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Reliability Analysis of Rainwater Harvesting Systems in Southern Italy

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Abstract

Water scarcity is a current problem for many urban areas in the Mediterranean region due to the increasing water demand related to the population growth and the expansion of urban and industrialized areas. Climate change will intensify the pressure on water resources. Rainwater harvesting (RWH) may be an effective alternative water supply solution to face water scarcity. It has recently become a particularly important option in arid and semi-arid areas, mostly because of its many benefits and relative low costs. The present study aims to analyse the reliability of a RWH system installed to supply water for toilet flushing purpose with reference to a single-family house in a residential area of Sicily (Southern Italy). Historical water consumption data were analysed to obtain a flushing water demand pattern. A water balance simulation of the rainwater storage tank was performed, and the yield-after-spillage algorithm was used to define the tank release rule. The model's performance was evaluated using data from more than 100 different sites located throughout the Sicilian territory. This regional analysis provided results having practical applications, e.g. the identification of the optimal rainwater tank size and the annual system reliability curves as a function of mean annual precipitation. The uncertainty related to the regional model predictions was also assessed. Results showed that RWH systems can provide environmental and economic advantages in Sicily over traditional water supply methods. In particular, the regional analysis identified areas where the application of this system would be most effective.

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1. Introduction

The rainwater harvesting (RWH) to supply water for domestic purposes is a common practice in developing countries, especially in arid and semi-arid areas affected by water scarcity [1 - 3], but also in urban areas [4, 5]. Recently, RWH systems have been widely identified as a measure of adaptation to the effects of climate change on water resources [6, 7]. Indeed, the availability of an alternative water supply reduces pressure on aquifers and surface water sources. RWH systems also have important economic advantages because they reduce the amount of water purchased from public systems by the consumers. For these reasons, several studies investigated the implementation of RWH systems as a response to the growing water demand in Africa [3, 8], Asia [9, 10] and Australia [11, 12]. In the Mediterranean region some analysis have been carried as well with regard to Greece [13], Italy [14, 15] and Spain [16].

A RWH system includes the catchment area, the collection device and the conveyance system. Rainwater is usually collected from rooftops, courtyards or other compacted or treated surfaces before being filtered and collected in storage tanks to be used. The performance of a RWH system is evaluated in terms of water saving efficiency and depends on the temporal and spatial distribution of the rainfall, the size of the catchment area, the capacity of the storage tank and the water demand pattern. Therefore, the storage capacity of a RWH tank cannot be standardized, nevertheless an optimal size can be identified on the basis of the system reliability or economic criteria [4].

In this study, the reliability of a RWH system for a single-family house in a residential area with four inhabitants has been evaluated, considering the use of rainwater for toilet flushing. The system performance has been tested for different catchment surfaces, tank sizes and mean annual precipitation using data from over 100 different sites in Sicily. In order to define a temporal pattern for flushing water demand, water consumption data have been recorded from single-family houses in Palermo (Northwestern Sicily). The application of the Yield-After-Spillage algorithm allowed to evaluate the system efficiency in each site of the study region. Simulations have been performed at daily scale using data from 2002 to 2004. Once the system reliability has been assessed, the tank sizes related to three thresholds of reliability (75%, 85% and 95%) have been determined. In order to provide a useful tool for practical applications, the spatial distributions of these tank capacities has been reported in some maps. To estimate the payback period on the capital cost for the RWH system installation, a cost-benefit analysis has been performed. Finally, for given tank sizes (10, 15 and 20 m^3), mathematical relationships between mean annual rainfall and water saving efficiency have been determined. The uncertainty related to these relationships has been evaluated through a data resampling procedure.

2. Methodology

2.1. Inflow to the RWH tank

The rainwater tank is filled using rainfall volumes collected from a building's rooftop, courtyard and pedestrian areas. Under the assumption of constant rainfall within each time step *t*, the rainwater volume can be calculated as follows:

$$Q_t = \phi \cdot A_{TOT} \cdot R_t = A \cdot R_t \tag{1}$$

where Q_t is the inflow volume supplied to the tank at time step *t* (m^3), ϕ is the runoff coefficient depending on water loss (dimensionless), R_t is the rainfall at time *t* (m), A_{TOT} is the total catchment surface area (m^2), and A is the effective impervious surface area (m^2). Evaporation losses from the tank are neglected. In this study, ϕ was set equal to 0.9 [17].

The stormwater quality of the initial discharge from the roof surface is of poor quality due to the presence of dust, sediments, ect. [18] , that are accumulated during dry periods and washed off at the beginning of the next rainfall event. The first flush is defined as the initial period of a rainwater runoff where a pollutant concentration is remarkably higher than during later periods [19]. According to Yaziz et al. [20], subtracting the first 0.33 mm of rainfall from the total daily rainfall as the first flush would considerably improve roof water quality. In this study, all the daily water balance simulations have been performed subtracting the first flush of 0.33 mm from the daily rainfall series.

2.2. Water demand for toilet flushing

In order to accurately modeling the daily water demand for toilet flushing, the average number of daily flushes per capita has to be estimated. In this study, the toilet flushing demand pattern was defined by analyzing water consumption data collected during a monitoring campaign of seven dwellings located in Palermo throughout the 2002–2004 period. Each monitored dwelling had a toilet WC flush tank with a volume of 9-10 L. Data have been processed as described by Liuzzo et al. [15]. The number of daily flushes per capita were then statistically analyzed to identify a well-fitting probability distribution function. The application of the Kolmogorov-Smirnov test showed that the Weibull distribution function fit the observed data best. In order to generalize these results to other users, 365 random points were sampled from the Weibull cumulative distribution function CDF fitting the cumulated frequency of the obtained per capita flushes. In this manner, a daily pattern for an entire year of toilet flushes per capita has been obtained. Finally, the series of daily household toilet flushes was computed by multiplying the number of flushes derived in the previous step by a selected number of users at home during the day.

2.3. Water balance simulation

In order to investigate the performance of a RWH system, behavioural models have been widely used because they allow a more detailed design and are relatively simple to develop. In this study, water balance has been simulated with a behavioural model based on the Yield-After-Spillage (YAS) algorithm [21]:

$$Q_{D_t} = \max\begin{cases} V_{t-1} + A \cdot R_t - S \\ 0 \end{cases} \tag{2}$$

$$Y_t = \min\begin{cases} D_t \\ V_{t-1} \end{cases} \tag{3}$$

$$V_t = \min\begin{cases} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{cases} \tag{4}$$

where Q_{D_t} (m^3) is the volume discharged as overflow from the storage tank at time step *t*, V_t (m^3) is the volume stored at time step *t*, Y_t (m^3) is the yield of rainwater from the storage tank at time step *t*, D_t (m^3) is the toilet water demand at time step *t*, and S (m^3) is the tank storage capacity. The performance of RWH systems is generally described in terms of water saving efficiency E_T :

$$E_T = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} D_t} \cdot 100 \tag{5}$$

where T is the total time period under consideration. E_T provides a measure of how much water has been conserved in comparison to the overall demand.

3. Results

3.1. Case study and dataset

In the present study, rainfall volumes were calculated using the daily rainfall series recorded from 111 rain gauges over the 2002–2004 period in Sicily. The total annual rainfall in this area ranges from 400 mm/year at lower elevations to 1300 mm/year at higher elevations (Figure 1a). Rainfall data have been provided by the *Osservatorio delle Acque - Agenzia Regionale per i Rifiuti e le Acque* (OA-ARRA) of Sicily. This period has been chosen because a large number of the evenly distributed rain gauges worked continuously during the entire period. These historical rainfall series are representative of the regional climate both in terms of annual and monthly mean values.

The water catchment surfaces of the model home include the home's rooftop and the courtyard. Three different catchment areas have been investigated: 100, 200 and 300 m^2. Rainfall is collected from these surfaces and stored in a rainwater tank for toilet flushing use. Figure 1b illustrates the analyzed RWH system.

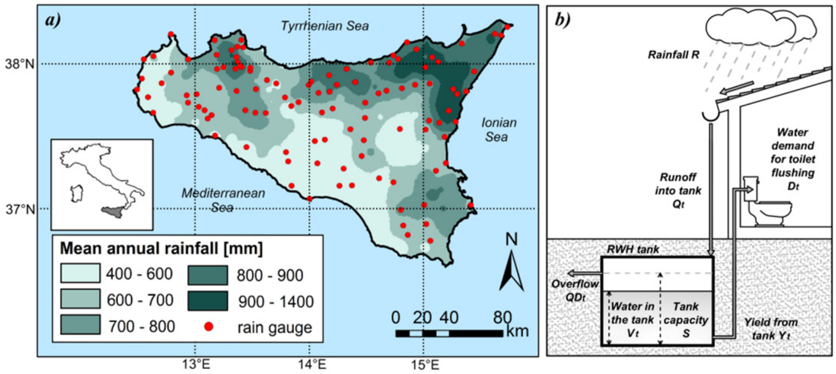

Fig. 1. a) Rain gauges location and mean annual rainfall (1981–2012); b) scheme of the RWH system

3.2. Evaluation of daily water saving efficiency

The historical rainfall series recorded at 111 rain gauges during the 2002–2004 period have been used to evaluate the performance of a RWH system in Sicily. Firstly, a preliminary analysis has been carried out in order to investigate the effect of the tank capacity S on the daily E_T and to identify the S that provides the most feasible value of the average daily E_T for each site in Sicily. In this analysis three different values of catchment surface A have been considered. Water balance simulations have been performed at daily scale, taking into account the effect of extreme rainfall of 24 h duration and dry spells on the RWH system. Specifically, for any tank size, the daily average E_T of each site has been calculated on the entire analysis period. Then, the related percentiles values have been estimated. Results are summarized in the box-whisker graphs in Figure 2. Focusing on the median line (50th percentile), the average daily ET increases with tank capacity. For S ranging between 1 and 30 m^3, E_T varies in the range from 38% to 72% for A =100 m^2, from 44% to 96% for A =200 m^2 and from 46% to 99% for A =300 m^2. In Figure 2a it can be observed that, for A =100 m^2, a tank capacity equal to 20 m^3 is able to provide a water saving efficiency of 70%. Further increases of S produce a slight improvement of E_T , with an achievable maximum value equal to 72%. Similarly, the performance improvement of the RWH system in terms of E_T is moderate and not advantageous for tank capacity greater than 20 m^3 for A equal to 200 and 300 m^2 (Figure 2b and 2c). Nevertheless, the increase of the catchment surface clearly implies higher values of the maximum achievable E_T .

In order to assess the uncertainty linked to the E_T appraisal for each site, the average width of the E_T percentiles band (shown in Figure 2) has been calculated. Regarding the 25th and 75th percentile bands, the average width values are 26%, 19% and 15% for A equal to 100, 200 and 300 m^2 respectively.

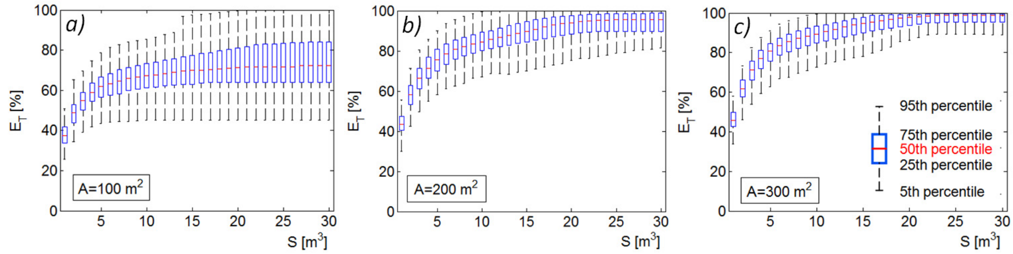

Fig. 2. Box-whisker graphs of the daily water saving efficiency E_T *vs* tank capacity S for different catchment surface A : a) 100 m^2; b) 200 m^2; c) 300 m^2.

3.3. Spatial distribution of optimal tank capacity

For S ranging between 1 and 30 m^3, the mean annual E_T of the RWH system for each site of the studied area has been assessed. Afterwards, the tank capacities able to ensure three different values of water saving efficiency (75%, 85% and 95%) have been evaluated and their spatial distribution has been reported in Figure 3. As regards to A=100 m^2, in great part of the region the RWH system is not able to ensure an E_T equal to 75% (Figure 3a). In some small areas of the northern coast this E_T threshold can be reached with tank capacities ranging from 2 to 8 m^3, but higher volumes are required in the rest of the area. E_T can reach the 85% and the 95% in a limited northeastern area of the island (Figure 3b and 3c). Nevertheless, these threshold can be obtained by means of tank sizes up to 20 m^3.

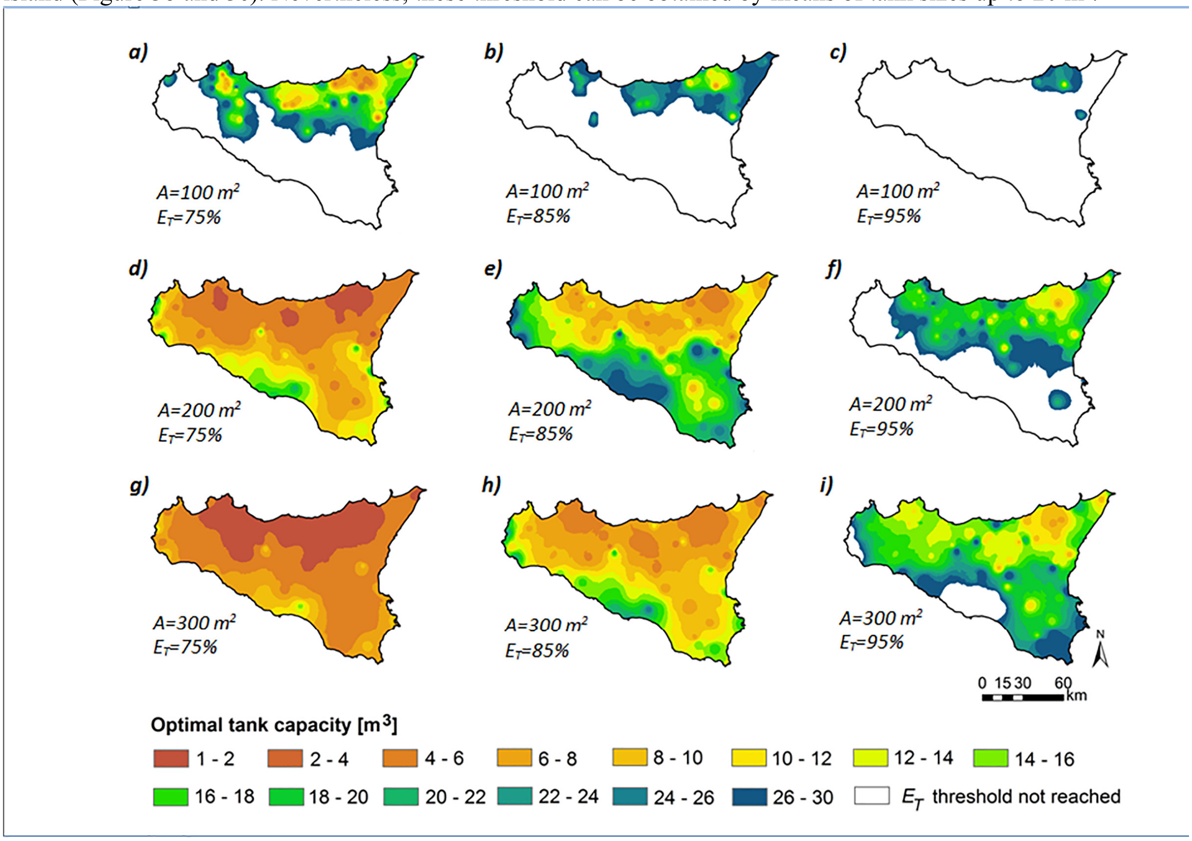

Fig. 3. Optimal tank capacity (m^3) for different E_T threshold (%) and A (m^2)

For A=200 m^2, E_T can reach the 75% in the entire island with tank sizes that range from 1 to 15 m^3 (Figure 3d). The achievement of the 85% and 95% of E_T clearly requires the installation of tanks with higher capacities (Figure 3e and 3f). The RWH system is able to provide a E_T of 95% in great part of the island, even if this threshold cannot be reached in a wide southern area and in a western area (Figure 3f). An E_T equal to the 75% can be obtained in the entire area of study with tank sizes ranging from 1 to 10 m^3 for A=300 m^2 (Figure 3g). Figure 3h shows that in the northern part of the island, tank sizes up to 6 - 8 m^3 are able to provide an E_T of 85%. The E_T threshold of 95% can be achieved in the entire region, except for two small areas, one in the eastern part of the island and one in the southern part (Figure 3i).

3.4. Cost-benefit analysis

A cost-benefit analysis has been carried out to investigate the balance between the investment/cost for system purchase and installation, and the benefits obtained by the rainwater use for toilet flushing use. A schematic underground installation of an RWH system has been considered, including a pre-fabricated concrete tank provided with a first flush device, a manhole with a rainwater filter, a pumping system and its Programmable Logic Controller (PLC) equipment, the drainage piping system inlet and outlet, the tank, and the piping distribution system to supply the rainwater for the analyzed uses. The costs of each element have been obtained from the unit rates, drawn from the official regional price list for civil infrastructures [22] and by means of a market survey. In this analysis, the costs related to the system maintenance have been neglected. The economic benefit has been quantified in terms of reduction of the annual water bill from water utilities. Even if relevant, in this analysis the environmental and social benefits have not been accounted. The analysis has been carried out according to the "*Guide to cost-benefit analysis of investment projects*" in Europe [23]. As a performance indicator, the payback period (PBP) has been calculated following the procedure described by Khastagir and Jayasuriya [24] and Matos et al. [25]. For each value of A, the spatial variations of the PBP corresponding to the tank sizes have been examined for an E_T threshold equal to 75%, 85% and 95%. Results showed that the PBP ranges from 20 to 30 years in a wide area of northern Sicily for A equal to 200 and 300 m^2 and E_T equal to 75%. In the other cases, the high values of PBP (up to 60 years) point out that the RWH system is not economically advantageous in most of the region.

3.5. Regional Curves of water saving efficiency

By means of the procedure described by Liuzzo et al. [15], the relationship between annual water saving efficiency E_T and mean annual precipitation P have been investigated in order to define equations for a system analogous to the one analyzed here (for S equal to 10, 15 and 20 m^3) and valid at the regional scale. The purpose of these mathematical laws is to provide the E_T that a RWH system can reach at the annual scale for each value of P and the uncertainty linked to its appraisal. For S=10 m^2, Figure 4 shows the interpolation curves and the resulting uncertainty bands (red lines) obtained by interpolating the 5th and 95th percentiles of the E_T values as a function of P.

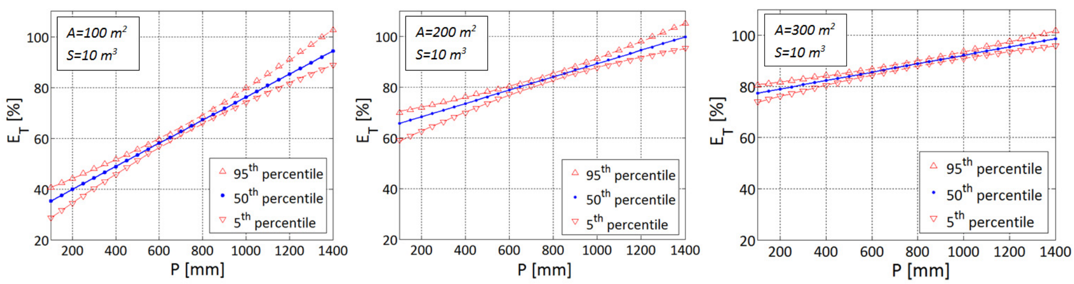

Fig. 4. Water saving efficiency curves and their uncertainty bands for S=10 m^3

In locations characterized by a mean annual precipitation ranging from 600 to 1000 mm, the RWH system is able to ensure an annual E_T that ranges from 58% and 98%, from 78% to 100% and from 85% to 100% for A equal to 100, 200 and 300 m^2 respectively. In this range of P, the system performance is affected by a lower level of uncertainty, as shown by the smaller width of the band. In sites where the mean annual precipitation is higher than 1400 mm, E_T can exceed the 100%, meaning that the installation of the RWH system could totally meet the water demand and supply an additional volume of water that could be used for other domestic purposes, such as garden irrigation. The interpolation curves for S=15 m^3 and S=20 m^3 showed a similar behaviour. Table 1 shows the equation of the curves and the uncertainty bands for each value of A and S. In general, E_T increases with mean annual precipitation and tank size.

Table 1. Equations of interpolating curves of 5th, 50th and 95th percentiles for each catchment surface A (m^2) and tank capacity S (m^3)

A [m^2]	S [m^3]	P-ET Curve	Uncertainty Band	Uncertainty Band
		50th Percentile	5th Percentile	95th Percentile
100	10	$0.0454 \cdot P + 30.763$	$-1 \cdot 10^{-5} \cdot P^2 + 0.0632 \cdot P + 22.374$	$1 \cdot 10^{-5} \cdot P^2 + 0.0300 \cdot P + 37.616$
	15	$0.0533 \cdot P + 27.947$	$-1 \cdot 10^{-5} \cdot P^2 + 0.0711 \cdot P + 19.341$	$1 \cdot 10^{-5} \cdot P^2 + 0.0374 \cdot P + 35.252$
	20	$0.0579 \cdot P + 26.597$	$-1 \cdot 10^{-5} \cdot P^2 + 0.0757 \cdot P + 18.335$	$1 \cdot 10^{-5} \cdot P^2 + 0.0419 \cdot P + 34.484$
200	10	$0.0262 \cdot P + 63.106$	$-1 \cdot 10^{-5} \cdot P^2 + 0.0436 \cdot P + 54.414$	$9 \cdot 10^{-6} \cdot P^2 + 0.0134 \cdot P + 69.131$
	15	$0.0301 \cdot P + 65.069$	$-8 \cdot 10^{-6} \cdot P^2 + 0.0434 \cdot P + 58.170$	$8 \cdot 10^{-6} \cdot P^2 + 0.0181 \cdot P + 70.805$
	20	$0.0305 \cdot P + 67.830$	$-9 \cdot 10^{-6} \cdot P^2 + 0.0454 \cdot P + 59.892$	$1 \cdot 10^{-5} \cdot P^2 + 0.0153 \cdot P + 75.747$
300	10	$0.0170 \cdot P + 75.276$	$-5 \cdot 10^{-6} \cdot P^2 + 0.0246 \cdot P + 71.409$	$6 \cdot 10^{-6} \cdot P^2 + 0.0080 \cdot P + 80.222$
	15	$0.0160 \cdot P + 80.784$	$-5 \cdot 10^{-6} \cdot P^2 + 0.0245 \cdot P + 76.451$	$5 \cdot 10^{-6} \cdot P^2 + 0.0074 \cdot P + 85.576$
	20	$0.0146 \cdot P + 84.608$	$-4 \cdot 10^{-6} \cdot P^2 + 0.0224 \cdot P + 80.117$	$5 \cdot 10^{-6} \cdot P^2 + 0.0067 \cdot P + 88.696$

4. Conclusions

Recently, the interest in RWH systems as an alternative water source has increased, due to their economic and environmental advantages. Indeed, these systems can provide a supplementary water supply in urban areas when integrated with an existing conventional water supply system, or the main water supply in rural areas affected by water scarcity. In the context of climate change, the installation of RWH tanks could represent a valuable adaptation measure against the reduction of water availability. In this analysis, a behavioral model has been applied to assess the performance of an RWH system in terms of water saving efficiency. Water balance simulations showed that, in terms of annual water saving efficiency, the RWH system is able to provide good performances when a catchment surface of 200 - 300 m^2 is available. In this case, water saving efficiency up to the 85% can be reached in most of the island. Lower values of the catchment surface make the installation of the RWH system not advantageous, due to the need for higher tank sizes. The cost-benefit analysis highlighted the importance of selecting the optimal tank size in order to reach high value of water saving efficiency and maximize the return of the initial investment. Starting from the application of the YAS algorithm to different sites in Sicily, the correlation between mean annual precipitation and water saving efficiency has been investigated in order to define some equations, valid at regional scale, useful to quickly evaluate the performance of a RWH system. In summary, the analysis highlighted that the RWH systems can play a considerable role as an additional water supply system. For this reason, the installation of a RWH system in residential urban areas should be encouraged by incentives and government supports.

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