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Potential for Peak Flow Reduction by Rainwater Harvesting Tanks

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Abstract

The objective of the paper is to evaluate the potential of tank-based rainwater harvesting systems as source control methods to mitigate runoff flow peaks in urban areas. Water balance simulations of the rainwater tanks at the resolution time scale of 1 minute were carried out for this purpose using both high-resolution rainfall series and toilet water demand data from a previous experimental campaign, which involved six experimental households in southern Italy. Simulations show that significant reduction of the flow peak may be obtained with rainwater tanks depending on the tank size and on the household water demand.

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1. Introduction

In the recent years, rainwater harvesting (RWH) is gaining increasing attention as a complementary supply source to save fresh water in urban areas [1].

RWH systems normally make use of relatively small-size tanks to store rainwater collected over the building rooftop. Subject to basic treatment (normally filtration and/or chlorination), stored rainwater are locally used for both internal and external non-potable consumption (i.e. toilet flushing, garden irrigation, terrace cleaning, etc.).

Several studies at the household scale have been conducted in various countries over the years to analyze the performance of rainwater tanks [2][3][4][5][6]. These studies indicate that the RWH system water saving performance is markedly influenced by site-specific variables, i.e. the local rainfall pattern, the roof type and surface area, the tank size, the demand for rainwater, the number of people in the household, etc.

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Rainwater tanks have been recognized also as a method to mitigate environmental impacts of urbanization on storm water drainage systems and receiving water bodies [7][8][9]. The presence of rainwater tanks throughout urban areas may significantly increase the retention potential of the catchment and help reducing frequency, volume and peaks of storm water runoff conveyed to drainage systems [10][8]. Specifically, RWH operates as a storage-based source control solution: during rain events, a portion of the rainfall is captured and stored into the tank with a reduction of the surface runoff component. The obtained water abstraction is demand-driven [10] with demand magnitude and patterns affecting the tank design and efficiency [11].

Multiple benefits of RWH tanks have also been explored using behavioural models based on the long-term water balance simulation of the tank, with rainfall and household water demand being the typical tank inflow and outflow, respectively [12][13][14][15][16]. In particular, very recently [9] have investigated how model structure and parameters may affect the results of the simulations (and then the correct estimation of the tank design/reliability) with specific reference to the evaluation of the time scale for the analysis. Results show that the daily time step resolution may be appropriate for a correct evaluation of water saving performances of the RWH system. However, increased time resolutions for water balance simulations (at least the hourly time scale) are required if the objective is to evaluate the tank potential to reduce runoff volumes.

It is then expected that very high time resolutions (in the order of the minute) are mandatory if the tank effect on the reduction of the storm water flow peak is explored. In that case, extended rainfall data sets have to be treated and specific methods to disaggregate the household water demand data are to be used [9].

The overall objective of the present paper is to explore the tank potential to retain rainwater and reduce peak flow during rain events. For such a purpose, measured data concerning water consumptions at six pilot households localized in the south of Italy were considered for the analysis [17].

The model developed by [9] was used to disaggregate data and to derive the synthetic series of the household water demands for toilet flushing at the resolution time scale of 1 minute from observed patterns. The obtained water demand series, together with the available rainfall series, was used as the input for the water balance simulation of the tank in order to explore the reduction of rainfall peak flow.

Nomenclature

A	effective impervious area of the rooftop [m^2]
A_{TOT}	total rooftop area [m^2]
d	demand fraction [-]
D_d	average daily toilet water demand [m^3]
D_t	toilet water demand at time t [m^3]
E_{PR}	peak retention efficiency [%]
ϕ	rooftop runoff coefficient [-]
$Q_{D\ peak}$	volume discharged as overflow from the storage tank at peak time [m^3]
Q_{Dt}	tank overflow discharge volume at time t [m^3]
Q_t	inflow volume to the tank at time step t [m^3]
R_d	average daily rainfall [m^3]
$R_{\ peak}$	rainfall at peak time [m]
R_t	collected rainfall at time step t [m]
S	tank storage capacity [m^3]
s	storage fraction [-]
t	time step [s]
V_t	volume in store at time t [m^3]
Y_t	yielded volume of rain water from the storage tank at time t [m^3]

2. Methods

The adopted simulation model [9] consists of three basic modules aimed i) at evaluating the rainwater inflow to the tank, ii) at estimating the rainwater demand pattern, and finally iii) at simulating the tank water balance.

As for the evaluation of the inflow, the tank is considered to be filled exclusively by the rainwater, which falls on the rooftop of the building. Assuming the rainfall constant within each computational time interval t (one minute), the volume of rainwater adducted to the tank is calculated as:

$$Q_t = \phi \cdot R_t \cdot A_{tot} = R_t \cdot A \quad (1)$$

where Q_t [m³] is the inflow volume supplied to the tank at time step t ; ϕ [-] is the runoff coefficient; A_{tot} [m²] is the total rooftop area for rain water collection connected to the tank; $A = \phi \cdot A_{tot}$ [m²] is the effective impervious area of the rooftop; and R_t [m] is the collected rainfall at time step t .

Toilet demands used for the analysis are determined according to a two-phase procedure. For the first phase, the series of toilet daily demands over the year is generated, i.e. the number of daily toilet flushes (per capita) occurring in the house during each of the 365 days of the year. To achieve such an aim, data on the users' habits concerning both the daily frequency of toilet use and the number of users present at each of the six houses during the day are examined. In particular, total flushes occurring during each day of the monitoring period are obtained and daily per capita toilet flushes are calculated based on the user presence at home. Obtained values are then fitted by a normal probability distribution function (PDF) that is finally assumed to represent the toilet use daily pattern for the whole year. The PDF is used to generate randomly 365 daily values of (per capita) toilet flushes for all the days of the year. Then, the obtained values have to be multiplied for the number of household users to obtain the total daily number of flushes in the house.

The second phase of the procedure allows for scaling the toilet use daily pattern down to the needed 1 minute time step resolution. The procedure is described in detail in [9] and is based on defining appropriate patterns of toilet use frequency (at the required time step), starting from the observed daily pattern. Each day of the period of observation is analyzed separately and each monitored flush event is labeled according to its occurrence time (hour, minute) during the day. Flushes during the day are chronologically aggregated using a 1-minute time interval. The obtained daily chronological series of aggregated flushes are "overlapped" and flushes falling within the same minute of different days are summed. They are then cumulated and normalized to the total number of flushes observed during the whole monitoring period to obtain a cumulated relative frequency distribution (CFD) of toilet use during the day at the selected 1-minute scale of aggregation (intra-daily demand pattern). At the end, random picks (with uniform distribution) from the obtained CFD (in number equal to the household daily flushes resulting from phase one) allow to determine the daytime minute to be assigned to each flush. Phase two is repeated for all the days of the year to obtain the series of toilet flushes for the tank simulation.

To simulate the tank water balance, a typical RWH system scheme was adopted: the rain water precipitated on the building roof is collected and temporarily stored within the tank that is equipped with a dedicated piping system to supply rainwater to the toilet cistern. The toilet is assumed to use primarily the water accumulated into the rainwater tank and to use the water from the main only if the tank is empty.

The routine used to track the tank water balance was based on the yield-after-spillage (YAS) algorithm as tank release rule [18].

To evaluate the performance of the tank to reduce peak flows to the downstream drainage system, the following parameter E_{PR} [%] measuring the peak retention efficiency is introduced:

$$E_{PR} = \left[1 - \frac{Q_{D \text{ peak}}}{A \cdot R_{\text{peak}}} \right] \cdot 100 \quad (2)$$

where $Q_{D\ peak}$ [m³] and $R_{\ peak}$ [m] are the volume discharged as overflow from the storage tank and the rainfall at the respective peak times. E_{PR} is a measure of how much the storage tank is able to reduce/retain the peak of rainfall intensity of the precipitation event. E_{PR} is evaluated for each event separately.

The tank performance was explored by following a non dimensional approach based on the use of two dimensionless parameters (the demand fraction d and the storage fraction s) allowing to account for different combinations of tank storage capacity, roof area, rain water demand and precipitation (Fewkes and Butler, 2010):

$$d = \frac{D_d}{A \cdot R_d}; \quad s = \frac{S}{A \cdot R_d} \quad (3)$$

with D_d and R_d being the average (in the year) daily values of toilet water demand and rainfall, respectively, and S [m³] is the tank storage capacity.

Values of d and s were selected for the model application based on the range of values that household demand, tank storage capacity, rooftop area and precipitation may assume in the practice. In particular, following results by [9] and by Fewkes and Butler (2000), different demand and storage scenarios were considered. Four values of demand fraction ($d = 0.5$; $d = 1.0$; $d = 2.0$; $d = 4.0$) were assumed while six values of storage fraction were used, with s equal to 1, 2, 3, 5, 10, and 20.

In principle, as d and s are defined at the daily scale (i.e. D_d and R_d are daily values), the selection of their value is irrespective of water demand and rainfall temporal distribution during the day. The influence of such distribution was directly taken into account at the time that detailed rainfall and water demand patterns are used for the water balance simulation of the tank.

3. Used data

Rainfall data for the investigation were provided by the Sicilian Agro-meteorological Service (SIAS) and consist of the precipitation series recorded at the rainfall gauging station of Catania S. F. La Rena, located in the east coast of Sicily close to Catania International Airport at about 3 m a.s.l. The selected gauge operates remotely since year 2002. The average annual precipitation is approximately 682 mm, with major concentration of rainfall during the semester September-February (see Fig. 1)

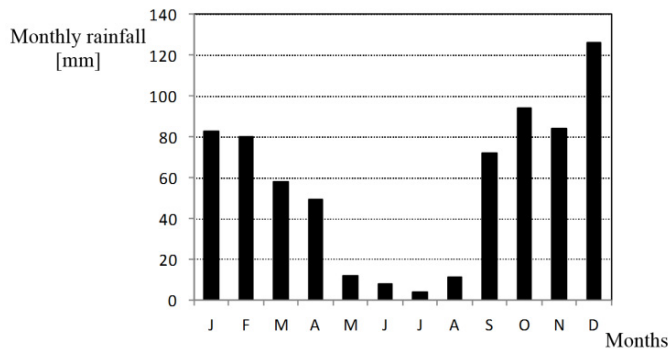


Fig. 1. Monthly distribution of observed rainfall at the considered rain station.

Very recently, the gauging stations has been updated to provide rainfall measurements with time resolution of 1 min and a 0.2 mm step. A complete one-year data set (from 18 April 2013 to 17 April 2014) of precipitation records has been made available by SIAS and was taken into account for the simulations. During such a period, the total observed precipitation was 481.6 mm.

Rainfall depths at time step of 1 minute for the whole year resulted in a series (and in the respective series of inflow volumes Q_i) of 525'600 data.

Data concerning water demands were extracted by the database of the results of a monitoring campaign conducted by the authors during the year 2006 in six households in Sicily (Italy). The toilet water use pattern of the six households was monitored for a 2-week period each. Specifically, the times of the day each toilet was flushed were recorded during the whole monitoring period with the accuracy of 1 sec.

A description of the households characteristics is presented in [17] while main results of the toilet demand monitoring campaign for the six households are summarized in Table 1.

Table 1. Demand characteristics of the six monitored households.

Household	Total flushes during the two weeks	Average daily flushes (flushes/day/capita)
1	226	3.8
2	143	4.2
3	311	6.3
4	186	5.2
5	345	4.9
6	129	3.8

Data concerning the toilet demand for the six households were grouped together in a resulting virtual “average” household. Then, the procedure described by [9] was applied to such an “average” household to generate water demand series at the toilet at the selected time scale of 1 minute.

The normal PDF used to fit the observed data of the “average” household at the daily scale is plotted in Fig. 2a, together with the observed cumulated frequency of per capita daily flushes (fourteen daily data for the two-week period having mean 4.69 flushes/day/capita and standard deviation 1.48 flushes/day/capita). The PDF was then used to generate the synthetic series of the number of daily toilet flushes for the whole year (by 365 random picks).

Then, recorded data aggregated at the selected time scale of 1 minute were used to determine the detailed intra-daily pattern of the toilet frequency of use. The resulting CFD for the 1 min time step is plotted in the graph of Fig. 2b and shows how flushes are distributed (on average for the 2-weeks of records) during the 24 hours in the considered “average” household.

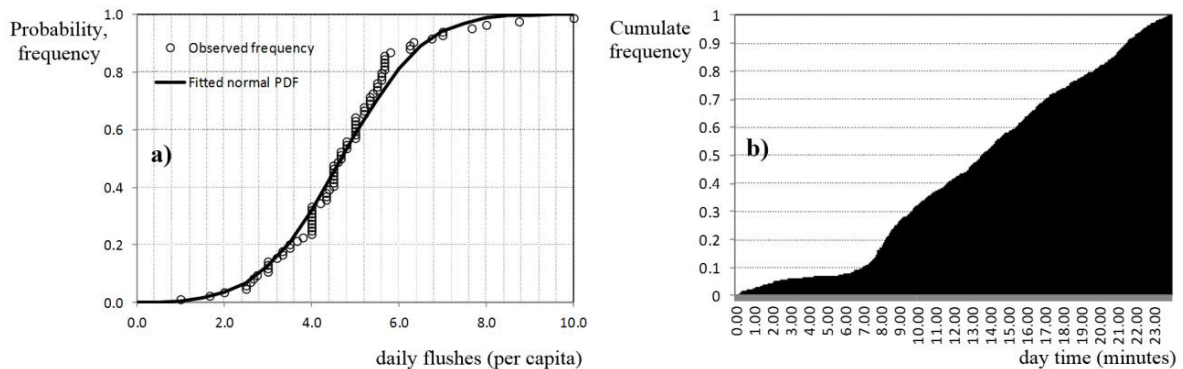


Fig. 2. (a) Fitted normal PDF to observed daily flush frequency; (b) Cumulated relative frequency distribution of toilet use during the day.

The obtained household toilet use intra-daily pattern was found to be similar to patterns reported in other studies from literature (Garcia et al., 2004; Blokker et al., 2010) with toilet use being mainly concentrated early morning when people is waking up, afternoon, and night before going to sleep. The CFD was used to determine the time

series of occurrence of toilet flushes during the day for the year of simulation (at the resolution of 1 minute), according to the procedure by [9].

4. Results of the simulations and discussion

The analysis of the overflow component from the water balance simulation of the tank allowed investigating the tank behavior with regard to its stormwater retention performance at the peak flow condition.

To show the behavior of the tank during rain events at the selected time scale, in Fig. 3a the results of the tank simulation during the event of February 22nd, 2014 (total rainfall 4.8, duration 11 min) are reported for $d=1$ and $s=0.5$. The event shows a peak of intensity of a 1.2 mm in 1 min at hour 14:16. At the beginning of the event, the tank is empty. The figure clearly shows that the rainwater tank acts an initial abstraction of volume from the rainfall event up to the achievement (at hour 14:15) of the condition of tank full (the tank retention capacity is saturated). Then, overflows from the tank start to occur. Results of the simulation of the same event for $d=1$ and $s=1$ (two times larger than the previous case) are reported in Fig. 3b. Overflows from the tank result to be delayed at hour 14:16 due to the increased retention capacity of the tank. More interestingly, the figure shows that the tank also has a positive effect on the reduction of the rainfall intensity peak from 1.2 mm/min to about 1.05 mm/min.

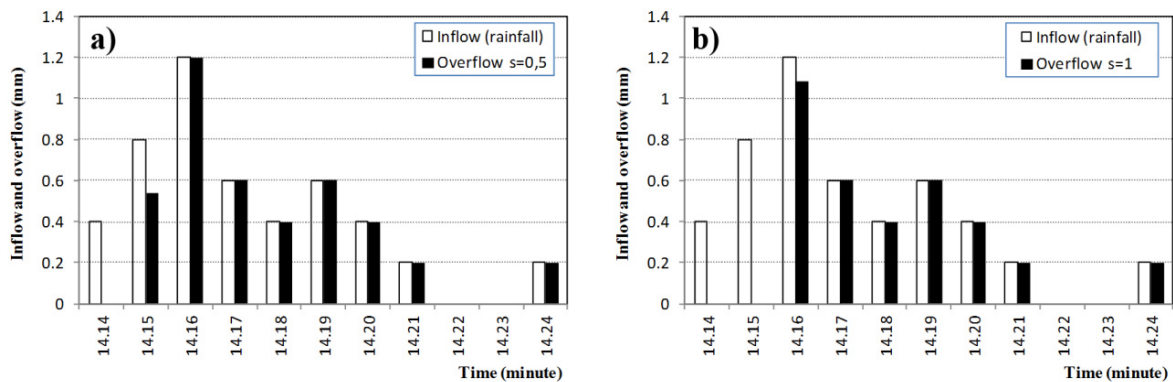


Fig. 3. Water balance simulation of the event of Feb 22nd, 2014, (a) simulation for $d=1$ and $s=0.5$; (b) simulation for $d=1$ and $s=1$.

This analysis was extended to the entire year and the effect of peak reduction was observed to occur for a number of rainfall events, depending on the characteristics of each event (i.e. the position of the peak intensity within the event time length) and of the tank (size, pre-event filling condition). The events were assumed independent if they had a minimum antecedent dry weather period of 1 hour and a frequency analysis was conducted to evaluate the events that showed a reduction of the rainfall intensity peak.

Part of the results of the simulations are presented in the dimensionless graphs of Fig. 4. The figure reports the curves of the tank peak retention efficiency E_{PR} as a function of the cumulated relative frequency (of exceedance) of rainfall events in the year. The plotted curves are exemplificative of a household with 1 user only and are obtained for the different values of s . The graphs show results for $d = 0.5$, $d = 1.0$, $d = 2.0$ and $d = 4.0$, respectively.

The curves decrease monotonically with steep (almost vertical) initial and final queues (close to $E_{PR} = 0$ and $E_{PR}=1$, respectively). Smaller curve derivatives are shown in the mid portion. Also small steps in the curves are shown at $E_{PR}=0.5$ due to the way the available rainfall data have been provided (multiple values of 0.2 mm).

A relatively high number of events for which the tank does not provide any reduction of the peak ($E_{PR} = 0$) is shown depending on values of s and d . As expected increased E_{PR} are obtained for increasing values of s . Also the more the demand d for toilet is the higher is the reduction of flow peaks due to augmented storage availability within the tank. As for example, for a typical tank size value $s = 5$, the curves show peak reductions in the range 30%-65% for at least 50% of the events depending on the value of d .

As expected, due to the used dimensionless approach, the effect of increasing the number of persons in the house was shown to be very limited. In fact, further simulations carried out using a toilet demand series derived from Fig. 2 for a 2-users and a 4-users household have conducted to curves very close to those presented in Fig. 4.

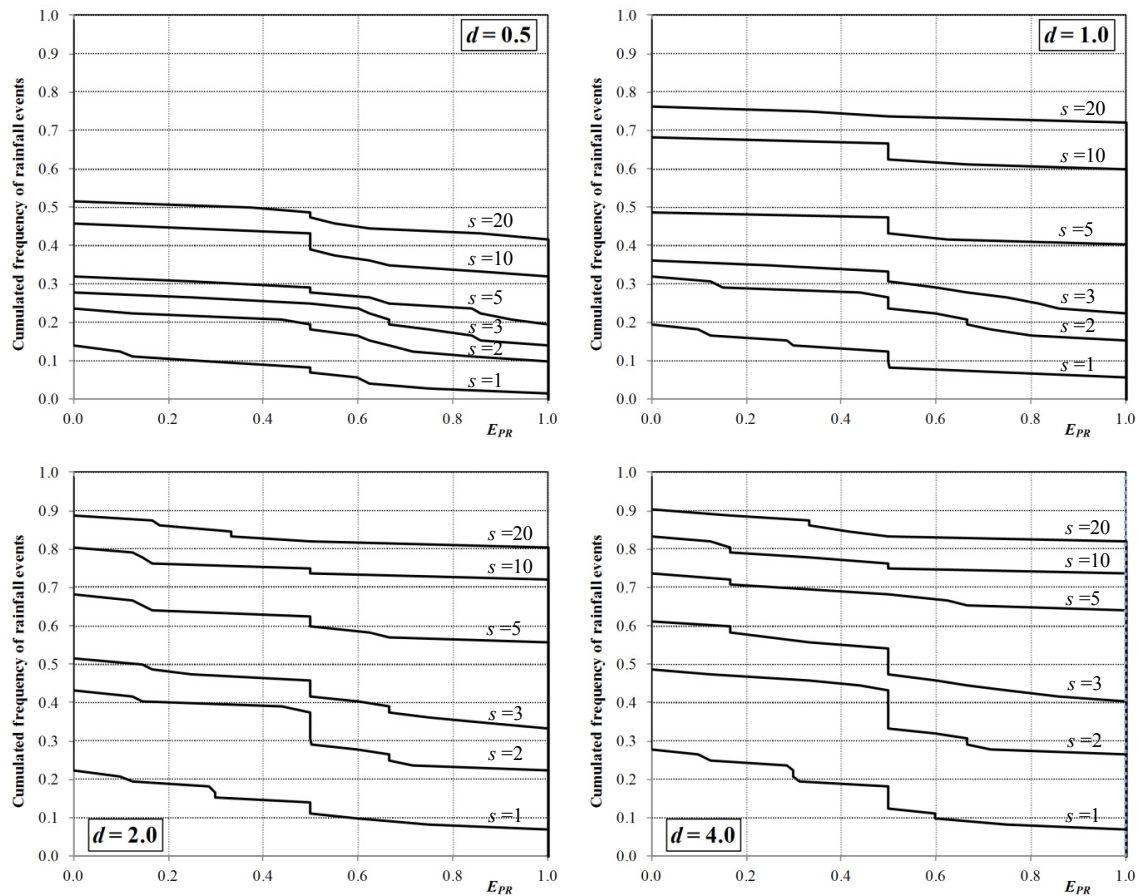


Fig. 4. Tank peak retention efficiency as function of the cumulated relative frequency of rainfall events in the year.

5. Conclusions

Water balance simulations of rainwater tanks were carried out in this paper to explore the potential benefits of tank-based rainwater harvesting systems to reduce runoff flow peaks at the household scale.

According to the aim of the analysis, simulations were carried using appropriate high temporal resolution sets of data of rainfall and water demand in the households (one minute time step), as input for the water balance model.

In particular, data concerning toilet water consumptions were extracted from the database of results of an experimental campaign involving six experimental households in southern Italy. A specific procedure from the literature was also adopted to disaggregate available data from the daily time scale and to generate a synthetic series of toilet water demands for the one-year water balance simulation of the rainwater tank.

The simulations were run using a dimensionless approach and showed the used time step to be appropriate for peak flow analysis. Specifically, results show that significant reduction of the flow peak may be obtained with the use of rainwater tanks depending on the tank size and on the household water demand patterns.

Results of the investigation may open discussion on using tank-based RWH as source control method to increase distributed retention in urban catchments and to reduce peak flow rates to the drainage system.

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