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# RAINWATER HARVESTING SYSTEMS FOR IRRIGATION OF URBAN GREEN AREAS: A CASE STUDY

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***KEY POINTS***

- *Use of rainwater for irrigation of urban green areas is investigated*
- *The soil water holding capacity is modelled to assess the irrigation demand*
- *A behavioural model is implemented to simulate the operation of the system*

## 1 INTRODUCTION

The present work addresses the alternative use of rainwater for irrigation of public green areas by focusing on the case study of a Rainwater Harvesting (RWH) system included in a reconversion project of a former military area located in the town of Genova (Italy), within the Mediterranean climate. The project provides for the rainwater to be collected and used for irrigation in the park, where a few nature-based solutions (NBSs) contribute to the management of stormwater drainage and control. The collection of rainwater is limited in this study to the paved portions, roofs, or semi-permeable areas of the park, including porous pavements.

The high-intermittency and randomness features of rainfall events in space and time require smart management capabilities to avoid that the adopted technical solutions are ineffective due to the scarce synchronization between the availability and the demand. In particular, the use of rainwater for irrigation is in opposition of phase with the occurrence of rainfall events (irrigation is activated in dry periods, while during wet periods irrigation is not needed). The most efficient solution is the use of RWH systems equipped with storage tanks, suitably designed according to the expected variability of rainfall events, as well as on the magnitude and temporal distribution of the demand.

## 2 METHODOLOGY

In the present work, we implemented a behavioural model to simulate the operation of the RWH system in different conditions. The daily water demand was calculated to meet the irrigation water needs only. The methodology adopted for the analysis is similar to the ones proposed in the literature by various authors (Fewkes and Butler, 2000; Mitchell, 2007), but suitably integrated by introducing a dedicated algorithm to account for the variation of the soil water content in calculating the daily irrigation demand.

The RWH system performance are analysed as a function of the system characteristics, and of the capacity of the storage tank. The analysis is performed using a non-dimensional approach, by examining the system performance according to the non-dimensional storage fraction $S/Q$ defined as the ratio between the storage capacity of the system $S$ and the annual inflow $Q$. The behavioural model is based on a conceptual scheme implying the collection of rainwater flow from the drainage of ground surfaces and some building roofs. In Figure 1, the RWH system is illustrated, and the variables used to describe the various components of the RWH model are indicated. The model performs, at the daily scale, the balance of the incoming and outgoing volumes from the collected rainwater flows and the daily water demand.

The rainwater inflow to the storage tank, $Q_t$ (in m$^3$), is evaluated based on the flow rate that is collected at each computational step $t$ and conveyed to the storage tank, using the rational formula.

Three different design scenarios were adopted, with the rainwater collection areas defined as follows, with $\phi_{eq}$ the equivalent runoff coefficient and $A_{tot}$ the total extension of each area:

- Scenario 1: rainwater collected from drainage of ground surfaces with $A_{tot}$ = 7925.6 m$^2$ and $\phi_{eq}$ = 0.4;
- Scenario 2: rainwater collected from a sheet metal roof with $A_{tot}$ = 1800 m$^2$ and $\phi_{eq}$ = 0.95;
- Scenario 3: rainwater collected from a brick roof with $A_{tot}$ = 4960 m$^2$ and $\phi_{eq}$ = 0.85.

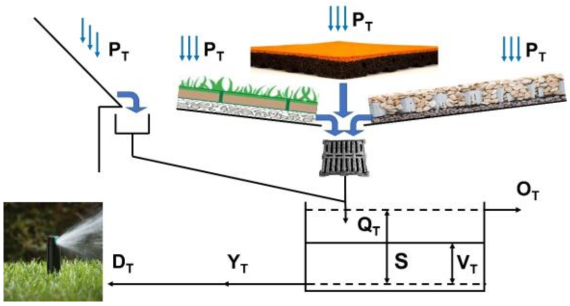

**Figure 1.** Schematics of the main elements of the simulated RWH system**.**

The technical report of the reconversion project establishes that irrigation, from June to August, should be 5 mm/m$^2$ for the areas with a vegetation cover made of meadows and shrubs, while 20 l/plant/day are established for trees. These values are halved in April, May, September, and October, while the irrigation is suspended from November to March. By measuring the extension of the areas covered with the three types of vegetation from the detailed plan views included in the final project, we calculated a maximum daily water need of 5 mm/day for meadows and shrubs, and 0.8 mm/day for trees.

As for the topsoil, we assumed fine sandy loam, with a corresponding Water Holding Capacity (WHC) equal to 158 mm per meter of soil depth (1.9’’/ft). For the meadows and shrub areas, the root depth is equal to 0.20 and 0.30 m, respectively, while for the areas where trees are planted, we assumed a root depth value of 1 m. Therefore, the corresponding WHC is equal to 32, 48 and 158 mm, respectively.

The soil water content was modelled according to the following criteria to calculate the associated daily demand for irrigation:

- the irrigation system is not activated if: i) it rains at least the daily water need, ii) in dry days the soil water content is at least 80% of the WHC.
- the irrigation system is always activated when the soil water content drops below the threshold of 80% of the WHC.
- the WHC of the soil is recovered only after sufficiently large precipitation events but not from irrigation, which is used to ensure that the water need of vegetation is fulfilled. The excess precipitation, when larger than the soil WHC, percolates due to gravity until the deep soil and is drained away.

The continuity equation of the storage tank was then applied at the daily scale, by using a typical algorithm involving the assessment of the rainwater volume $V_t$ (in m$^3$), stored in the system at time t, following the releasing of the volume $Y_t$ (in m$^3$):

$$V_t = Q_t + V_{t-1} - Y_t - O_t \qquad Y_t = \min\left\{ \begin{array}{l} D_t \\ V_{t-1} \end{array} \right. \; and \quad V_t = \min\left\{ \begin{array}{l} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{array} \right. \tag{1}$$

where $O_t$ (in m$^3$) is the overflow volume, $D_t$ (in m$^3$) the water demand and $S$ (in m$^3$) the tank capacity. This algorithm, named Yield After Spillage (YAS), provides a cautionary assessment of the system efficiency, independently on the temporal scale adopted for the model (Fewkes, 2000; Fewkes and Butler, 2000).

Given that previous studies demonstrated the scarce influence of the initial condition of the tank (Mitchell et al., 2008), we adopted here an empty storage tank condition at the beginning of our simulations. According to the final design, the tanks is assumed to be covered, therefore evaporation from the tank between rainfall events is assumed to be negligible.

## 3 RESULTS AND DISCUSSION

The analysis of the efficiency of a RWH system is based on the simulation of the system performance over a sufficiently long period. To this aim, we assumed as a reference in this work the quasi bi-centennial historical rainfall series (1833-2008) recorded at the meteorological station of Genova University (see Palla et al. 2011). As indicators of the performance of the RWH system, two temporal reliability indexes (fraction of time when storage is not empty, *R*, and when the demand is fully met, $R_e$) and two volumetric reliability indexes (efficiency, $E_T$, and overflow ratio, $O_T$) were used. In particular, the temporal reliability indexes are non-dimensional variables, respectively defined as:

$$R = m/N \qquad\qquad R_e = 1 - n/N^* \tag{2}$$

where *m* is the number of days when the tank is not empty, *N* is the total number of days, *n* is the number of days when the stored volume does not fully meet the demand and N* is the number of days when $D_t > 0$.

The two non-dimensional volumetric reliability indexes are:

$$E_T = \frac{\sum_{t=1}^{N} Y_t}{\sum_{t=1}^{N} D_t} \qquad O_T = \frac{\sum_{t=1}^{N} O_t}{\sum_{t=1}^{N} Q_t} \tag{3}$$

where $E_T$ is defined as the ratio between the rainwater volume provided by the tank and the associated water demand over the simulation period, while $O_T$ is defined as the ratio between the overflow volume and the total rainwater volume collected over the simulation period.

The behavioral model of the RWH system provides the daily evolution of the following variables: rainwater inflow, stored and overflow volume. The trend of the temporal (*R* and $R_e$) and volumetric ($E_T$ and $O_T$) reliability indexes was determined per each of the adopted scenarios upon varying the size of the tank.

The annual mean demand fractions *D/Q* derive from the total water demand for irrigation, which depends on the distribution of daily precipitation amount along the year and the amount of water collected from the various surfaces. For the three adopted rainwater collection scenarios the values of the demand fractions are equal to 0.295, 0.547, and 0.222, respectively. For each scenario the storage tank was set equal to 30, 60, 120, 240 and 480 $m^3$ and the associated storage fractions (*S/Q*) are indicated in Table 1, together with the mean values of the rainwater amount that is used for irrigation ($Y_T$) at the yearly scale, corresponding to the amount of potable water saved with respect to a “traditional” supply from the urban water distribution system.

In the following graphs, the values of the performance indexes are reported, as a function of the storage fraction. The reported values are calculated with reference to an annual time frame, for the whole historic series of the observed precipitation. The graphs report, in the form of boxplots, the non-parametric distribution of the values obtained per each index.

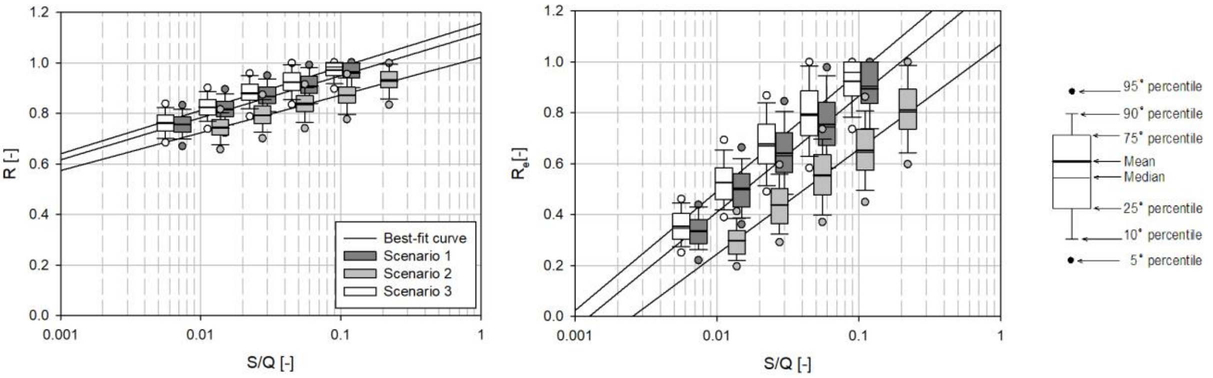

**Figure 2.** Temporal reliability indexes as a function of the storage fraction for the three investigated scenarios.

| *S* [m$^3$] | | *S/Q* [-] | | | $Y_T$ [m$^3$] | | |
|---|---|---|---|---|---|---|---|
| | Scenario | 1 | 2 | 3 | 1 | 2 | 3 |
| 30 | | 0.007 | 0.014 | 0.006 | 374 | 326 | 395 |
| 60 | | 0.015 | 0.028 | 0.011 | 530 | 454 | 561 |
| 120 | | 0.030 | 0.055 | 0.022 | 688 | 575 | 733 |
| 240 | | 0.060 | 0.111 | 0.045 | 840 | 707 | 894 |
| 480 | | 0.119 | 0.221 | 0.090 | 1046 | 940 | 1082 |

**Table 1.** Storage fraction and total annual saving obtained for the RWH system in the three simulated scenarios.

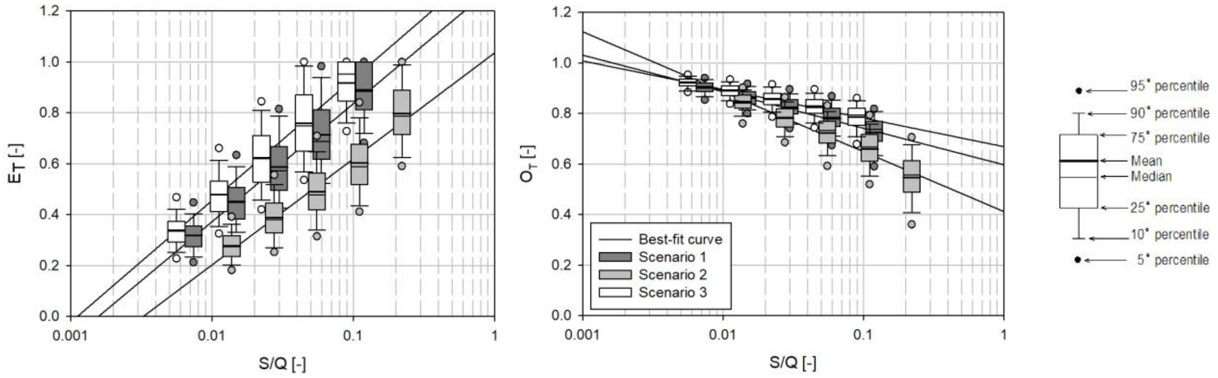

**Figure 3.** Volumetric reliability indexes as a function of the storage fraction for the three investigated scenarios.

Results show that the most efficient scenario is the one collecting rainwater from the brick roof (Scenario 3), although very similar performance are obtained in Scenario 1, where the drainage from ground surfaces is collected (the demand fraction is indeed very similar in the two cases). Scenario 2, with the rainwater collected from the sheet metal roof is less performant due to the reduced size of the collecting surface (and a demand fraction *D/Q* = 0.547, more than twice the other two scenarios). The fraction of time when the demand is fully met ($R_e$) and the efficiency ($E_T$) range between 0.2 and 1, and obviously increases with the tank size. Both are larger than 60% when the storage fraction is larger than 0.03, 0.1, 0.02 for Scenarios 1, 2 and 3, respectively. This means that a larger tank volume is required in Scenario 2 to achieve the same system reliability of the other two solutions. In all cases, the overflow ratio is quite high, reflecting the large portion of rainwater that is collected but not used for irrigation (due to the scarce synchronization between the availability and the demand). This indicates that further usages of the collected rainwater would be compatible with the demand for irrigation, e.g., the supply of toilet flushing in the public or nearby areas.

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