MATEC Web of Conferences **73**, 03006 (2016) DOI: 10.1051/matecconf/20167303006
TPACEE-2016

Performance based evaluation of rainwater harvesting system in public buildings

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Abstract. Harvested rainwater has become an inseparable part of sustainable development a long before term 'sustainability' appeared. Even though domestic systems have been investigated to some extent, there are few recent studies of larger non-domestic systems used in public and commercial buildings, especially in Russia. This paper aims to describe a combined performance evaluation of a configured rainwater harvesting system for a specific study case of public building located in St. Petersburg. The careful analyses of empirical and theoretical data set was applied while calculating water demand, optimal storage sizing and subsequent economical juxtaposition of scenarios. The results provide useful information for optimizing the economic response of every specific scenario in terms of payback period, initial costs and end use.

1 Introduction

The total usable freshwater supply for ecosystems and humans, according to the United Nations water organization, UN-Water [1], is only about 200 000 km^3 of water – less than one percent (<1%) of all freshwater resources. And, water use has been growing at more than twice the rate of the population increase in the last century. Based on the map published by the Consultative Group on International Agricultural Research (CGIAR), the countries and regions suffering most water stress are North Africa, the Middle East, India, Central Asia, China, Chile, Colombia, South Africa and Australia. Water scarcity is also increasing in South Asia. With this, good management of water resources and corresponding water infrastructure can jointly manage human water security [2].

The domestic use of freshwater accounts for approximately 10% of the total global freshwater consumption [3]. The use of rainwater harvesting systems (RHS) and rainwater tanks specifically is an old practice, which corresponds to these environmental and social issues. RHS stores rainwater from impervious catchments, usually a rooftop for non-potable use. Water is typically used for outdoor irrigation or indoor non-potable uses like flushing toilets. Components usually include a roof catchment, a filter to remove the initial fraction of roof runoff, a storage tank (also known as a cistern), and a pump to supply system demand.

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Currently, RHS are widely used for non-potable applications in countries such as Australia, South Africa, the USA, Italia and Spain, where funding is provided for the construction of rainwater harvesting systems [4], or where significant water scarcity is explicitly manifested. A thorough inspection of RHS studies also demonstrates that, although historically used in areas where the water supply was limited by climate or infrastructure, the practice of rainwater harvesting has recently been used in humid and well developed regions, namely in response to the increased interest in green building practices which support the smart use of water [5,6]. This is concerned of such countries as England, Germany, France and some others.

With this, Russian Federation has never been regarded as a part of a European vanguard in the matter of sustainability and St. Petersburg, being an article's case study, has never been lack of fresh potable water. But, giving to world's increasing demand, the use of RHS in St. Petersburg area seems to us as a very provident move.

Common practices show that performance of RHS model is predominantly influenced by the following:

1. Identification of rainfall trends in location. It can be analyzed by taking data from the last years and calculated as mean [7] or data horizon can be broaden and calculated as a trend [8]. Otherwise, more representational rainfall years can be taken for further analyses;
2. Roof area, tank sizing, piping, co-related dimensions and end uses scenarios affect financial feasibility of a system [9];
3. The selection of time scale for modeling RHS is important. Although time step selection often depends on the objective of the analysis and on the availability of data, a sensitivity analysis conducted by Mitchell [10] has shown that it may influence the estimation of the tank volumetric reliability (up to about 8%) depending on the algorithm used to run the water balance simulation. A variety of time steps have been used for RHS, ranging from 5 min [11] to daily [10] and monthly. Early results by Fewkes and Butler [12] point out that simulations with monthly time steps may provide inaccurate evaluation of the RHS system water saving performance and suggest to use the daily time step resolution for such an evaluation.

2 Materials and Methods

2.1 Case Study

The RHS system was analyzed for Hydrocampus – 2 of Peter the Great St.Petersburg Polytechnic University located in St. Petersburg, Russian Federation. This is a public building which was built in 70's and currently passes the stage of a major overhaul. The 3D model of the existing building is presented on Fig. 1.

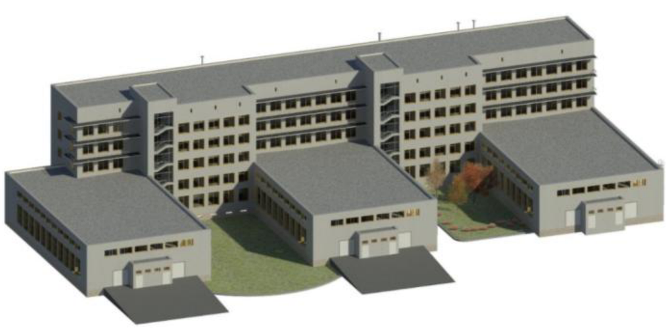

Fig. 1. Hydrocampus – 2.

Hydrocampus – 2 was selected in this study because it is representative of other higher education campuses. It is a five-story building with a total area of 8559 m^2, roof area of 4050 m^2, and lawn area of 3992 m^2. It has 3 embedded lab buildings and 10 lavatory rooms. All the area-volume data set is presented in the Table 1.

Table 1. Area data.

№	Parameter	Value
1	Overall height of the building	23.40 m
2	Total floor area	8 559.00 m^2
3	Total volume	41 609.00 m^3
4	Total lawn area	3992.00 m^2
5	Parking area	3780.00 m^2
6	Total collecting area of the roof	4049.62 m^2

To provide thorough analyses, the RHS was modelled for this building (Figure 2). Inspection of the object revealed that existing rainfall drainage system (marked in green) is in a sufficiently good state so to reduce initial costs we decided to leave it as it is. Storage tank was decided to place in the middle laboratory building. This building formerly included a pool for hydraulic tests and now this space is unoccupied.

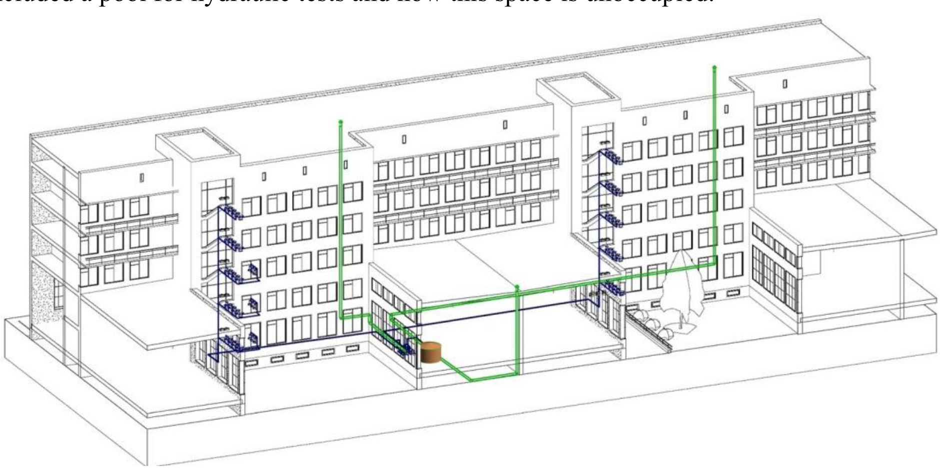

Fig. 2. RHS model.

For the hydraulic head reaches the height of 18 meters it is impossible to omit hydraulic pumps – 2 of them were placed in the middle laboratory building along with storage tank. Water supply pipes (marked in blue) provides lavatory rooms on every floor with non-potable water for flushing. In every lavatory room, a small water storage has to be placed in order to ensure continuous water flow.

2.2 Rainfall Data for St. Petersburg

The rainfall data was obtained from the Hydrometeorological Research Centre of Russian Federation (Hydrometcentre of Russia). Average monthly and annual rainfall data set in the considered period (1970–2005) was collected; however due to some missing data the years of 1999 and 1986 were not included in the analysis. Thus, the studied overall record period was 33 years (Table 2).

Table 2. Average monthly rainfalls.

Month	Average rainfall, [mm]	Minimum rainfall, [mm]	Maximum rainfall, [mm]	Daily maximum, [mm]
Jan	44	2 (1838)	82 (2011)	23 (1955)
Feb	33	3 (1886)	92 (1990)	23 (19900
Mar	37	0.7 (1923)	90 (1763)	26 (1971)
Apr	31	2 (1850)	99 (1764)	29 (1991)
May	46	2 (1978)	127 (2003)	56 (1916)
Jun	71	8 (1889)	199 (1742)	44 (2004)
Jul	79	5 (1919)	166 (1979)	69 (2002)
Aug	83	1 (1955)	197 (1869)	76 (1947)
Sep	64	2 (1851)	190 (1767)	34 (1912)
Oct	68	5 (1987)	150 (1984)	37 (2003)
Nov	55	2 (1993)	118 (2010)	31 (2010)
Dec	51	4 (1852)	112 (1981)	28 (2009)
Year	661	395 (1882)	861 (2012)	76 (1947)

2.3 Occupants

Using the design occupancy of the building in estimating demand lead to an over-sizing of the storage tank, when the actual occupancy of the building, as a rule, ends up being significantly lower [6]. In order to assess sufficiently precise demand in water, the number of students and employees for the building was asked to the institute's management team. This number was carried out through study plan and divided among weekdays and time zones (Table 3).

Table 3. Estimated occupants.

Semester:	**Winter semester**					
Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Visitors	1265	1099	1205	1204	1175	1085
Semester:	**Summer semester**					
Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Visitors	1102	936	1042	1041	1012	922

These figures were reduced for the summer semester by the number of graduating master students for it they do not visit institute during that semester on a daily basis.

2.4 Specific Water Demand

Specific end use of non-potable water was divided into 3 parts. Frequency of toilet and urinals flushing was assessed according to data derived from Heaton and Radvan [13]. Day consumption can be calculated as:

$$C_{tf}\left(\frac{m^3}{day}\right) = \frac{\sum n^i F^i C_u^i \cdot pop}{1000}, \quad (1)$$

where
n^i – estimated number of flushes per unitary;
F^i – estimated percentage of people using toilet/urinal flush, [%];
C_u^i – unitary consumption of the toilet/urinal flush, [liters];
Pop – number of visitors.
Floor/pavement washing is calculated as:

$$C_{pw}\left(\frac{m^3}{day}\right) = \frac{A \cdot C_u \cdot NW}{1000}, \quad (2)$$

where
A – floor/parking area, [m^2];
C_u – unit consumption for washing floors, as recommended by the Technical Specification ANQIP (ETA 0701) [14], [liters/m^2];
NW – number of washes provided. For irrigation of territory this formula is to be rewritten as:

$$C_I\left(\frac{m^3}{day}\right) = \frac{A \cdot C_u \cdot d}{1000}, \quad (3)$$

where
A – area of garden [m^2];
C_u – consumption unit for garden irrigation as recommended by the Technical Specification ANQIP (ETA 0701) [14], [liters/m^2];
NI – number of watering provided.
Total monthly consumption per end use is presented in the Table 4.

Table 4. Consumption in non-potable use.

Month	Toilet flushing, [m^3]	Floor washing, [m^3]	Parking washing, [m^3]	Irrigation, [m^3]
Jan	42.20	3.42	0.00	0.00
Feb	63.30	3.42	0.00	0.00
Mar	127.15	3.42	0.00	0.00
Apr	145.32	3.42	75.60	239.52
May	108.99	6.85	75.60	319.36
Jun	108.99	6.85	75.60	239.52
Jul	24.22	6.85	75.60	319.36
Aug	24.22	6.85	75.60	239.52
Sep	168.79	6.85	75.60	319.36
Oct	168.79	3.42	75.60	239.52
Nov	189.89	3.42	0.00	0.00
Dec	189.89	3.42	0.00	0.00

Four scenarios were developed to investigate the best way to utilize rainwater harvesting at the Hydrocampus – 2 (Table 5). Currently, the potable municipal water is the only source of water used. The scenarios varied with respect to water demand, end use and initial costs:

— Basic scenario: City supplied potable water is used for both flushing toilets and irrigation.

— Scenario 1: Drainage system was modeled as being renovated to collect roof runoff for its use in flushing and floor washing.

— Scenario 2: Drainage system was modeled as being renovated to collect roof runoff for its use in toilet flushing, floor and parking washing.

— Scenario 3: Drainage system was modeled as being renovated to collect roof runoff for its use in toilet flushing, floor and parking washing and irrigation.

Total daily non-potable consumption for j-scenario:

$$C_w^j = \sum_{i=1}^{i} C_i , \qquad (4)$$

where

C_w^j- total daily consumption for j-scenario, [m^3/day];

C_i – specific daily consumption (Eq. 1, Eq. 2, Eq. 3), [m^3/day];

Table 5. Scenarios.

Scenario	Rainwater re-use				Additional supply	
	Toilet flushing	Floor washing	Parking washing	Irrigation	Municipal water	Electricity for pumps
Basic scenario	-	-	-	-	+	-
1	+	+	-	-	-	+
2	+	+	+	-	-	+
3	+	+	+	+	-	+

2.5 Water Tank Dimensioning

The water storage unit is usually the most expensive part of the rainwater harvesting system, so an accurate analysis and optimization is critical to create an overall efficient water supply. Therefore, the capacity and all other construction parameters should be determined properly, among others, to minimize the payback period.

There are various methods to estimate the design of storage tank. The Ripple method [15] involves calculating the volume of water that needs to be stored throughout the year to compensate the lack of water during the dry period. According to the Ripple method, the reservoir volume corresponds to the maximum of the positive accumulated differences between the consumption of non-potable water and the collectable rainwater volume, observed within an evaluation period. This method tends to oversize the reservoir volume because it is prepared to meet the water demands of critical drought periods [16]. Nevertheless, it has the benefit of checking the upper limit for the volume of a storage reservoir [4], corresponding to the ideal situation of 100% efficiency.

The average rainfall distribution is enlisted in Table 2. Average daily precipitations are shown on Figure 3. Despite the fact, that recent studies [19] have shown the influence of time scale resolution for modeling the consumption, for high-demand applications, like in the current study.

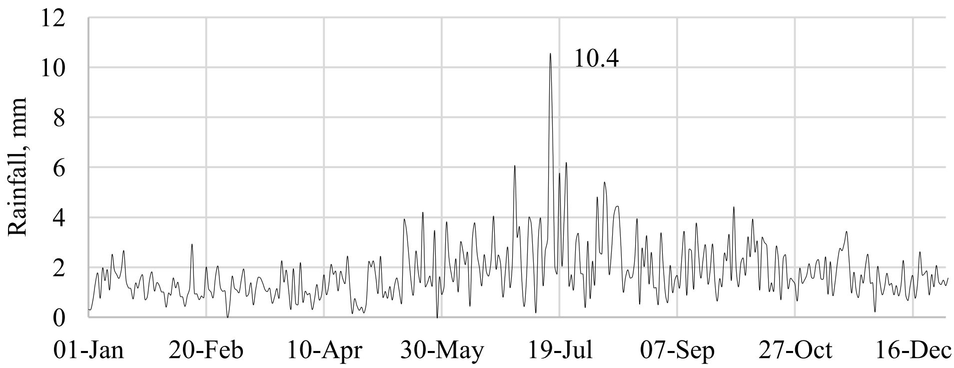

Fig. 3. Average precipitations distribution throughout the year.

The roofs of building are covered with black sheeting rolls. A collecting surface [A_r, m^2] is 4049.62 m^2. According to Roebuck [17], the runoff coefficient [C, dimensionless] of these surfaces is around 0.8 – 0.95. The value used in the present design was set to 0.8.

The volume of water, available for collecting, was calculated using the equation:

$$V_m = C \cdot (10^{-3} \cdot P) \cdot A_r \cdot n_f, \tag{5}$$

where

V_m – available volume of rainwater, [m^3];

P – daily average of precipitations, [m^3];

n_f – hydraulic filtration efficiency of the system, [dimensionless].

Hydraulic filtration efficiency is the ratio of the quantity of filtered rainwater arriving at the reservoir and the amount of rainwater that reaches the filter. In case the maintenance and cleaning of the filters are ensured, the hydraulic filtration efficiency may be considered constant and equal to 0.95 [14].

Further, the sequences of positive accumulated differences [S_t, m^3] were calculated as follows:

$$\begin{cases} S_t = 0, & C_{w,t} - V_{w,t} \le 0 \\ S_t = C_{w,t} - V_{w,t}, & C_{w,t} - V_{w,t} > 0 \end{cases}, \quad t = 1 \tag{6}$$

$$\begin{cases} S_t = 0, & S_{t-1} + C_{w,t} - V_{w,t} \le 0 \\ S_t = C_{w,t} - V_{w,t}, & S_{t-1} + C_{w,t} - V_{w,t} > 0 \end{cases}, \quad t > 1 \tag{7}$$

where

S_t – positive accumulated difference of the time period t, [m^3];

S_{t-1} – positive accumulated difference of the time period t-1, [m^3];

$C_{w,t}$ – total daily non-potable consumption of the time period t, [m^3];

V_{wt} – volume of water, available for collecting of the time period t, [m^3].

Results are enlisted in Table 6.

Table 6. Reservoir volume according to different scenarios and years.

		Maximum reservoir volume, m^3		
Year	Precipitations, [mm]	Scenario 1	Scenario 2	Scenario 3
1992	504	138	254	1692
2000	713	122	245	1085
2001	685	103	157	1143
2002	610	103	272	1416
2003	842	110	185	616
2004	699	141	254	1053
2005	650	152	303	1306
Average year	657	28	91	1150

The average rainfall data was proven inaccurate, as the difference between the calculated reservoir volume between average and realistic models was significant.

Therefore, in order to create a sustainable and relevant system, real precipitation among the most recent data should be used for determining the volume of the tank.

The Ripple approach considers only the environmental benefit, and does not reveal the most economically efficient result. So it should be improved with some modeling techniques [19], and in this study, performance evaluation approach is suggested.

To estimate the efficiency of the system, energy consumption should be calculated first.

2.6 Booster Pumps

Booster pumps are required to transport the rainwater for flushing toilets and urinals. The sizing of the pumps and their annual energy requirements were estimated using the standard pump power equation:

$$N_{real} = \frac{Q \cdot \gamma \cdot (h_e + h_p)(1 + \alpha)}{\eta}, \tag{8}$$

where,

N_{real} – power input to pump [W],

η – combined mechanical and hydraulic efficiency of the pump,

Q – flow rate [m3/s],

γ – specific weight of water [N/m3],

α – percentage of energy lost to friction,

h_e – elevation head provided by pump [m],

h_p – pressure head provided by pump [m].

Obtained results are shown in Table 7.

Table 7. Demand of pumps.

Parameter	1st pump	2nd pump
Q, [m^3/sec]	0.00338	0.00274
H, [m]	18	18
γ, [N/m^3]	9810	9810
η	0.72	0.72
1 + α	1.5	1.5
N_{useful}, [kWt]	0.60	0.48
N_{real}, [kWt]	1.24	1.00

2.7 Performance Evaluation

The resulting parameter, that was used to determine the efficiency, is payback period [PB, years]. It was calculated as follows:

$$V_t^{wT} = \begin{cases} V_{w,t} + V_{t-1}^{wT} - C_{w,i}, & V_{w,t} + V_{t-1}^{T} - C_{w,i} < V^T \\ V^T, & V_{w,t} + V_{t-1}^{T} - C_{w,i} \geq V^T \end{cases} \tag{9}$$

$$V_t^{ru} = \begin{cases} C_{w,t}, & V_{w,t} + V_t^{wT} - C_{w,t} \geq 0 \\ V_{w,t} + V_t^{wT}, & V_{w,t} + V_t^{wT} - C_{w,t} < 0 \end{cases} \tag{10}$$

$$V^{ru} = \sum_{t=1}^{n} V_t^{ru} \tag{11}$$

$$P_r = P_m \cdot A_r + P_w \cdot A_r \tag{12}$$

$$A = f(V^T) \tag{13}$$

$$P_s = P_r + P_o \tag{14}$$

$$S = (P_{wu} + P_{ww}) \cdot V^{ru} - P_e \cdot N_{real} \cdot t_d \cdot N \tag{15}$$

$$PB = \frac{P_s}{S} \tag{16}$$

where
V_i^{wT} – volume of water in a tank at the time period t, [m^3];
V_t^{ru} – volume of collected rainwater, that was used during the time period t, [m^3];
P_r – price of a reservoir, [rub.];
P_m – price of materials for a reservoir, [rub.];
P_m – price of construction of a reservoir, [rub.];
P_s – price of the rainwater harvesting system, [rub.];

P_o – price of other components of the system, [rub.];
S – amount of savings after applying the system, [rub./year];
P_{wu} – price of water utilization, [rub./m^3];
P_{ww} – price of water supply, [rub.];
N_{real} – power demand for the pump, [W];
t_d – working hours in a day, [h];
N – number of working days in a year, [days].

Reservoir volume changes from 0 to V_{max}, and that affects whole model in an unpredictable way, therefore the simulation was carried through all years and scenarios. Results of simulation for the first scenario are shown on Figure 4, for the second – on Figure 5.

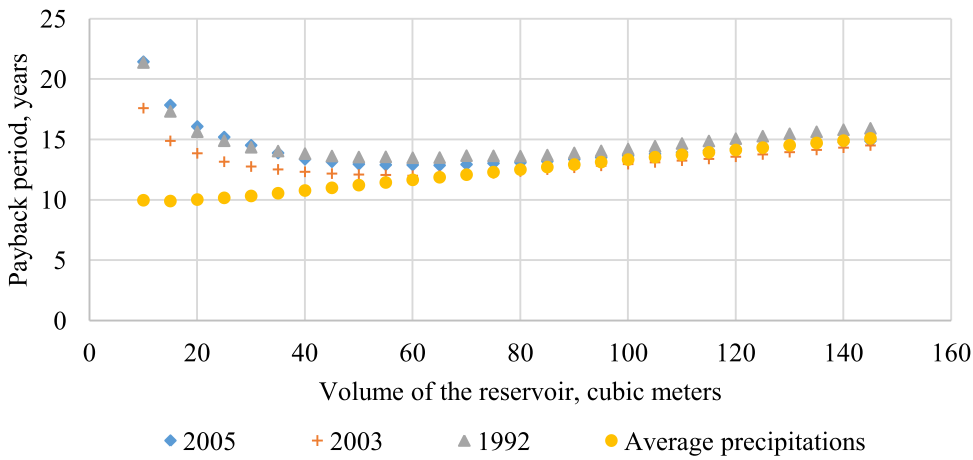

Fig. 4. Payback period depending by the volume of the reservoir for the year 2005, 2003, 1992.

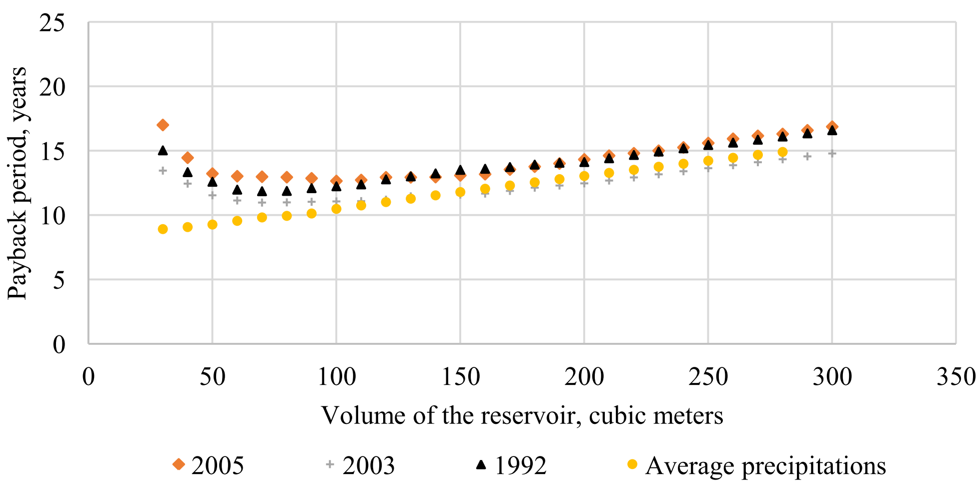

Fig. 5. Payback period depending by the volume of the reservoir for the year 2005, 2003, 1992.

3 Results and Discussion

3.1 Optimum Tank Sizes

Performance evaluation revealed that optimal storage volume for the first scenario is 60..65 cubic meters. With exception for average precipitations model. This confirms the fact, that average data can not be used for designing RHS.

The average payback period for the first scenario in case of applying the 60 m^3 storage is 12.77 years. Spread of performance evaluation results for the second scenario is higher, as it is shown on Figure 5. But the average payback period for 80 m^3 reservoir is 11.94 years. Therefore, the second scenario is more beneficial.

Overall, this technique allows us to choose both main parameters of the system – for what purposes rainwater can be used to maximize efficiency, and how big should the storage be.

Performance evaluation also revealed that volume of a tank depends not on the total amount of rainfall in a year, but on the distribution within a year, which is confirmed by longer payback period for 2005 precipitation model.

Figures 6 and 7 show the comparison of Ripple approach and suggested performance evaluation approach. These graphs show the volume of water in the tank at every day of the year, with the second consumption scenario and 2005 precipitation model.

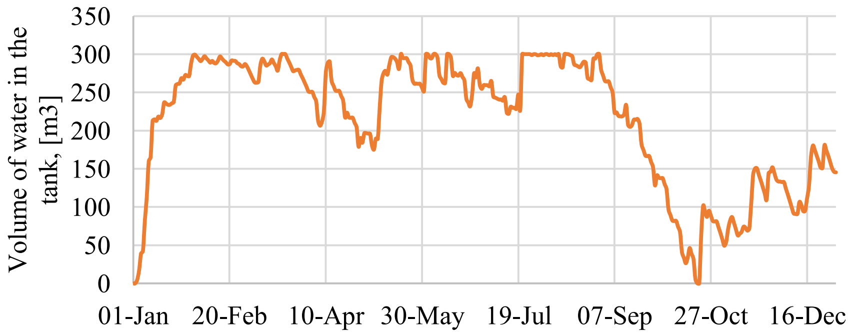

Fig.6. Water balance in the tank for the year 2005, second scenario and Ripple approach.

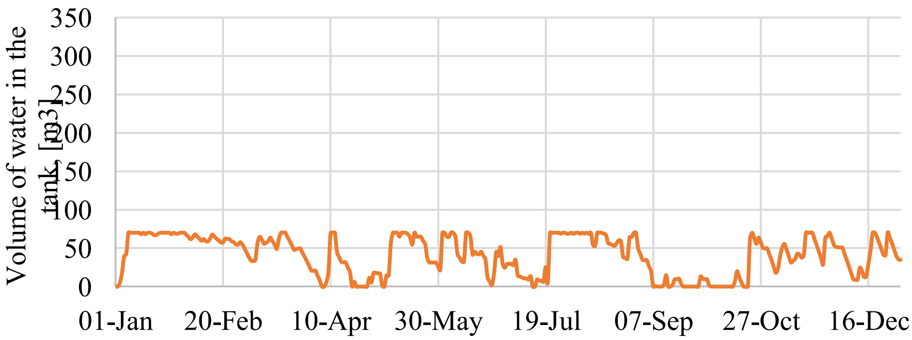

Fig. 7. Water balance in the tank for the year 2005, second scenario and economic approach.

Despite the fact, that Ripple approach allows to save more water, it is economically inefficient, which is proven by performance evaluation. Even taking into account periods, when the system can not supply the building, it is more efficient to reduce the volume of the tank to 80 m^3.

Another valuable detail, that these graphs show, is the most appropriate time for system installation. In this particular application the best timing will be from January to February, or from the middle of July to the beginning of September, where graphs for all the three chosen years behave similarly and are at their peaks, as it is shown on Figure 8.

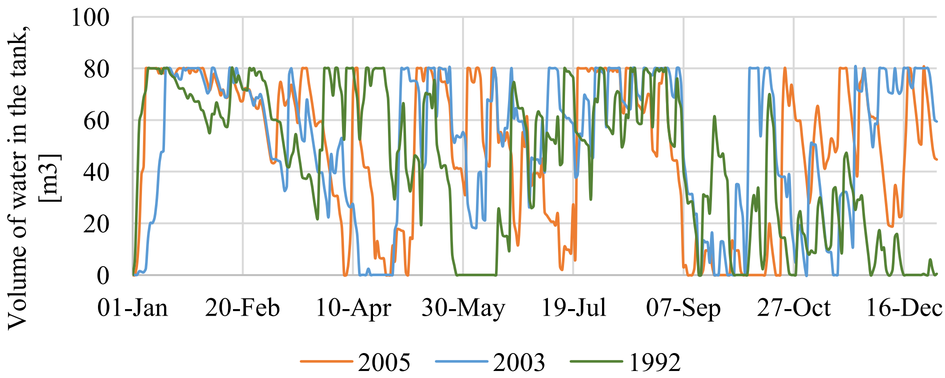

Fig. 8. Water balance in the 80 m^3 tank for the 2005, 2003, 1992, second scenario

3.2 Economic Effect

According to the results of performance evaluation, maximum economic effect was achieved when rainwater is used for toilet flushing, floor cleaning and parking washing. That consumption scenario, combined with the tank of 80 [m^3], reduces the payback period of the system to approximately 12 years.

4 Conclusions

The empirical and theoretical assessment of the modelled RHS system for the existing public building has produced the following conclusions and recommendations:

1. RHS system, that was modelled for the Hydrocampus – 2, ensures significant level of fresh water savings;
2. According to calculations of initial costs and related to RHS electricity consumption, payback period for the 2nd scenario is equal to 12 years. Energy consumption of pumps, however, can be further reduced by supporting innovations in RHS system design, for example around gravity-based systems;
3. Results of RHS modelling, carried by Ripple method, may not be accurate to proper size the system. Ripple method maximizes the ecological impact, and is good for determining modeling limits. It should be improved with additional techniques, like performance evaluation, that leads to determining the optimum volume;
4. The performance evaluation approach provides users with significantly more accurate results, than any other technique, if the algorithm stands on daily data. Use of monthly or weekly averages increase inaccuracy;
5. Application of the developed technique to existing university campus gives the optimal storage volume of 80 m^3.

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