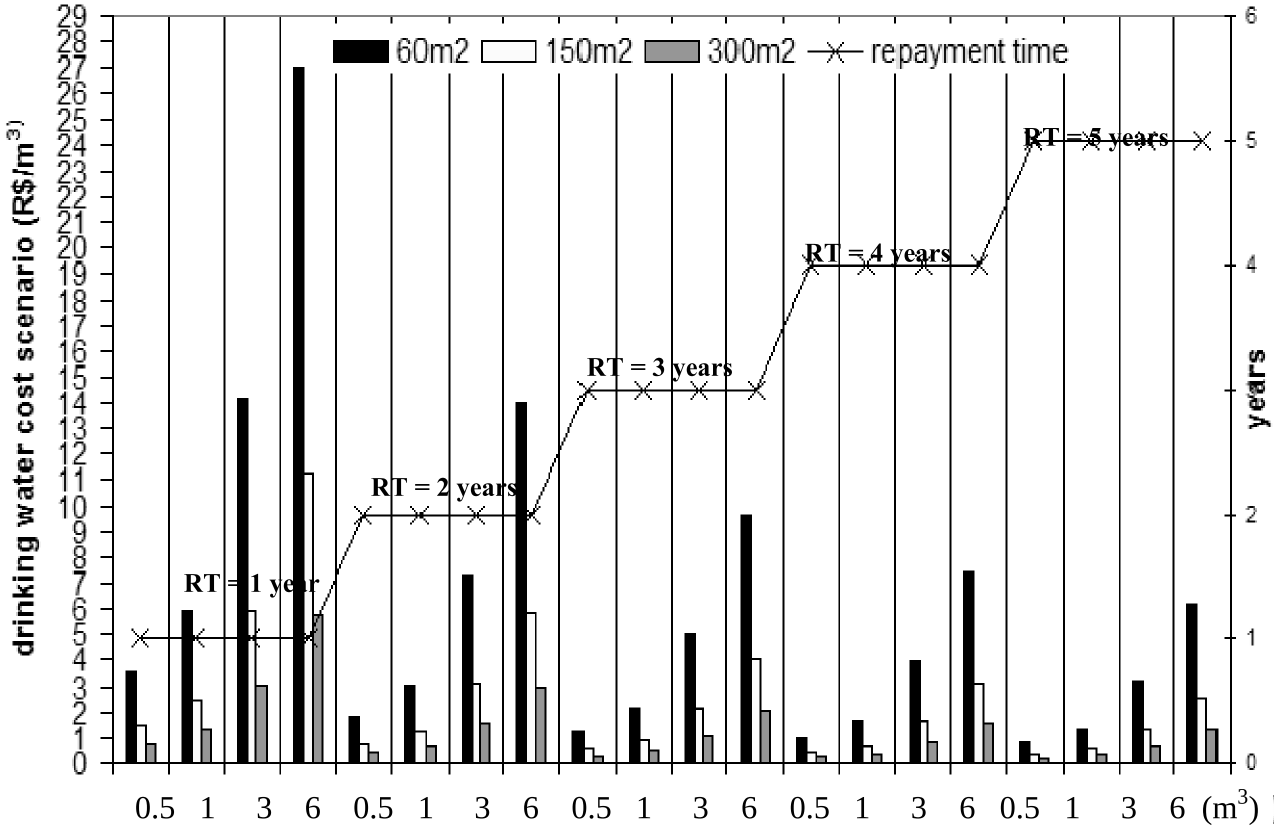


**Fig. 8 Water cost simulations for different reservoir volumes (Table 1) at fixed RT (repayment times).**

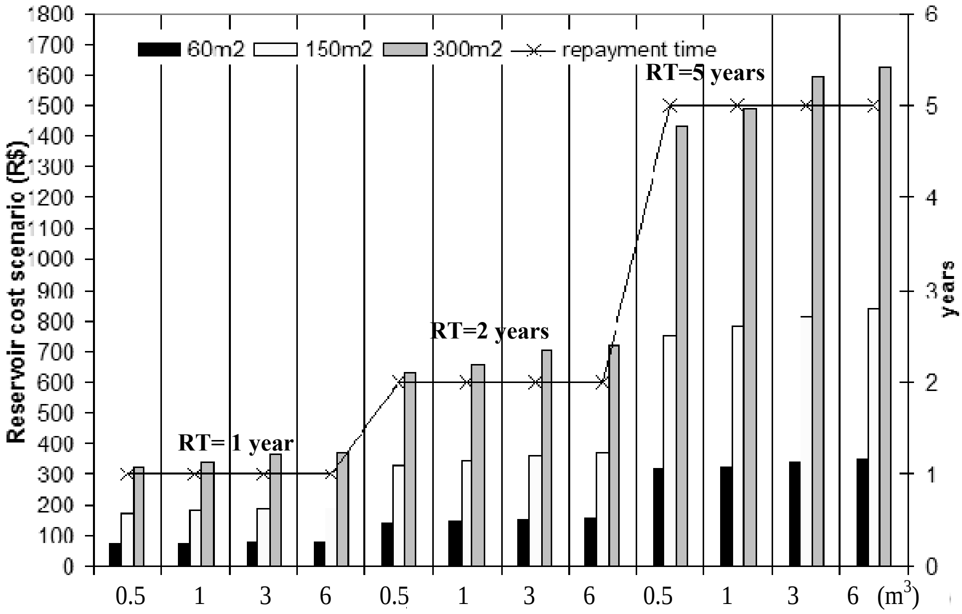


**Fig. 9 Tank cost simulations for different reservoir volumes at fixed RT (repayment times), cost of drinking water was extracted from SNIS [6] and fixed at R$2.02/m$^3$.**

## 4. Conclusions

In cases in which rainwater can be used to partially attend the water demand, i.e., communities with drinking water supply system, the integrated analysis here proposed showed to be a powerful tool to assist designers for reservoir volume calculation. The reservoir use can be optimized by calculating the appropriate demands so that the efficiencies are higher and the repayment times are shorter.

If the conditions $Ea = Eh$ are reached, the repayment times are shorter. These vary from 1.6 to 30 years for reservoirs from 0.5 to 6 m$^3$ for roof area of 60 m$^2$, from 0.7 to 6.7 years for reservoirs from 0.5 to 6 m$^3$ and area of 150 m$^2$; and from 3.1 to 17 years for reservoirs from 6 to 15 m$^3$ and area of 300 m$^2$. The paybacks are significantly increased with demand reduction ($Ea > Eh$).

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