

EVALUATION OF DOMESTIC WATER SAVING BY ROOFTOP RAIN WATER COLLECTION IN SICILY

Alberto CAMPISANO¹ & Carlo MODICA²

(1) Department of Civil and Environmental Engineering, University of Catania, Italy, e-mail: acampisa@dica.unict.it

(2) Department of Civil and Environmental Engineering, University of Catania, Italy, e-mail: cmodica@dica.unict.it

ABSTRACT

In this paper, a regional scale analysis to evaluate the water saving performance of rooftop rain water harvesting systems for domestic use is developed. The adopted methodology to evaluate water saving is presented along with an application to 17 rainfall gauging stations in Sicily (Italy). Compared to literature existing methods, a novel dimensionless parameter is proposed to better describe the intra-annual character of the rainfall patterns. Easy-to-use regional regressive models to evaluate the water saving performance and the overflow discharges of the harvesting system at regional scale are determined, based on the simulation results of a daily time step behavioral model with a yield-after-spillage algorithm as release rule from the rain tank. The regional models demonstrate good fits between model predictions and simulated values of both system water savings and overflows from the tank.

1 INTRODUCTION

In many parts of the world, domestic water saving practices have awakened increasing attention due to the grow of water demands in urban areas. Some of these practices have concerned with the installation of systems able to reduce the household water consumption (i.e dual flush toilet systems, tap flow aerators, etc.) and also with the adoption of educational programs to diffuse water sustainability concepts within the population.

In this context, also domestic rain water harvesting (DRWH) has recently become an important option as a water source, especially for urban and sub-urban areas affected by restricted availability of freshwater.

DRWH defines the small-scale concentration, collection, storage and use of rainwater runoff coming from rooftops, courtyards and other treated surfaces for domestic purposes. It is largely recognized (Vickers, 2001; USEPA, 2004) that rain waters can replace potable water from mains for several less quality-exigent water uses in houses such as toilet flushing, terrace cleaning or private garden watering. Moreover, despite studies from different parts of the world reveal the presence of contaminants in rooftop rain waters (Meera and Mansoor; 2006), in specific geographical contexts these waters have been identified also as a major source also for drinking, cooking and sanitary purposes (Duncker, 2000) since they did not present increased risk of

gastrointestinal illness when compared with public mains water (Dillaha III and Zolan, 1985; Heyworth, 2001; Abdulla and Al-Shareef, 2009).

Results of investigations concerning the analysis of water uses in urban households for water saving objectives (Butler et al., 1995; Mukhopadhyay et al., 2001; Lazaroza et al., 2003 Campisano and Modica, 2010) have shown that a significant part (up to 30%) of water in houses is typically used for toilet flushing. This value suggests potentially high water saving benefits from the primary use of harvested rain water to the flush of toilets (Glist, 2005; Jones and Hunt, 2008; Jones et al., 2009). For this use, only basic water treatment (i.e. filtration and chlorination) should be accomplished, and storage tanks with limited size would be required, being the daily toilet water demand as relatively constant during the year.

Many DRWH systems and schemes have been proposed by researchers in the past few decades (Donati, 1995; Fewkes, 1999; Aylward et al., 2006). Other authors (Pandey et al., 1991; Mikkelsen et al., 1999; Sturm et al., 2009) have investigated the economical feasibility of these systems with particular reference to rooftop rainwater harvesting techniques. Normally, for the examined cases, the costs of rainwater collection result quite small, whereas the largest economic issue is the capital cost to construct the system. Then, in most of the cases, the most important design decision concerns the evaluation of the storage capacity to be built according to the desired level of performance of the adopted DRWH system.

There is a large literature concerning methodologies to estimate performance and sizing of rainwater harvesting systems. Approaches include water balance simulation analysis (Fewkes and Butler, 2000; Handia et al., 2002; Goel and Kumar, 2005; Villareal and Dixon, 2005; Ghisi and Ferreira, 2007; Panigrahi et al., 2007), probabilistic methods (Lee et al., 2000; Guo and Baetz, 2007) and economic optimization (Dominguez et al., 2001; Liaw and Tsai, 2004). In general, results indicate that storage capacity cannot be standardized, being markedly influenced by site-specific variables such as local rainfall, roof area, water demand and number of people in the household (Mwenge Kahinda et al., 2007; Aladenola and Adeboye, 2009; Stys, 2009; Eroksuz and Rahman, 2010).

In order to generalise results, some authors have recently started exploring the variability of water saving at different spatial and temporal scales. In this context, Fewkes (2000) investigated how spatial and temporal fluctuations in rainfall could be incorporated into behavioural models of DRWH systems. In particular, water balance simulation analysis has been conducted according to different reservoir operating algorithms and various temporal scales.

Cheng and Liao (2009a; 2009b) explored regional zoning for rainwater harvesting systems in northern Taiwan using cluster analysis. Using the precipitation data from 72 stations, they derived a dimensional indicator to score rainwater harvesting system potential as function of regional rainfall characteristics and system storage size.

Hanson et al. (2009) provided a log-linear regressive relationship to calculate required storage capacity for a rainwater harvesting system which is generally applicable in the U.S.. The equation is based on results of a behavioral model of a DRWH system and applied to daily time step records at 232 U.S. precipitation gauging stations. Although, the equation demonstrates good predictive performances at national scale, its application requires data elaboration to calculate climatic variables (daily rainfall statistics) to predict storage capacity.

In 2009, a research program has been launched at the University of Catania (Italy) to investigate water saving obtainable by rooftop rain water harvesting for domestic use.

A methodology to specifically evaluate water saving at regional scale, based on the introduction of a novel dimensionless parameter, is presented in this paper and an application of the methodology to 17 Sicilian rain gauging stations is reported.

A parameter-parsimonious and easy-to-use regional regressive model to evaluate the water saving performance of a DRWH system was derived, based on the results of the simulations of a daily time step behavioral model with a yield-after-spillage algorithm as rain tank release rule.

2 METHODOLOGY

The typical scheme of a domestic rainwater harvesting system is based on the collection of rain waters coming from the building roof (and/or other treated surfaces) and to their temporary storage within a rain water tank. In this scheme, demand for water uses in the house which are compatible with rain water quality is satisfied primarily by water accumulated in the storage tank, and only then by water from the mains supply. In the present research, the demand was limited to the toilet flushing use and it was assumed to occur at a constant daily rate since toilet usage does not show large daily variability (Fewkes, 2000).

The evaluation of the water saving derived by such a DRWH system scheme was carried out by means of water balance simulations using a behavioral model based on the well known yield-after-spillage (YAS) algorithm tank release rule. The YAS operating rule assumes the current yield as the minimum value between the volume of stored rainwater at the previous time interval and the demand in the current time interval. The current stored rainwater is then obtained adding the current rooftop rainwater runoff and subtracting the current yield to the volume of rainwater in storage at the previous time interval, with any excess (with respect to tank storage capacity) discharged via the overflow to the sewer system (Jenkins et al., 1978). According to Fewkes (2000), this operating algorithm was found to provide a conservative estimate of system performance in comparison to other algorithms, irrespectively of the model time interval.

Several variables contribute to the water saving performances of the DRWH systems. Along with the characteristics of the installation (i.e. rain water tank storage capacity), of the household consumption (water demand patterns) and of the building (effective rooftop area), the pluviometric characteristics of the site result crucial to evaluate the obtainable water saving. Then, the identification of specific variables representing the pluviometric characteristics (such as average precipitation, dry weather periods) can allow to derive useful relationships for the evaluation of water saving at regional scale.

To consider different combinations of demand, storage capacity, roof area and precipitation, two dimensionless ratios are traditionally taken into account in the literature, namely demand fraction and storage fraction. The demand fraction d is calculated as D/AR , where D is the water demand (m^3) in a fixed time period, A is the effective roof area (m^2) and R is the total rainfall (m) in the same period. The storage fraction s is calculated as S/AR where S is the storage capacity (m^3).

Normally, the two described ratios have been applied with reference to the yearly

rainfall R . In this paper, the average daily values of D and R are considered and the modified storage fraction:

$$s_m = \frac{S}{D \cdot n_D / n_R} \quad (1)$$

is proposed for the simulations as alternative parameter to the dimensionless ratio s , to better describe the character of the intra-annual rainfall patterns.

In eq. (1) n_D and n_R are the number of dry and rainy days in the year, respectively. Since the ratio n_D / n_R can be taken as the average dry period (days) in the year per each rainy day, parameter s_m allows to relate the available storage capacity to the required water demand during the defined time period. It should be emphasized that s_m results of easy calculation being values of n_D and n_R normally provided as basic data of rainfall stations.

The daily time step was adopted for the simulations, as recommended by Fewkes and Butler (2000). Simulations with larger time intervals (monthly) result in a more economic data set but they would provide inaccurate prediction of system water saving performance. On the other hand, smaller time intervals (typically hourly) would require to treat a too extended set of rain data (often difficult to find) and also to know detailed information on the demand use patterns in houses.

Yearly water balance simulations were performed by the described model to determine the performance of the DRWH system for a range of the adopted dimensionless ratios.

The performance of the DRWH system was described by evaluating the yearly water saving W_S (in percent):

$$W_S = \frac{\sum Y}{\sum D} \cdot 100 = \left(1 - \frac{\sum M}{\sum D} \right) \cdot 100 \quad (2)$$

where Y is the volume yielded from the storage tank, M is the volume supplied by the mains, and where the sums are extended to each year of the water balance simulation.

Eq. 2 shows that water saving assumes the value 0% when only water from mains is used ($M = D$) and the value 100% when only stored rain water is used ($M = 0$).

The yearly overflow discharge O_D from the tank (in percent) was also evaluated to derive indications on the amount of excess rain waters which can be used for other domestic purposes:

$$O_D = \frac{\sum Q_D}{\sum AR} \cdot 100 \quad (3)$$

where Q_D is the volume discharged as overflow from the storage tank, and sums are extended to each simulation year as well.

Results of simulations were statistically elaborated by a frequency analysis. In detail, values of W_S and O_D characterised by prefixed levels of exceedance frequency f were determined. The frequency levels 50%, 75% and 90% were taken into account for both water saving and overflow discharge evaluation.

Finally, a regression analysis at regional scale was conducted to relate the system

performance to the adopted dimensionless parameters. To this purpose, the following regressive relationships were proposed, based on the simulation results:

$$W_s = \frac{a_1 \cdot s_m}{b_1 + s_m} \cdot d^{c_1} \quad (4)$$

$$O_D = 100 - \frac{a_2 \cdot s_m}{b_2 + s_m} \cdot d^{c_2} \quad (5)$$

where a_1 , b_1 and c_1 and a_2 , b_2 and c_2 are the regressive coefficients to be calibrated.

The form of eqs. (4) and (5) assures asymptotically increasing values of W_s and decreasing values of O_D as s_m increases, the asymptote being strictly dependent on the demand fraction d .

3 THE CASE STUDY

3.1 Used data

The comprehensive plan of the research provides to evaluate potential water saving deriving by the use of rooftop rainwater for the domestic toilet flushing by applying the presented methodology to the data series recorded at several rain gauging stations in Sicily. The island is the largest Italian region with a total surface area of 25.711 km² and a population over 5 million people, mostly localised in coastal areas. The climate is typically Mediterranean with an average yearly rainfall of about 720 mm prevalently concentrated within the semester October-March. Peaks of precipitation (above 1000 mm/year) are typical in the north-east sea-side of the island due to the presence of Etna Volcano which plays an important role in the formation of orographic precipitation. Smaller precipitations are localised in the southern and western areas. Mean monthly precipitation in the island is reported in Table 1.

Table 1. Average monthly rainfalls (mm) in Sicily (1921-2005).

G	F	M	A	M	J	J	A	S	O	N	D
103.6	79.3	70.4	52.1	30.9	14.6	7.1	17.7	45.2	88.8	97.0	112.9

For the purpose of the investigation, daily rainfall data from 17 gauging stations operated by the Sicilian Regional Department of Water and Waste were considered. The chosen stations cover the whole region area (Figure 1) and are characterised by precipitation series with at least 25 year records in order to avoid inaccuracies in the estimation of water saving due to the shortness of data sets (Mitchell et al., 2008).

Characteristics of the selected stations are summarised in Table 2. In particular, the table reports the average values of the yearly rainfall h and of n_R for each station for the entire record period. Only days with precipitation higher than 1.0 mm are assumed as rainy days by the data provider.

The table shows high variability of data with yearly rainfall ranging between about 400 mm (Gela) and more than 1300 mm (Zafferana Etnea) and with rainy day number ranging between about 88 (Mistretta) and 46 (Cozzo Spadaro).

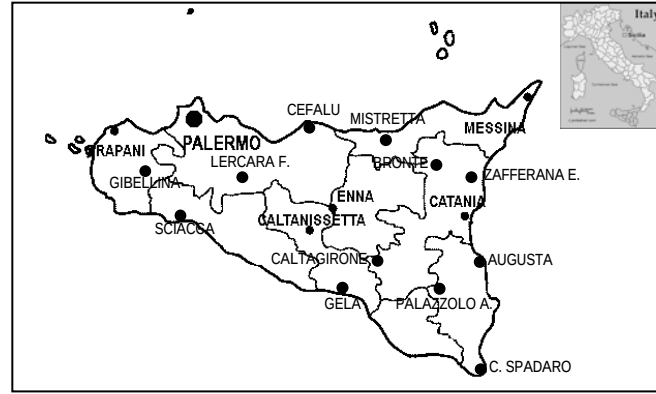


Figure 1. Selected rainfall gauging stations in the region.

Table 2. Main characteristics of the 17 considered rainfall gauging stations.

Rain station	Elevation (m a.s.l.)	h (mm)	n_R	Rain station	Elevation (m a.s.l.)	h (mm)	n_R
Bronte	780	595.6	73.5	Cefalù	30	679.9	70.9
Caltagirone	513	536.9	58.5	Palermo	31	474.4	64.4
Cozzo S.	50	433.0	46.0	Trapani	2	457.1	59.8
Palazzolo A.	607	662.1	66.1	Gibellina	410	705.2	76.7
Augusta	15	566.4	47.9	Sciacca	56	526.0	60.3
Zafferana E.	590	1311.8	81.1	Lercara F.	658	587.1	72.2
Catania	30	478.1	46.2	Enna	950	776.8	72.4
Messina	54	846.5	83.8	Gela	50	400.9	49.2
Mistretta	910	986.4	87.8				

3.2 Results and discussion

Daily water balance simulations using the described YAS model were carried out to evaluate the water saving performance of the DRWH system at each of the 17 sites.

The performance of the system was modelled considering values of the demand fraction d in the range 0.2 - 4.0 and values of the modified storage fraction s_m in the range 0.05 - 40.0. Selected ranges allow to consider values of water demand, storage capacity, roof area and precipitation characteristics useful for practical applications.

Results of simulations are presented by means of the dimensionless graphs illustrated in Figures 2 and 3 at demand fraction values of 0.2, 0.5, 1.0 and 4.0. In particular, the two figures show results relative to $f=50\%$.

Curves plotted in the left side graphs of Figure 2 show results of W_S predictions as function of s_m for all the examined rainfall stations. As expected, values of W_S increase for all the sites as the modified storage fraction increases (i.e. as S increases and/or D and n_D/n_R decrease). Moreover, curve derivatives tend to decrease, showing reduced marginal water savings as the modified storage fraction grows.

Also, the figure shows that water saving values tend to decrease as D/AR increases (i.e. as demand for toilet flushing increases and/or as roof area and daily rainfall

decrease). In addition, the graphs of the figure show that the curves flatten as D/AR increases; this behaviour clearly points out reduced benefits of adopting high-storage tanks when limited rooftop areas and rainfall are available and/or when very high water demands are required to the flush of toilets.

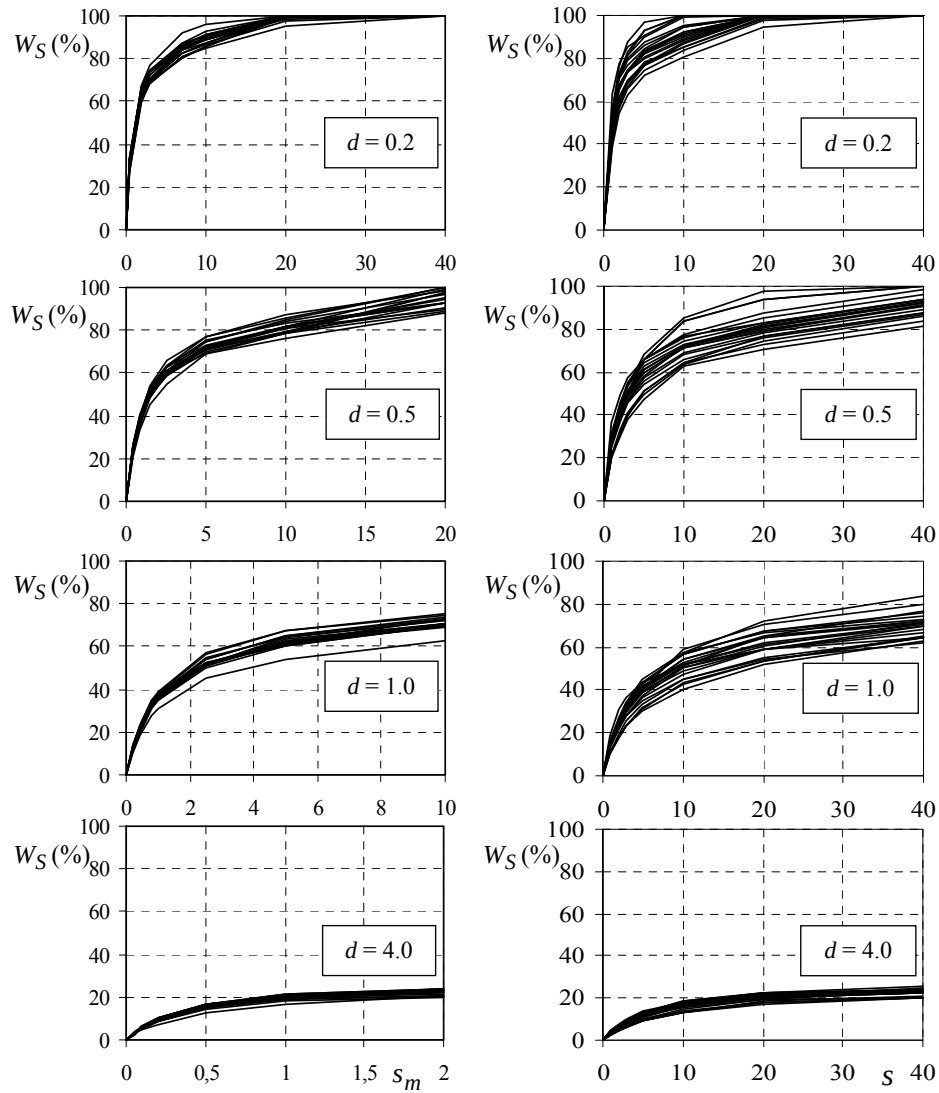


Figure 2. Water saving values for the 17 examined rainfall stations as function of demand fraction d and a) modified storage fraction s_m , b) storage fraction s .

From a general point of view, the curves of W_S for all the analysed rainfall sites result almost close one each other with differences of some percents. This behaviour confirms the ability of the chosen dimensionless parameters d and s_m to model the

DRWH system performances at the selected regional scale. In comparison, the curves on the right side graphs of Figure 2, obtained using the ratio s instead of s_m resulted not so tightly grouped. A proper range of s was considered for appropriate comparison with left side graphs. Globally, similar comparison results were obtained also for the other analysed levels of frequency.

Analogous considerations can be carried out for the graphs of Figure 3. The plotted curves show decreasing values of O_D and increasing curve flattening as s_m increases. Also, the figure shows that overflow discharge values tend to reduce as D/AR increases, with possible zero values (for $d = 4.0$) for large s_m values.

As for water saving, the curves of O_D result almost close one each other for the different D/AR , with the exception of the rainfall station of Zafferana Etnea that presents increased overflows due to its high yearly precipitation compared to the other examined stations.

Globally, significantly high overflow values are obtained in most of the examined cases pointing out the possibility to extend rain water harvesting to other domestic uses as well.

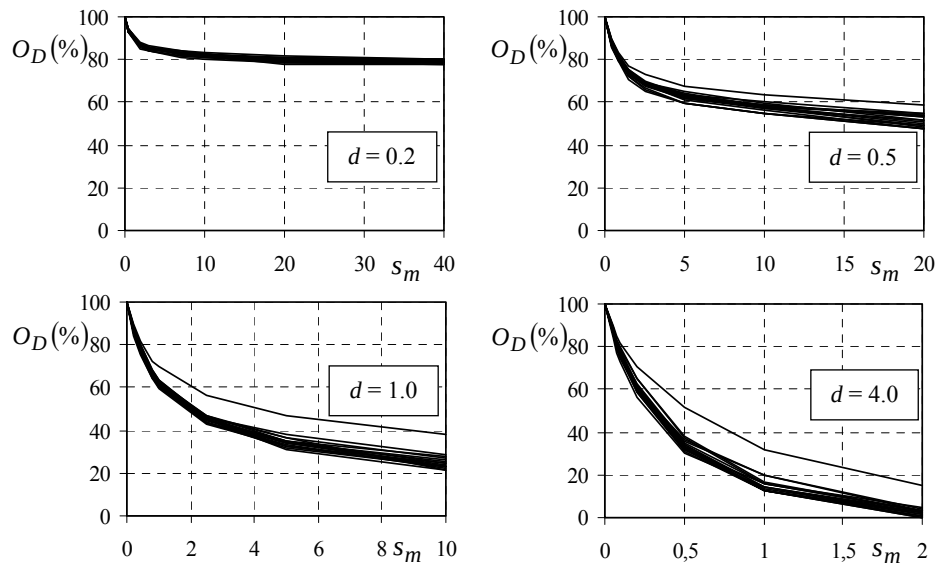


Figure 3. Overflow discharge values for the 17 examined rainfall stations as function of demand fraction d and modified storage fraction s_m .

Results of water saving and overflow discharge predictions for the 17 selected rainfall sites were finally used as input base of data to determine regional relationships (eqs. 4 and 5) for the three analysed f levels. In particular, obtained regressive coefficients a_1 , b_1 and c_1 and a_2 , b_2 and c_2 are reported in Tables 3 and 4 respectively, together with R^2 and mean absolute error (MAE) statistics.

Very high values of R^2 (all close to 0.98) were obtained for water savings. Slightly lower values of R^2 (between 0.92 and 0.96) were found for the tank overflows.

Table 3. Coefficients of the regional regressive equation of water saving and values of statistics.

f	a_1	b_1	c_1	R^2	MAE
50%	75.645	1.226	-0.206	0.981	2.934
75%	71.170	1.399	-0.227	0.979	3.005
90%	65.491	1.547	-0.259	0.976	3.186

Table 4. Coefficients of the regional regressive equation of overflow discharge and values of statistics.

f	a_2	b_2	c_2	R^2	MAE
50%	66.763	0.732	0.597	0.961	3.869
75%	74.472	0.664	0.543	0.946	4.948
90%	81.504	0.572	0.482	0.925	6.168

The generally good agreement obtained with regressions is also attested in Figures 4 and 5 where the graphical comparisons between simulated values of W_S^{sim} (from water balance simulations) and predicted ones W_S^{pred} (by eq. 3) and between simulated values of O_D^{sim} and predicted ones O_D^{pred} (by eq. 4) respectively, for the three level of exceedance frequency is shown.

Obtained high values of R^2 induce to not research for sub-region cluster analysis and to use eqs. 4 and 5 with coefficients from Tables 3 and 4 for the whole island.

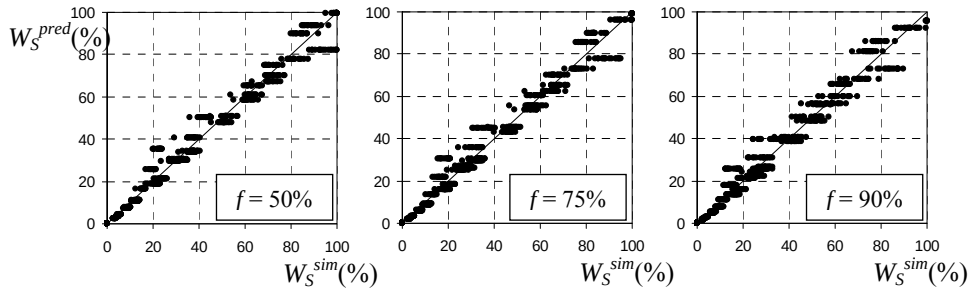


Figure 4. Comparison between simulated (from water balance) and predicted (by eq. 3) water saving for the considered levels of exceedance frequency.

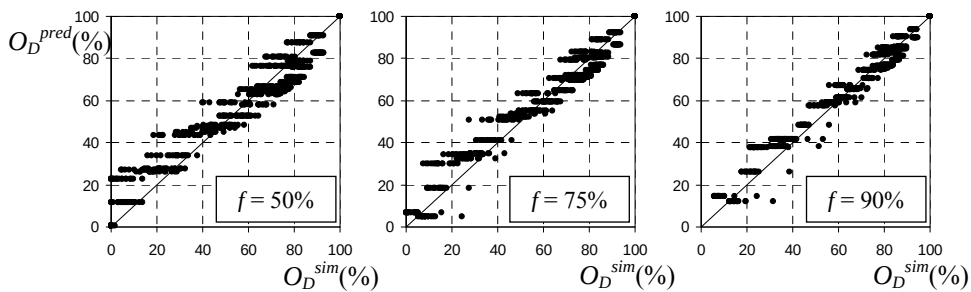


Figure 5. Comparison between simulated (from water balance) and predicted (by eq. 3) overflow discharge for the considered levels of exceedance frequency.

4 CONCLUSIONS

In this paper a regional scale analysis to evaluate the water saving performance of rooftop rain water harvesting systems for domestic use was developed.

A dimensionless methodology to evaluate the harvesting system performance was presented, based on long-term water balance simulations and allowing to consider practical ranges of demand, storage capacity, roof area and precipitation.

Compared to previous literature research, a novel dimensionless parameter, namely modified storage fraction, was introduced to better describe the character of the intra-annual rainfall patterns.

An application of the methodology to 17 rainfall stations in Sicily (Italy) was also presented, showing increased ability of the chosen dimensionless parameters (in comparison to literature methods) to model the DRWH system performances at the selected regional scale.

Results of daily time step water balance simulations show reduced marginal water saving increase as the modified storage fraction grows and point out the uselessness of setting up high-storage tanks when limited rainfalls and rooftop areas are available and/or when high toilet water demands are required.

Moreover, significant high overflow values were obtained in most of the examined cases suggesting the possibility to extend rain water harvesting to other domestic uses as well.

Easy-to-use regional regressive models to evaluate the water saving performance of the harvesting system and the overflows from the system tank were finally derived, based on the results of the simulations. The obtained region wide regression models for fixed frequencies of exceedance demonstrate good fits between model predictions and simulated values of both water saving and overflow discharges.

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