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SYSTEMS FOR RAINWATER HARVESTING AND GREYWATER REUSE AT THE BUILDING SCALE: A MODELLING APPROACH

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Abstract

In the light of water shortages, frequently affecting many regions worldwide, domestic rainwater harvesting, and greywater reuse systems represent an alternative source of water. This study fits this framework providing a hydraulic/hydrological model developed by means of the EPA's Storm Water Management Model. The model has been applied to a case study, which consists of an apartment building located in the city of Bologna and equipped with a hybrid rainwater-greywater recycling system. Cold, hot and recycled water consumptions were monitored for four flats located in the same building. Data analysis shows that the recycled water consumption accounts for a third of the total one, when considering only the supply for toilet flushing, while in garden flats, where recycled water is used also for watering, non-potable water consumption accounts for about 56% of the total. Continuous simulations were performed with 13 years daily rainfall data, and the long-term performance of different system combinations were evaluated. The case study shows a non-potable water saving efficiency of 75.86%, which accounts by 26.71% of the mains water withdrawal. Simulations performed by changing system type demonstrated that, due to the high number of inhabitants and of the great extension of the areas to be irrigated, the contribution of rainwater harvesting is moderate. In fact, non-potable water saving efficiency curves tend to flatten as the values of the tank volume increase. Furthermore, the system demonstrates a good ability in lowering both stomwater runoff and greywater volumes.

Key words: grey water recycling, rain water harvesting, SWMM, water saving

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1. Introduction

1.1. Context of the study

Water scarcity already affects every continent. Provide safe water and sanitation to people, ensuring at the same time a sound management of freshwater ecosystems, the environmental sustainability of solutions, and the economic prosperity of people, is widely recognized as one of the most demanding challenge of the millennium (http://sustainabledevelopment.un.org).

To face this challenge researchers, policy and decision makers cannot neglect that global water consumption rate is double the rate of population increase, which is growing by 83 million people annually (Bitterman et al., 2016). In addition, climate change is nowadays an unquestionable phenomenon that will likely increase precipitation in some places, while reducing it in others, increasing the frequency of both drought and flooding periods. However, population growth and climate change are only two of many factors that influence drinking water availability and then human health, ecosystems and social well-being. Both short-term and long-term water shortages can be addressed only by implementing wise policies that encourages water savings at the agricultural, industrial, and urban levels and through the

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simultaneous development and diffusion of technologies that facilitate this transition (WWAP, 2015).

To the maximum extent feasible, building sector should drive this transition by reducing the needs for water and increasing efficiency. At the building scale, several solutions to reduce and reuse water could be promoted, such as for example: the use of high efficiency plumbing fixtures (Maglionico and Stojkov, 2015), the eliminations of leaks (Franchini and Brunone, 2016); the use of rainwater or greywater for on-site activities such as flushing toilets and garden irrigation (Al-Zouby et al., 2017; Campisano and Modica, 2012; De Gisi et al., 2015; Ferraris et al., 2016; Ghisi and Mengotti de Oliveira, 2007; Santos and de Farias, 2017); the capture and use of condensate from HVAC (Heating, Ventilation and Air Conditioning) systems (Dyballa and Hoffman, 2015; Stephan and Stephan, 2017, Zanni et al., 2019).

Although water saving potential differs among buildings type and user habits, several studies agree that water conservation devices such as aerators, high efficiency showerheads, and low flush toilets offer an immediate reduction in water consumption and short payback periods (Ferraris et al., 2016; Mostafavi et al., 2018). Water efficiency efforts can be linked with solutions that, at least, partly replace mains water supply with on-site alternate water sources such as rainwater and grey water.

Rainwater harvesting systems (RHS) are far from being considered new technologies, in fact, the first installations date back to thousands of years ago in many parts of the world (Mays, 2014). RHSs are an alternative to public mains water supply for a variety of non-potable water uses at the home, workplace and garden. Moreover, acting as a source control technology, they reduce the volumes of stormwater discharged into the sewer system (Cipolla et al., 2016; Gambi et al., 2011; Palla et al., 2017). A traditional RHS comprises four basic elements: a collection surface, a collection system, a storage tank (cistern), and a pump system. RHSs are based on a relatively clean natural resource, which can be stored safely for long periods. However, the amount of water harvested depends on rainfall pattern and intensity, consecutive dry weather days, number of inhabitants, roof properties and design return period. Consequently, the water saving efficiency can range from less than 1% to 100% (Domínguez et al., 2017; Ghisi and Mengotti de Oliveira, 2007; Silva et al., 2015). Such a large variation range depends on the fact that this data includes studies carried out in both developing and developed countries, and while for the first ones RHSs efficiency is a matter of economics, for the last ones it is often a human health problem (Imteaz et al., 2012). However, as this study is related to the Italian context, only the possibility to use rainwater to meet non-potable water supply (toilet flushing, garden watering, and car washing) will be investigated.

As the RHS sector expands, there is a need for standardization to protect citizens and to ensure that reliable RHSs are designed, installed and maintained. There are many countries that have technical standards to provide recommendations on the design, installation, testing and maintenance of rainwater harvesting systems supplying non-potable water; e.g. the DIN 1989-1:2002 in Germany, the BS 8515:2009+A1:2013 in UK, the Manual on rainwater Harvesting in Texas (TWDB, 2005), the Rainwater Harvesting and Use Research Report (ABCB, 2016) in Australia, and the UNI/TS 11445 (2012) "Installations for use and collection of rainwater not intended for human consumption - Design, installation and maintenance" in Italy. All of them point up that the reduction of the payback period of the entire system is strongly related to the optimization of the tank volume. This is confirmed by the fact that tank volume optimization is a problem frequently faced by the international scientific community both by authors who aim to satisfy 100% of the non-potable supply (Farreny et al., 2011; Lee et al., 2016; Okoye et al., 2015; Palla et al., 2011; Pelak and Porporato, 2016), and from those who aim to minimize stormwater outflows into the sewers (Campisano and Modica, 2015; Palla et al., 2017). Many authors argue that rainwater harvesting systems are unlikely to pay for themselves during their lifetime (Amos et al., 2018), and this has led some others to investigate others on-site source of water such as for example greywater (De Gisi et al., 2015; Leong et al., 2017b; Oh et al., 2018).

Greywater is the once-used household water, discharged from washing machines, showers, tubs, and bathroom sinks. Greywater makes up the largest proportion of the total wastewater flow from homes and it has a very low nutrient content; it guarantees a daily supply proportional to the inhabitant's consumptions, and it is generated regardless of climate conditions.

Greywater is not recommended for storage because, without treatment, it becomes black-water in less than one day. In terms of daily production, the literature indicates that the greywater volumes can represent from the 50% to the 80% of the total in-house water demand (Failla et al., 2001; Ghisi and Mengotti de Oliveira, 2007; Leong et al., 2017a; Oh et al., 2018). As greywater quality and volume depend significantly on the behaviour of the people using the collection appliances, reliable data providing information on user habits are needed. In Italy, the only data available are those recorded during the monitoring activities carried out within the AQUASAVE project (LIFE 97 ENV/IT/000106). This study measured and analysed the water supply of each plumbing fixture (low consumption) for eight apartments located in the same building in the city of Bologna. Results show that the average consumption of potable water is about 106.35 l/p/d of which 23% is used for toilet flushing; 12% for dishwashers and washing machines, 4% for food preparation, and 28% for other uses. It results in a greywater production of 44.67 l/p/d equal to the 42% of the total drinking water consumption (Failla et al., 2001).

In addition, in this case, as the greywater sector expands, there is a need for standardization to protect public and to ensure that reliable GWSs are designed, installed and maintained. Currently, a very few standards exist that regulate greywater system design, installation and maintenance (e.g. BS 8525-1:2010, BS 8525-2:2011 in UK), and this lack of clear criteria may cause many problems. In fact, from one hand, public authorities provide incentives for the installation of GWSs, from the other the engineers may not have the tools to design the system in the proper way. Moreover, usually grey water systems do not have to be registered or checked on their completion, and this may represent a potential danger for the inhabitants.

Since the systems for the recovery of greywater (GRSs) are often combined with RHSs, giving rise to the so-called "hybrid rainwater-greywater systems" (Leong et al., 2017a), the regulatory gap of the former influences the latter. Hybrid greywater-rainwater systems (HGRSs) are spreading rapidly, and there is a need of tools to support engineers during their design.

The success of HGRSs is determined by the fact that they can achieve a higher water saving potential, with a payback period shorter than those of greywater or rainwater systems (Leong et al., 2017a). Hybrid systems furthermore, offer the combined benefits of rainwater and greywater respectively: managing rainwater locally (Leong et al., 2017b), mitigating urban flooding (Palla et al., 2017), reducing the volume of wastewater, and concentrating the pollution load (Penn et al., 2013). Moreover, HGRSs are generally less sensitive than greywater systems to the variation in the number of inhabitants, and less sensitive than rainwater systems to precipitation changes because the continuous supply of greywater makes it possible to compensate for the seasonal variation in rainfall. Considering all this, it is evident that the achievement of all these benefits is intrinsically connected to a correct design of the overall system.

Based on that, this paper presents a simplified hydrological/hydraulic numerical model, developed by means of EPA's SWMM software (Rossman and Huber, 2016). The model can be used by designers and local authorities to optimise the storage tank volume of a hybrid rainwater-greywater decentralised system, by considering both the water saving efficiency and the stormwater runoff reduction they want achieve (Zanni et al., 2019). To support the investigation the model has been used to simulate the long-term behaviour of a hybrid rainwater-greywater systems installed in 2014 in a building located in the city of Bologna (Italy). Thus this paper aims to: (i) present a simplified model able to simulate the long term hydrological/hydraulic behaviour of a hybrid rainwater-greywater systems; (ii) analyse the overall water consumption (drinking and non-potable water) of 4 flats located in the building proposed as case study; (iii) use the previously presented model to simulate the long term behaviour of a HGRS really present in the building; and finally iv) to provide evidences of the benefits that could be obtained by using a numerical model during the design of the hybrid rainwater-greywater system.

1.2. Hybrid rainwater-greywater systems: design parameters

Hybrid systems contain both a greywater recycling and a rainwater harvesting systems. They can either be operated as separate independent systems or be combined into a single supply source (Fig. 1). Greywater and rainwater may be mixed within cistern or within the distribution network.

As previously said, the cistern is the most difficult element to size in an RHS or in a HGRS. To find its optimum storage capacity the following factors should be taken into consideration: i) the amount and the distribution of rainfall; ii) the type (impervious, green roofs, gravel roof, etc.) and the size of the collection surface; iii) the type and number of intended applications; iv) the volume and usage pattern of these applications.

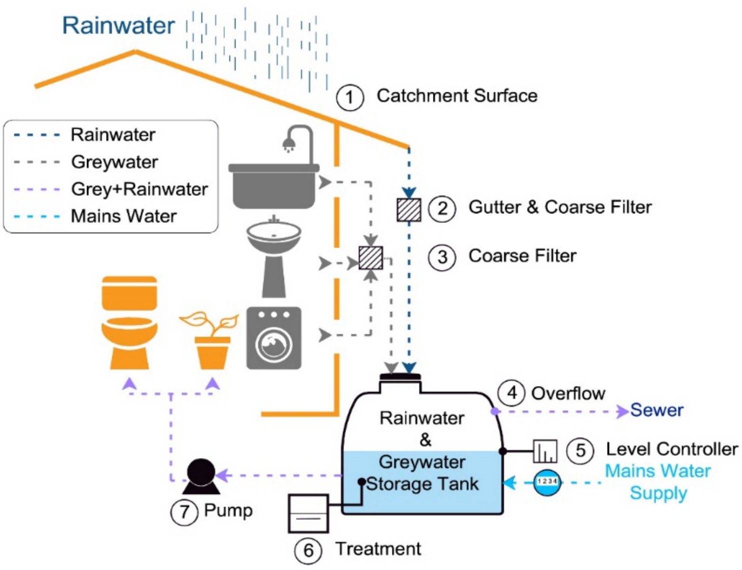

Fig. 1. Scheme of a hybrid system in which the rainwater and the greywater are combined into a single supply source

When considering a hybrid system, several further factors should be considered, including: iv) discharged pattern for all the applications (showers, baths, wash and hand basins and washing machines) connected for reuse; and v) peak capacity treatment rate. As this study is focused on a single supply source configuration, with greywater and rainwater integrated within the cistern, the combined behaviour and the compatibility of the two systems will be investigated and considered. In addition, as the study focuses mostly on the analysis of quantitative aspects rather than qualitative, all the aspects connected with water quality will be neglected.

2. Material and methods

2.1. Case study analysis

The case study is an apartment building built in 2014 and located in the western suburbs of the city of Bologna (Italy). It consists of 7 floors, and it includes 22 apartments of different sizes, ranging from studios (50 m^2) to 4 bedrooms flats (170 m^2). The building has a garden of 892 m^2 of which the 87% (781 m^2) is owned by 3 ground floor flats, while the remaining is a shared garden (Fig. 2).

The building is equipped with water-saving plumbing fixtures and a hybrid system for collecting and recovering rainwater and greywater. Treated rainwater and greywater are integrated in the same cistern that has a capacity of 16 m^3. Systems overflows are discharged into the public combined sewer system (Cipolla and Maglionico, 2014). Cold, hot and recycled water consumptions were measured from 01/12/2014 to 01/04/2016 only for 4 of the total 22 apartments because the others were still uninhabited. Table 1 reports the main characteristics of the building.

2.2. Monitoring activity

The monitoring activity was carried out from 18/12/2014 to 19/02/2016 for 4 flats. Two of them were empty, but the facilty manager irrigated their gardens with non-potable water when were for sale. The others two were inhabited by a family (4 AE), and a single person (1 AE). Cold and hot drinking water, and non-potable water consumptions were measured for each flat. All appartments are equipped with low-consumption plumbing fixture. Table 2 shows the characteristics of the four flats monitored.

Fig. 2. Aerial view of the city of Bologna (left) and of the case study building (right)

Table 1. Characteristics of the building

Variable	***Value***	***System Unit***
City	Bologna (Italy)	[-]
System Type	Hybrid rainwater-greywater	[-]
Area of the roof - impervious	400	[m^2]
Area of the garden	892	[m^2]
Non-potable water cistern	16	[m^3]
Irrigation months	Apr.-Sept.	[-]

Table 2. Characteristics of the four flats monitored

Flat	A1	A2	A3	A4
Size [m^2]	51	103	85	92
Garden size [m^2]	-	243	257	281
Floor	3rd	ground	ground	ground
Inhabitants	1 adult	2 adults and 3 children	-	-

2.3. Hydrologic hydraulic modelling

The hydraulic/hydrological model has been undertaken by means of EPA's SWMM (Storm Water Management Model) software, version 5.1.012 (Rossman and Huber, 2016), as done by other authors (see (Palla et al., 2011) for an overview). Fig. 3 shows each element of the model, which consist of: a subcathment (A), a rain gauge (B), a pipe (C), two storage units (D and E), two pumps (F and G), a weir (I), and two outfalls (L and H).

Greywater has been modelled as a positive constant daily inflow to the tank (D), while the non-potable water demand to meet toilet flushing and garden irrigation supply has been modelled as a negative inflow to the tank (D), and a pump system respectively (G). Water can continue to enter into the tank, raising the water level until it reached the overflow pipe, at that level the water will be discharged into the sewer system though the overflow (I and L). A SWMM rule controls the water level within the tank (A), it allows water to enter from the main water supply (E and F) when the water level drops below the minimum required level.

This model uses the "subcatchment" element (A) to model the roof (rainfall catchments area). A subcatchment is a hydrologic unit whose parameters influence the runoff and thus the storage tank inflow (Rossman, 2015). Subcatchment has modelled as impervious catchments in which the total surface area is the footprint of the roof. Its main parameters (depression depth, N Manning, and% Zero-Imperv) have been assigned in agreement with those proposed by Cipolla et al. (2016b) and are summarized in Table 3. A predesigned Low Impact Development (LID) module can be applied to the roof catchment to model green technologies such as green roofs, pervious pavements, biofilters etc. (Cipolla et al., 2016b; Gambi et al., 2011). Subcatchment runoff is the inflow of the storage unit (D), which represents the cistern of the system. This model considers the indoor water demand (toilette flushing) constant for each time step. This assumption has been considered adequate by other studies (Palla et al., 2011). Regarding outdoor non-potable water demand (i.e. garden irrigation), it usually exhibits a seasonal variation that needs to be parameterised. Irrigation timing and volumes have been determined based on rules depending on the month of the year and the size of the garden. The outputs from this model are the predicted yield and overflow over the period simulated for the specified roof area, rainwater demand, and tank storage volume. Finally, continuous simulations are performed over 13-years at 1-day time interval; as for the initial condition the tank is assumed empty as generally recommended (Palla et al., 2017).

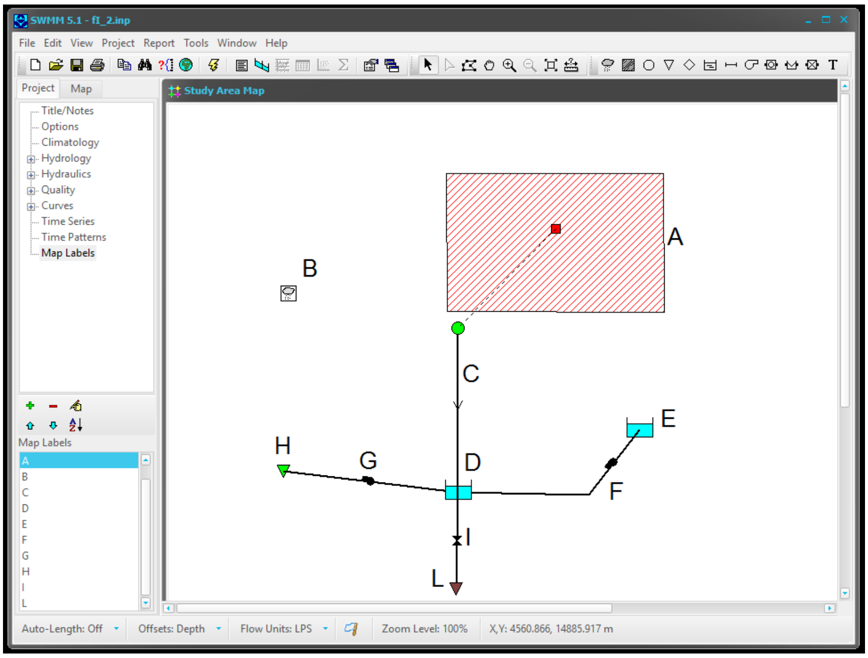

Fig. 3. Graphical representation of the SWMM model. The elements shown in the figure are: a subcathment (A), a rain gauge (B), a pipe (C), two storage units (D and E), two pumps (F and G), a weir (I), and two outfalls (L and H)

Table 3. Parameters assigned to the subcatchment in the SWMM model

SWMM Parameter	*Values*	*System Unit*
Depression depth	1	[mm]
N-Manning	0.011	[s/m$^{1/3}$]
% Zero-Imperv	5	[%]

2.4. Performance analysis

Two indexes, evaluated with respect of the entire simulation period, provide the performances of different system configurations. The first is the non-potable water-saving efficiency, *E* (Eq. 1), in which the non-potable water (rainwater + greywater) supply Y_t [m^3] is compared with the non-potable water demand D_t [m^3] both in each time step *t*, and *T* is the total number of time steps in the period of simulation (Andrade et al., 2017).

$$E = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} D_t} \tag{1}$$

The second index is the wastewater (rainwater + greywater) overflow ratio, *O* (Eq. 2), in which the wastewater exceeding the tank capacity O_t [m^3] is compared with system inflow Q_t [m^3] both in each time step *t*, and *T* is the total number of time steps in the period of simulation.

$$O = \frac{\sum_{t=1}^{T} O_t}{\sum_{t=1}^{T} Q_t} \tag{2}$$

2.5. Model set-up

Despite the model can be used to simulate any system configuration, rainfall pattern, and water-end use, it has been used to simulate the long-term behaviour of the hybrid system located in the case study.

2.5.1. Weather data

Simulations were performed using daily rainfall and air temperature data for a 13-year period, i.e., 1st January 2004 – 31st December 2016. Data were sourced from the historical daily climate records provided by the ARPAE - Regional Agency for Prevention, Environment and Energy (http://www.arpae.it/dettaglio_generale.asp?id=3284&idlivello=1625). Rainfall data was used as input into the rain gauge (Fig. 4).

The average rainfall depth, obtained for the whole period of 13 years, is 804.5 mm/year, while the minimum and maximum rainfall depth recorded were 464.2 mm in 2011 and 1083.2 mm in 2004 respectively. It can be observed that rainfall is mainly concentrated in fall and winter (October- March), while summers (June - September) are quite dry.

2.5.2. Water end-uses

The total water consumption was assumed equal to 106.35 l/p/d as indicate by Failla et al. (2001). By considering a maximum capacity of 66 inhabitants (one inhabitant for each bedroom with a surface of less than 14.0 m^2, and two for those with upper surfaces), and a garden area 892 m^2, the water consumption of non-potable water for WC flushing ($Cons_{WC}$) and irrigation ($Cons_{Garden}$) were estimated by using Eq. (3) and Eq. (4). Others non-potable water end-uses were not considered.

$$Cons_{WC} = Cons_{Tot} \times Perc_{WC} \times I\,[\,{}^{l}\!/_{d}\,] \tag{3}$$

where: $Cons_{Tot}$ is the total water consumption, assumed equal to 106.35 l/p/d as indicate by Failla et al. (2001) and $Perc_{WC}$ is the percentage of the potable water demand consumed for toilet flushing, 23% as suggested by Failla et al. (2001).

$$Cons_{Garden} = Vol_G \times A_G \times m\,[\,{}^{l}\!/_{d}\,] \tag{4}$$

where: Vol_G is the average irrigation demand (4 l/m^2/day), A_G is the size of the garden (m^2), and *m* is equal to 1 from April to September and 0 in the other months.

$Cons_{WC}$ has been simulated as negative inflow to the cistern (element D in Fig. 5) while $Cons_{Garden}$ represents the flow rate attributed to the irrigation pump (element G in Fig. 5).

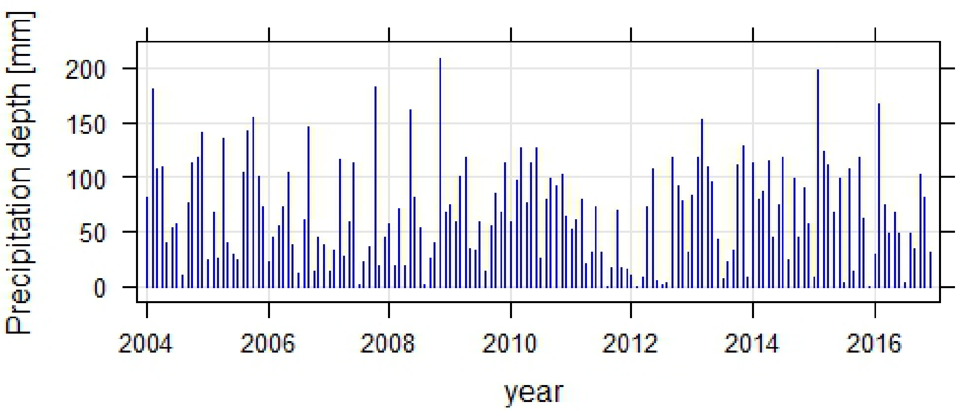

Fig. 4. Precipitation depth from 01/01/2004 to 31/12/2016, rainfall depth is shown on a month base

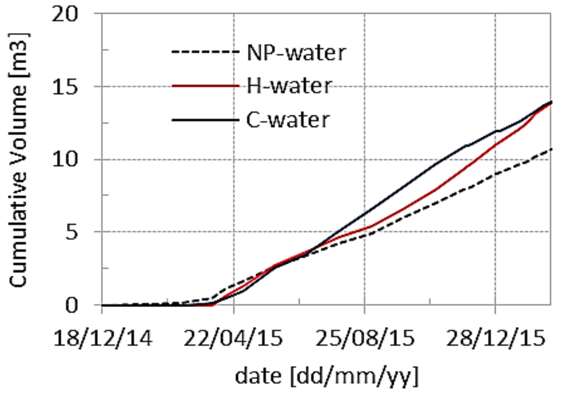

Fig. 5. Hot, cold and non-potable water consumption for flat A1

2.5.3. Greywater production

The volume of greywater produced day by day in the building was determined according with the plumbing fixtures really connected to the existing hybrid plant (showers, lavatories, and washing machines) and with the values proposed by Failla et al. (2001). Thus, the greywater inflow ($Inflow_{GW}$) to the cistern was estimated by using Eq. (5).

$$Inflow_{GW} = Cons_{Tot} \times Perc_{GW} \times I\,[\,^{l}/_{d}\,] \qquad (5)$$

$Perc_{GW}$ is the percentage of the potable water demand consumed by plumbing fixtures that however generate greywater, equal to 42% as suggested by Failla et al. (2001). $Cons_{WC}$ has been simulated as a positive inflow to the cistern (element D in Fig. 2).

3. Results and discussion

3.1. Data analysis

Flat A1 is a one bedroom flat of 51 m^2 located on the third floor of the building, with no garden. It has been inhabited by a female person (40 years old) since April 1st 2015. Recycled water is used only for toilet flushing. Fig. 6 shows the water consumptions during the monitoring activity (354 days). The average total daily consumption is of 108.76 l/p/d, of which 72.26% is potable water subdivided in hot (36.0% or 39.43 l/p/d) and cold (36.26% or 39.1 l/p/d) water. The remaining 27.2% (30.17 l/p/d) is non potable water used for toilet flushing. Non-potable water consumption remains almost constant throughout the year, while in summer there is a reduction in the consumption of hot water in favour of the cold one, and vice-versa in winter.

Flat A2 is a 103 m^2 flat located at the ground floor. It consists of a living room, a kitchen, a double bedroom, two single bedrooms and two bathrooms, one with the shower and the other with a bathtub. This appartment has a private garden of 243 m^2. It has been inhabited since December 18, 2014 by a family of 5 people including a new-born and two childrens. Non-potable water is used for both toilet flushing and garden watering (Apr. - Sept). Fig. 6 shows the cold, hot and non-potable water consumptions during the monitoring activity (428 days). By considering 4 equivalent inhabitants, the average hot and cold water consumption results in 31.15 l/p/d and 28.06 l/p/d respectively. The consumption of hot water is higher than the cold one during the entire monitoring period, both consumptions show a constant trend. The consumption of non-drinking water shows a trend which is completely different from those observed in flat the warmest months (April-September) summer.

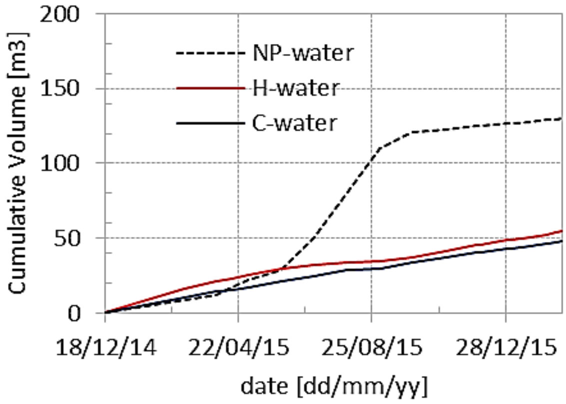

Fig. 6. Hot, cold and non-potable water consumption for flat A2

Table 4 shows the measured recycled water comsuntion (toilet flushing + irrigation) of apartment (A2), and the main weather parameters sourced from ARPAE database. As non-potable water has been measured on a aggregate basis (toilet flushing + irrigation), it was necessary to identify a procedure that would make it possible to split such volumes. The average non-potable water consumption recorded in cold months (Oct.- March) was 21.44 l/p/d (standard deviation 6.24). In order to estimate the volumes of non-potable water used for garden watering, this value have been subtracted from the measured data. Values estimated with this procedure have been highlighted in bold in Table 3.

Irrigation volume ranges between 0.94 (May) and 4.06 l/m^2/d (August). Moreover, it seems that there is no direct correlation between the monthly precipitation depth and volumes of water used for irrigation.

Flat A3 and flat A4 are an 85 and a 92 m^2 ground floor flats with 257 m^2 and 281 m^2 garden surfaces respectively. During the monitoring period, the apartments were for sale, but the building's owner irrigated the lawn. This allows measuring the volumes of non-potable water, used exclusively for irrigation purposes (Fig. 7 and Fig. 8).

Table 5 shows the average monthly consumption of non-drinking water for garden watering, it ranges from a minimum value of 0.5 l/m^2/d (A4, March 2015) to a maximum of 8.0 l/m^2/d (A4, August 2015), with an average value of 4.0 and 3.5 l/m^2/d for flats A3 and A4 respectively.

Table 4. Non-potable water consumption for the flat A2, total monthly rainfall, maximum and minimum average monthly air temperature

Date	*WC flushing*	*Irrigation*	*Rainfall*	*Temperature max*	*Temperature min*
	l/p/d	*[l/m²/d]*	*[mm]*	*[°C]*	*[°C]*
Jan-15	30.74	-	7.8	17.2	1.3
Feb-15	30.74	-	197.2	14	1.8
Mar-15	21.50	-	122.4	23.4	7
Apr-15*	**21.44**	**1.39**	110.0	26.6	7.8
May-15*	**21.44**	**0.94**	67.6	29.1	12.8
Jun-15*	**21.44**	**2.86**	98.2	32.8	19.3
Jul-15*	**21.44**	**3.96**	2.6	37.5	22
Aug-15*	**21.44**	**4.06**	107.0	35.9	20.9
Sep-15*	**21.44**	**1.42**	13.6	34.1	14.7
Oct-15	19.60	-	117.2	25.2	10.9
Nov-15	17.08	-	62.8	21.9	3.8
Dic-15	13.71	-	0.0	13.5	3
Jan-16	17.28	-	28.4	18.4	0.6
Feb-16	20.83	-	166.6	16.2	5.7

** is used to indicate the months in which the garden has been watered*

Table 5. Non-potable water consumption for the flat A3 and A4

Date	**A3** *[l/m²/d]*	**A4** *[l/m²/d]*
Jan-15	-	-
Feb-15	-	-
Mar-15	-	2.4
Apr-15	2.6	0.5
May-15	1.8	2.0
Jun-15	3.5	3.8
Jul-15	4.7	3.2
Aug-15	5.2	4.5
Sep-15	6.0	8.0
Oct-15	-	-
Nov-15	-	-
Dic-15	-	-
Jan-16	-	-
Feb-16	-	-

The values measured in these apartments are slightly higher than those that have measured in the apartment inhabited by the family, this is certainly due to the greater sensitivity of private citizens towards their consumption.

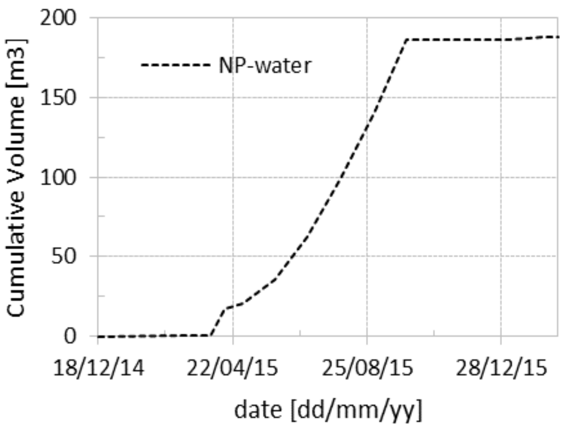

Fig. 7. Non-potable water consumption for flat A3

To sum up, the monitoring campaign allowed to measure the hot, cold and recycled water consumption for 2 flats (A1 and A2), and the recycled water used for garden watering for the others two flats (A3 and A4).

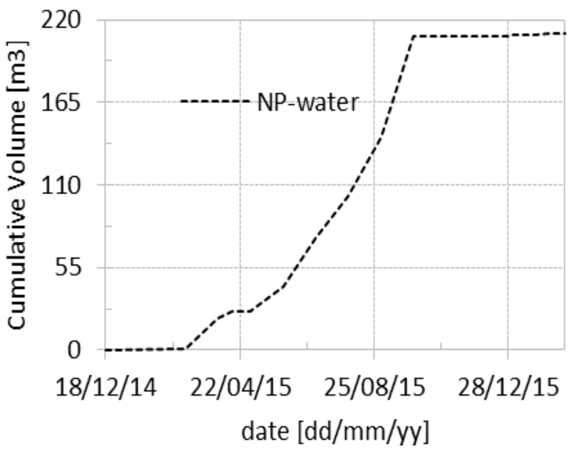

Fig. 8. Non-potable water consumption for flat A4

The results obtained are comparable with those published by Failla et al. (2001) and related to the Italian context, but also with others (Antonopoulou et al., 2013; Ghisi and Mengotti de Oliveira, 2007; Marinoski et al., 2018).

Due to the reduced number of measured data (low number of families, short monitoring period, etc), they were not used for modelling, but to support the choice of using results already published by other authors.

3.2. Simulation results

Thirteen years of daily rainfall data were used to perform the simulations. During that time, there were 1393 rainfall days, of which 341, 59 and 5 with a daily precipitation above 10, 30 and 60 mm respectively. September 09, 2005 was the rainiest day of the dataset (109.4 mm).

Table 6 reports the total number of wet days for each year and the number of consecutive dry weather days. The longest dry weather period was recorded in 2012 (60 days), while the average number of consecutive days without precipitation ranges between 2.57 (2010) and 4.18 (2017). By considering the whole data set, the number of consecutive days without precipitation longer than 10, 20 and 30 days was 97, 28 and 9 respectively.

As demonstrated by some studies (Silva et al., 2015), consecutive dry weather days strongly influences the behaviour of rainwater harvesting systems. The longer the dry weather periods, the bigger the volume of the storage tank. Since the modelled system is hybrid, the daily supply of graywater should be able to compensate for the high number of consecutive dry weather days.

Simulation results show that the HRGS, with a cistern of 16 m^3, assures an average non-potable water saving efficiency (*E*) of 75.86%. It means that only the 24.14% of non-potable demand should be supplied from the mains. Considering the building as a whole, HRGS reduces the drinking water withdrawal by around 16%.

The other performance indicator, *O*, assumes an average value of 26.71%, demonstrating the effectiveness of the system in reducing the volume of wastewater discharged by the building into the sewers. In fact, it expresses the capability of the system to reduce the amount of wastewater (graywater + rainwater) discharged into the drainage system. The lower *O* the better the impact of the HGRS on the environment.

The model was then used to estimate the potential for water savings for different cistern capacities. Fig. 9 shows the results in terms of both *E* and *O* index. *E* increases with the tank capacity, ranging from 72.46% with 4 m^3 to 76.38% with 20 m^3, the general trend of the curve highlights a linear increase of *E* as the storage fraction increases. Fig.9 shows how, despite the tank volume increases by 16m^3 (from 4 to 20 m^3), efficiency increases only by 3.92%.

Table 6. Precipitation statistics in Bologna between 2004 and 2016

Year	*Number of wet day*	*Consecutive dry weather day*		
		Avg	*Max*	*St.dev*
2004	116	3.087	37	23.48
2005	109	3.278	31	20.44
2006	89	4	24	26.86
2007	86	4.188	28	30.01
2008	103	3.559	29	28.84
2009	124	2.959	25	18.21
2010	141	2.571	21	8.16
2011	89	4.011	39	37.09
2012	87	4.174	60	80.14
2013	122	2.992	31	15.87
2014	131	2.754	21	12.24
2015	85	3.643	33	27.43
2016	111	3.218	17	12.96

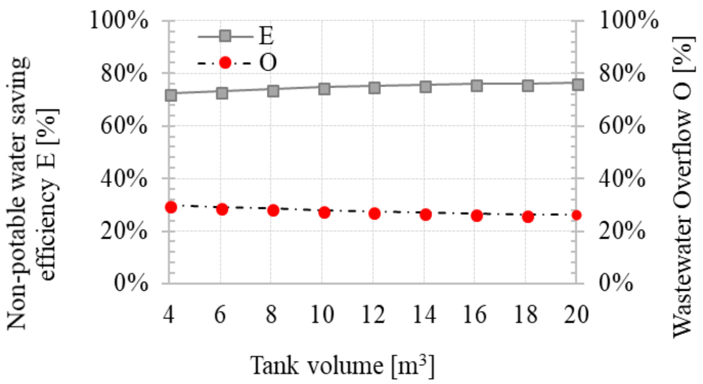

Fig. 9. Non-potable water saving efficiency -*E* and Overflow-*O* for different values of tank storage volume

This result is due to the contribution of two unfavorable factors: 1) the small size of the collection surface; and 2) the large extent of the areas to be irrigated during the summer. In summer, in order to supply only the non-potable demand for garden watering, a volume of 3368 l/d would be needed. It became clear that, the emptying rate, due to irrigation demand, is greater than the capacity of the self-loading system. Simulation results confirm the impact of HRGSs on wastewater mitigation: *O* values, evaluated for the 13 years rainfall, are respectively equal to 30.04% and 26.16% for 4 m^3 and 20 m^3 storage volumes. *O* does not decrease below such values because in winter, the daily production of gray water is higher than non-potable demand and therefore greywater spills are inevitable. To sum up, due to the building characteristics (small size of the roof), and the high non-potable demand in summer periods, simulations revealed a reduced water saving benefits as the tank size grows.

By considering the same building conditions, the model allows evaluating the hydraulic behaviour of other systems type such as for example a rainwater harvesting system or a greywater reusing system.

Thus, the model has been used to simulate the case study building, but under the hypothesis of replacing the hybrid system with a rainwater harvesting system. Results of simulations show (Fig. 10) that the non-potable water saving efficiency increases non-linearly as the storage volume increases. The *E* curve tends to flatten as the values of tank volume increase. This phenomena, already observed in other studies focussed on rainwater harvesting (Campisano and Lupia, 2017), reveals a reducing water saving benefit as the cistern size grows.

Fig. 10 reports two O curves indicated respectively with *O* and *O**. The first one has been obtained by using Eq. (2), and thus considering both greywater and rainwater inflows. On the contrary, *O** has been calculated by neglecting the greywater inflow. This allow *O** to provide information on stormwater runoff attenuation as the volume of the tank increases. The general trend of both curves shows the typical non-linear decrease of system overflows as the volume increases. O* decreases more rapidly than O demonstrating, as expected, an increasing efficiency on stormwater runoff attenuation as the cistern size grows. By considering the building, the RHS does not provide any benefit in terms of greywater reduction; however, it can reduce stormwater runoff by 86.8%with 4 m^3 cistern and by 97.84 with 20 m^3.

Finally, the model has been used to simulate the case study building, but under the hypothesis of replacing the hybrid system with a GRS. Fig. 11 shows the result of simulations. The *E* curves is almost flat, in fact efficiency stands at around 67% regardless of tank volume, demonstrating that is not possible to increase efficiency above this threshold.

The variations in *O* are minimal, demonstrating that, even in this case, it has been reached a benefit threshold beyond which, regardless of the volume of tank used, it is not possible to arrive.

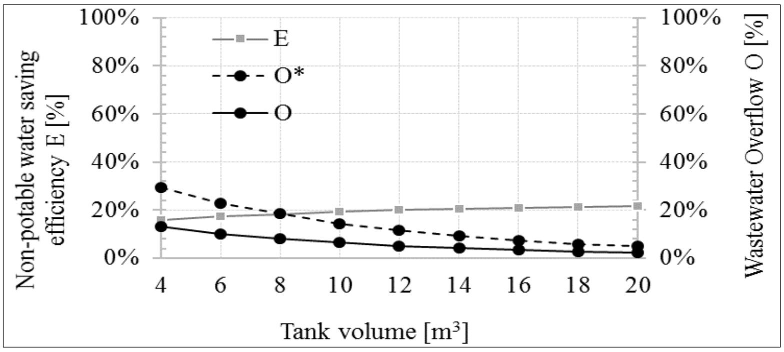

Fig. 10. Rainwater harvesting system: non-potable water saving efficiency -*E* and Overflow-*O* for different values of tank storage volume

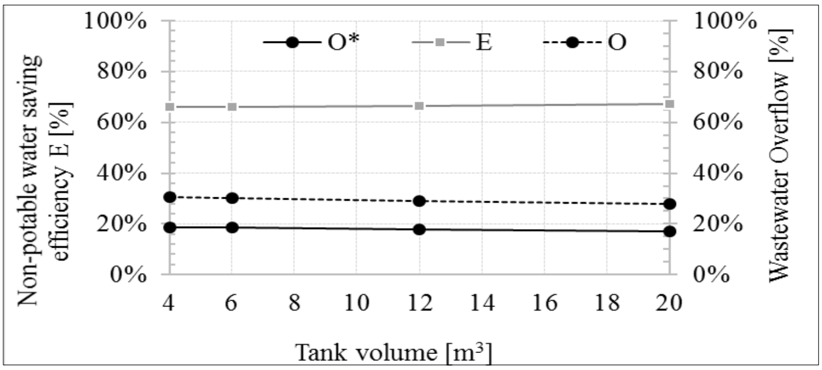

Fig. 11. Greywater reusing system: non-potable water saving efficiency -*E* and Overflow-*O* for different values of tank storage volume

In this case O* has been calculated by considering only the greywater inflow. This parameter allows to quantify the reduction of waste water (only greywater) sent into the sewer system, and its value range from 30.4 with 4 m^3 to 27.75 with 20 m^3 storage tank.

4. Conclusions

The study has quantified the non-potable water saving efficiency *E*, and system overflow *O* for an apartments building located in the city of Bologna (Italy). The first index provides information on the amount of non-water demand that can be effectively satisfied by on-site sources, while the second one provides an estimate of the reduction of volumes discharged into the sewer system. Both indexes were calculated for the real system configuration, and for a wide range of other scenarios obtained by varying the tank volume and the system type (Hybrid system, rainwater harvesting system, and greywater reusing system). Scenarios have been investigated by means of a long-term hydraulic/hydrological numerical model realised by means of SWMM software. To support the choice of the water end-use consumptions and of the greywater production, that were set up into the model, the water consumption (cold, hot, and recycled water) of four flats, located into the case study building, have been analysed.

Data were collected by the facility manager of the building for billing purposes Although they are not extremely accurate and referred to only 4 residential units, they provide several useful information. Data confirm that non-potable consumption accounts for almost a third of the total one, when considering only the toilet flushing water supply. Moreover, the monitoring of garden flats allowed to estimate the average irrigation needs. Measured data are comparable with those shown in other studies, validating the choice to use literature data for modelling purposes.

The performances of different systems configurations have been estimated by using 13 years of real daily rainfall data as input. The model shows that the real system configuration has a water saving efficiency of 75.86%, and that the volumes of wastewater (greywater + rainwater discharged into the combined sewer systems), are reduced by 73.29%. Model has then been used to estimate both *E* and *O*, for nine different tank volumes. Simulations revealed a marginal water saving benefits as the tank size grows, which is mainly attributable to the general characteristics of the building (small size of the roof, high number of inhabitants, and large extent of irrigated gardens). Despite this, the hybrid system, compared to a rainwater harvesting system or a greywater system, seems to be the most efficient because it is able to supply the highest water. From one hand, further researches might evaluate the possibility of using real time series or detailed parameterizations to estimate the non-potable water-end uses and greywater productions. On the other, to estimate others type of collection surfaces such as green roofs, permeable pavements, etc.

The presented model, here applied at the building scale, can also be applied at the district scale or at the city scale to evaluate the effectiveness of policy implementations both in terms of water saving efficiency and stormwater runoff mitigation.

The final goal of this paper, as a matter of fact, was to provide a simple tool to lay down the level of technical performance to be attained and define the minimum water saving efficiency of rainwater/greywater systems intended to benefit of the incentives or tax deduction promoted by the local authorities. The technical methods applied to achieve those goals are a matter of choice, but the minimal performances to be achieved themselves should be mandatory.

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