Water Resources Management (2023) 37:3897–3919
https://doi.org/10.1007/s11269-023-03531-y

# Hybrid Decentralized Systems of Non-potable Water Supply: Performance and Effectiveness Analysis

**A Ferreira[1] · C. Santos[1,2] · M. A. Imteaz[3] · C. Matos[2,4]**

Received: 23 December 2022 / Accepted: 1 May 2023 / Published online: 11 May 2023


**Abstract**
This article presents a study of Hybrid Rainwater/Greywater Systems (HRGS), with the objective of perceiving the main factors that influence their performance and how they can be optimized. For this goal, a decision support tool, that makes their dimensioning and performs an economic and performance analysis, was used for four different types of buildings: a single-family house, a multifamily building and two service buildings. For each case, distinct scenarios were defined, considering different end-uses of non-potable water, in order to evaluate the performance of the systems using effectiveness and performance indicators. Results show that the effectiveness of "non-potable water consumption" is influenced by two main factors: the final uses considered for non-potable water and the storage volume. In most of the study cases, values of effectiveness (ratio between the volume of non-potable water used and non-potable water demand for the final uses considered) greater than 50% were obtained. In the case of domestic buildings, such as single-family house and multifamily building effectiveness values above 67%, were obtained. And for the case of service buildings, the effectiveness was between 42.8 and 65.6% in one case, and between 12.9 and 93.6% for the other. The best performance of the studied hybrid systems is achieved when the volume of non-potable water used in the building is maximized, resulting in greater savings of potable water. In addition, the larger the fraction of greywater reused, the lower the volume of wastewater produced and sent directly to the sanitation network.

**Keywords** Sustainable water use · Hybrid systems · Rainwater · Greywater

✉ C. Santos
csantos@fe.up.pt

1 Faculty of Engineering, University of Porto, Porto, Portugal

2 CIIMAR - Interdisciplinary Centre of Marine and Environmental Research, University of Porto, Porto, Portugal

3 Department of Civil & Construction Engineering, Swinburne University of Technology, Melbourne, Australia

4 ECT—School of Science and Technology, University of Trás-os-Montes and Alto Douro UTAD, Quinta de Prados, Vila Real 5000-801, Portugal

## 1 Introduction

Rainwater and greywater are commonly available sources of non-potable water that should be collected, treated and transported in rainwater harvesting systems (RWH) and/or greywater reuse systems (GRS), respectively. These systems, when integrated in a building, are classified as decentralized ones, and allow the collection and treatment of these waters at source, without the need for transport to long distances as it is done in a centralized system (Leong et al. 2019; Matos et al. 2014). Shanableh et al. (2012) using a case study for UAE buildings demonstrated that individual GRS is not economically feasible for single residential buildings, however, for high-rise buildings a cost-recovery of 5 years is achievable even with a 10-storey building using only GRS. Generally, RWH and GRS are installed independently, limiting the potential for savings that they can provide (Leong et al. 2018). Zhang et al. ( 2010), studied both systems independently and concluded that greywater recycling contributes to the greater saving of mains water supply when compared to rainwater use.

Hybrid Rainwater/Greywater Systems (HRGS) can be a potentially more efficient alternative, in terms of potable water savings, compared to independent RWH and GRS (Leong et al. 2018), taking advantage of their individual benefits. Comparing to RWH systems, the hybrid ones can provide non-potable water in a more constant way throughout the year, due the contribution of the affluent greywater. On the other hand, the hybrid ones use raw water with better quality (rainwater, less contaminated, dilutes the pollutants of greywater) with lower treatment requirements and costs when comparing to GRS supplying the same volumes of non-potable water. In addition, these systems reduce the dependence on single factors like the occupation of buildings, the roof area and climatic conditions (Leong et al. 2018). The combination of these systems in buildings will make it possible to standardize variations in the amount of rainwater collected and improve the quality of greywater (Leong et al. 2018).

The configuration of a HRGS may vary, considering the location of the treatment in relation to the storage(s) and the fact that the storage can be joint or individual for each type of water. In recent years, a few authors have studied hybrid systems compared to rainwater harvesting and greywater reuse systems in order to assess their effectiveness and study their economic and environmental benefits. Ghisi & Mengotti de Oliveira (2007) presented a study of a HRGS in a residential building in Brazil, considering the use of water for toilets flushing and washing machines. They obtained savings of potable water between 33.8 and 36.4%, and these values were slightly higher than those obtained for the rainwater utilization system and reuse of graywater separately, namely 30.4 and 33.8% for RWH and 33.6 and 35.5% for GRS. Leong et al. (2018), estimated the water saving potential of a HRGS in a commercial building and found that the rainwater and greywater collected in the building provided a supply of 24.4 to 25.1% of the total potable water. Rainwater accounted for 3.5 to 4.0% of total potable water consumption, while greywater accounted for 21.1%. Thus, in commercial buildings, the authors concluded that the reuse of greywater should be prioritized. Santos et al. (2011) analyzed the implementation of a hybrid system in two types of buildings: a hotel and a commercial building. For the hotel, considering the supply of non-potable water for flush discharges and for the garden irrigation system, the return period obtained was 14 years, and the effectiveness was 43.7% of the demand of non-potable uses (66% from the reuse of greywater and 34% from the use of rainwater). Regarding the commercial building, for the same final uses of potable water, the effectiveness obtained was

45.7% and the return period was 23 years. Chen et al. (2022) found that hybrid systems have a strong adaptability to seasonal water variations in Japan, adapting to the two scenarios of non-potable consumption: stable and seasonal.

Other studies have focused on the environmental and economic impacts of these systems. Leong et al. (2019) found that, for commercial buildings, the option that minimizes the impacts of life cycle analysis (LCA) and maximizes the cost of life cycle, is a HRGS (when comparing to independent RWH and GRS), achieving an effectiveness related to the consumption of non-potable water of 55.3%, for flushing and watering discharges. Whereas, for domestic buildings, the HRGS obtained 100% effectiveness, considering the same end uses as the commercial building. However, the most advantageous option, which has lower environmental impacts, was the rainwater use system, achieving an effectiveness of 95.3%. Marinoski and Ghisi (2019) evaluated the performance of a HRGS in a single-family domestic building in Brazil, through the LCA and concluded that for domestic housing, the conventional system has more impacts when compared to the hybrid system. In this study, the effectiveness related to the consumption of non-potable water was 41.9% and the potential for reducing the amount of wastewater in hybrid systems was about 40% compared to the conventional system. The reduction of energy consumption was 36.1%.

Nevertheless, studies about HRGS for non-domestic buildings are still scarce. Extending the application of these systems to other types of buildings, Ghafourian et al. (2022) proposed the implementation of this systems in an ecotourism facility in Greece and concluded about the feasibility of the system when considering the environmental and social benefits of the project. The return period obtained was about 10 years. Chen et al. (2021) studied a HRGS in a campus in Japan, achieving an effectiveness regarding the non-potable water consumption of 74.1% (ranging from 47.66 to 100%) and a reduction in electricity consumption of about 22%. However, in economic terms, the high maintenance costs and waste of excess stored water are reasons for the economic unviability of the HRGS, not achieving economic benefits within a life cycle of 15 years.

Table 1 presents a summary of the results obtained in the referred studies, regarding the type of building, the final uses of non-potable water, the treatment, the number of storages and performance indicators. Effectiveness values range from 35 to 45% and the effectiveness for commercial buildings is generally higher compared to domestic buildings.

In the evaluation of HRGS, the use of performance indicators is current, allowing the comparison between different systems and study cases. From the literature review it can be seen that the main performance indicators that have been used are the effectiveness related to the consumption of non-potable water, environmental impacts, the return period and the initial investment. However, they are not enough to make a complete assessment of the system's performance and to identify improvements. To ensure the feasibility of hybrid systems and thus foster their large-scale application, it is critical to improve the assessment of the system's potential by adding new effectiveness, performance and economic indicators. For example, it is important to determine the effectiveness of the system related to the rainwater production and to the greywater production in separate, to optimize its configuration in future developments, if necessary. On the other hand, besides the return period (a general indicator for non-potable water systems) it is also important to inform the users and promoters about the reduction on water bill and the average annual economic savings. These values are important decision support elements and must be present to investor.

**Table 1** Synthesis of the results obtained in previous studies

| Author | Building type[1] | Non-potable water End Uses | Treatment | | Storage tanks | Performance indicators | |
|---|---|---|---|---|---|---|---|
| | | | Rainwater (RW) | Greywater (GW) | | Effectiveness [2] | Return period (years) |
| Ghisi & Mengotti de Oliveira (2007) | D [3] | Toilet flushing, laundry | Filter and natural treatment systems | | 2 RW tanks<br>2 GR tanks | 33.8–36.4% | 28–92 years |
| Leong et al. (2018) | C | Toilet flushing, garden irrigation, laundry | *First Flush*[4] | Media filter, activated carbon filter and disinfection step | 2 separated tanks for RW and GR<br>1 tank for RW and GR after treatment | 24.4–25.1% [5] | - |
| Santos et al. (2011) | S | Toilet flushing, garden irrigation | Filtration and disinfection system | Compact system | 1 tank for RW before treatment<br>1 tank for RW and GR after treatment | 43.7% | 14 years |
| | C | Toilet flushing and urinals, garden irrigation | | | 1 tank for RW and GR after treatment | 45.7% | 23 years |
| Leong et al. (2019) | C | Toilet flushing, garden irrigation | Sand filter, Activated carbon filter and ozone disinfection | | 1 tank for GR before treatment | 55.3% | - |
| | D | | | | | 100% | - |
| Marinoski and Ghisi (2019) | D [3] | Garden irrigation, floor washing and vehicles, laundry | *Fisrt Flush*<br>Disinfection | Natural treatment and disinfection systems | 2 tanks for RW and GR | 41.9% | - |
| Ghafouriana et al. (2022) | S | Toilet flushing, garden irrigation | - | Natural UV treatment and disinfection systems | 2 RW tanks<br>2 tanks for GR, before and after treatment | - | 10 years [6] |
| Chen et al. (2021) | S | Garden irrigation, fire fighting, cooling towers … | Filter | Filter, membrane reactor, ozone injection and disinfection | 2 tanks before and after treatment for RW and GR | 74.1% | - |

[1]*D - Domestic; C - Commercial; S - Services.*

[2]*Ratio between the volume of non-potable water used and non-potable water demand for the final uses considered.*

[3]*Single-family domestic.*

[4]*Device for the flow of the first rainwater harvested.*

[5]*Effectiveness related to the total potable water demand.*

[6]*Return period considering economic, environmental and social benefits.*

This paper makes, for the first time, a study of the performance of HRGS in different types of buildings, proposing new indicators for a more complete assessment. The research made for the state of the art, showed that many studies were already made for separate rainwater harvesting and greywater reuse systems. Hybrid systems are very recent and few investigations were made so far, being mainly focused on domestic uses and single house buildings. To boost the investigation and promote the development of hybrid systems, it is fundamental to make complete performance studies of Hybrid Systems in different types of buildings, with consumptions patters and used volumes very distinct from domestic single house units.

Thus, the main goal of the present study is to contribute to the improvement of the performance of decentralized hybrid systems, through the definition and optimization of performance indicators, using different case studies based on real buildings, namely a dwelling, a multifamily building, an educational building and a research building. This study can be a significant contribution to the promotion of this systems and an incentive to their large-scale implementation in large buildings with great potential to significantly optimize the use of water.

For this purpose, different study cases, based on real buildings, were analyzed (namely a dwelling, a multifamily building, an educational building and a research building). For each case, distinct scenarios were defined, in order to evaluate the influence of several parameters on the performance of the systems.

## 2 Hybrid Systems

### 2.1 Configuration

HRGS include the use of rainwater and the reuse of greywater, in an integrated manner, in a building. Rainwater is collected on the rooftops and terraces and it is important to consider that the type of material of the cover can negatively affect the quality of the collected water (EN 16941-1, 2018). Greywater is collected in bathtubs, showers and washbasins. The water drained from the kitchen and washing machines has a higher pollutant load and is not usually used in this type of systems (EN 16941-2, 2021).

In HRGS, rainwater and greywater are routed to the storage through conventional drainage networks. The treatment equipment can be differentiated for the two types of water, or unique in the same stage. The selection of the treatment must include a previous physical, chemical and microbiological characterization of the water, in order to quantify the pollutant load of the water to be treated. The main objective of the treatment is to ensure compliance with the reference values for the final uses of the non-potable water, in order to avoid the risks to public health and also to protect the components of the system. The selected treatment typology is determined by the characteristics of the effluent and the intended end use (Shaikh and Ahammed 2020). Treatments may involve biological, chemical or physical processes, as well as their combination (EN 16941-1, 2018).

In a system with differentiated treatment, rainwater is stored in a storage tank and the collected greywater is treated. Untreated rainwater, treated greywater and potable water from the network are gathered in another storage tank to supply non-potable uses, in which an additional disinfection system can be added. On the other hand, in a hybrid joint treatment system, rainwater and greywater are stored in the same tank and all that water is treated, which usually includes two filtration stages and one disinfection.

HRGS combining rainwater and greywater in a single tank, prior to treatment, should simultaneously remove high concentrations of organic compounds from greywater and other elements (e.g. heavy metals) present in rainwater. The main advantage of combining both waters prior to treatment is the neutralization of rainwater acidity by greywater, which reduces corrosion rates and the dilution of other components present in greywater, by the rainwater which is usually lees polluted. However, the high concentrations of pathogens in the combination of these two types of water may result in a greater need for disinfectant and, consequently, higher operating costs (Leong et al. 2017). A potable water supply system must be activated when non-potable water is not sufficient (ANQIP, 2021).

Figure 1 presents the configuration of HRGS considered in the present study.

The rainwater and greywater will be collected and submitted to a different treatment. As for the treatment, for rainwater, a filtration step was considered, and for greywater a compact system was included. The compact system integrates the following steps: (i) screening; (ii) sequential batch reactor (SBT) and (iii) Filtration/disinfection module. After the treatment, rainwater and greywater should be stored in the same tank, that will be equipped with a disinfection system with sodium hypochlorite.

One of the critical factors in the systems, being generally the most expensive stage, is the storage tank (Santos and Taveira-Pinto 2013). The effectiveness of the system depends on an adequate storage capacity, but it should be noted that the volume of the storage may be limited by the area available in the building for its implementation and available initial investment and area for the construction (Silva et al. 2015; Valente Neves et al. 2006).

In addition, maximum storage periods should be limited in the design of the storage tanks in order to avoid water deterioration. For rainwater, the water storage period must be between 20 and 30 days (ANQIP, 2021) and for greywater, the storage period will be shorter in order to prevent the proliferation of bacteria.

## 2.2 Study Cases

To analyze the performance of the hybrid systems in different types of buildings, this study was done for a total of four buildings: a single-family dwelling in Esmoriz, a multifamily building in Oporto, an educational building and a research building (these two are part of the Campus of the Faculty of Engineering of the University of Porto).

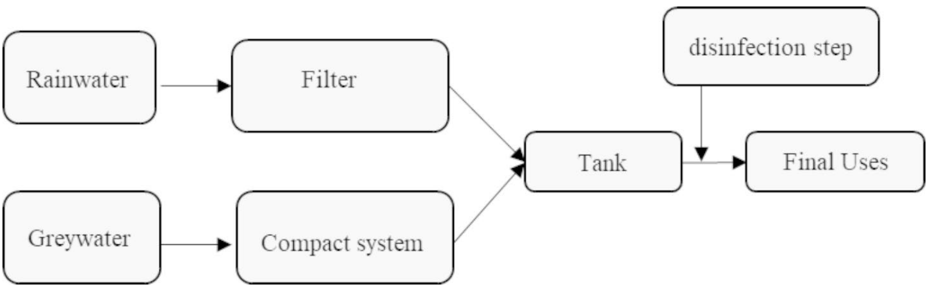


**Fig. 1** Configuration of hybrid systems

For single-family housing, the implementation of a hybrid system for the use of rainwater and reuse of greywater was studied, considering the following uses of non-potable water: toilet flushing, washing machine, garden taps and garden irrigation (total area of 212 $m^2$, composed of grass and with sprinkler irrigation). In the greywater recycler, the collected water initially undergoes a grading process, for the removal of coarse solids, then the effluent is sent to the biological reactor (Sequencing Batch Reactor, SBR) for organic matter removal. In the last stage of treatment, the effluent is pumped into the Filtration/Disinfection module, where a sodium hypochlorite disinfectant solution is added to the effluent for the elimination of pathogenic microorganisms. In this system, the collected rainwater is just filtered. After the treatments, the rainwater and greywater are gathered in the same storage tank, equipped with a sodium hypochlorite post-disinfection system to ensure the supply of non-potable water in accordance with the limits set by the local legislation.

The multifamily building analyzed consists of 2 apartment blocks and 12 shops. It is intended to supply non-potable water for toilet flushing (176) and washing machines (65). The building has a total of 65 housing fractions, estimating an occupancy of 301 inhabitants. Rainwater will be collected from the rooftop of the building, corresponding to a collection area of 3088 $m^2$ and the reused greywater will be collected from the 176 washbasins, 164 showers/baths and 113 bidets. Regarding the recommended treatment, it will be identical to the one described in the previous dwelling. A filter will be installed for rainwater at the storage entrance and, for greywater, an additional equalization step after the SBR reactor will be installed to reduce the flow and pollutant load variations. Tertiary treatment will consist of a filtration step, through an activated carbon filter and with a disinfection step with sodium hypochlorite. After the treatment, non-potable water will be gathered in the storage tank, equipped with a post-disinfection system with sodium hypochlorite.

The case of the Faculty of Engineering of the University of Porto (FEUP) was also analyzed. This complex of buildings has a high potential for the use of rainwater, due to the high coverage areas, as well as the reuse of greywater. Two buildings were studied independently: building B (lecture rooms) and building H (investigation). Building B is most frequented by the students, obtaining a higher production of greywater. In addition, it has a large coverage area that allows the use of rainwater. It was estimated a daily occupation of 3127 students, considering that, of the total number of students who attend FEUP daily, only about 40% use the bathrooms. The greywater considered in the study will be collected from the 66 washing basins and rainwater collected on the roof of the building, with an area of 5900 $m^2$. In the building, the drainage network of greywater is separated from the wastewater drainage network, so it is possible to use this network, and build only the connection to the storage tank. For rainwater, the building also has a drainage network that will be intersected and will drain the water to the storage tank. The treatment will be identical to that described earlier for the multifamily building. A compact greywater treatment unit will be installed for the treatment of greywater. It is intended to study the supply of non-potable water for toilet flushing (48) and urinals (60) in the building and supply the garden irrigation system, with an area of 10,270 $m^2$.

In building H, the frequency of students is lower, with an estimated occupation of 79 people in daily functions/exercises (mostly investigators, teachers and office workers). The greywater will be collected in 19 washbasins and for the collection of rainwater, the building has a total area of 3074 $m^2$. The treatment to be implemented will be the same as that considered for the other buildings under study. Thus, like building B, building H also has drainage networks of greywater, and it is only necessary to connect them to the storage. The use of rainwater throughout the building will require the construction of the rainwater drainage network for the larger coverage. In this case, non-potable water is considered to be the supply of non-potable water for flushing of toilets (31) and urinals (12) and also for the watering of the garden with an area of 10,270 m$^2$.

For each study case, different scenarios are considered, varying the final uses of non-potable water, in order to evaluate the influence of this factor on the performance of the system. Table 2 presents six scenarios considering different final uses of non-potable water. The scenarios studied for the dwelling were scenarios 1, 2, 3, 4 and 5, for the multifamily building, scenarios 1 and 3, and for the FEUP, scenarios 1, 2 and 6.

## 3 Methods

### 3.1 Calculation Tool

The decision support tool used in this study is called *SAPRA - Rainwater harvesting and greywater reuse systems in buildings*. It was developed by Santos (2012) using Microsoft Office Excel 2007 and programmed in Microsoft Visual Basic for Applications (VBA). SAPRA allows to size the volume of the storage tank for rainwater and greywater and makes a performance analysis of the system. In addition, this tool makes an economic study and estimates the return period of the investment.

The calculation tool is divided into three parts: Data Introduction, Data Base and Results.

In the Data Introduction sheet, the characteristics of the system under study are introduced in the program, namely the type of building, the location, the number of occupants, the equipment to be supplied with non-potable water, the characteristics of the system and the costs of installation. Table 3 presents these data for each study cases.

The second sheet, Data Base, presents the various data necessary for the calculations, namely: capitation and distribution of consumption for the different types of buildings, the spatial distribution of areas, types of coverage and irrigation needs, treatment costs, tariffs, material and equipment costs and precipitation records.

On the third and last page, the results are presented. SAPRA works by modules: the first module calculates the recommended storage volume and the performance of the system in terms of volume of water consumed in non-potable uses, volumes of rainwater and greywater use, and the second module analyses the economic viability (payback period, maintenance costs, economical savings, etc.) of the system under study.

**Table 2** Scenarios admitted for final uses of non-potable water

| NON-POTABLE WATER End Uses | Toilet flushing/ Urinals (Tf/U) | Garden Irriga-tion (Ir) | Washing machine (Wm) | Wash-ing Taps (Tp) |
|---|---|---|---|---|
| Scenario 1 (Sc 1) | ✓ | | | |
| Scenario 2 (Sc 2) | ✓ | ✓ | | |
| Scenario 3 (Sc 3) | ✓ | | ✓ | |
| Scenario 4 (Sc 4) | ✓ | ✓ | ✓ | |
| Scenario 5 (Sc 5) | ✓ | ✓ | ✓ | ✓ |
| Scenario 6 (Sc 6) | | ✓ | | |

**Table 3** Scenarios admitted for final uses of non-potable water

| System characteristics | | Single-family House | Multifamily building | Education building, FEUP | Investigation building, FEUP |
|---|---|---|---|---|---|
| Type of building | | Domestic | Domestic | Services | Services |
| Location | | Esmoriz, Portugal | OPorto, Portugal | OPorto, Portugal | OPorto, Portugal |
| Number of occupants | | 4 | 313 | 3 127 | 79 |
| Equipment to be supplied with non-potable water | | Toilet flushing/Urinals; Garden irrigation; Washing Machine and Washing Taps | Toilet flushing/Urinals and Washing Machine | Toilet flushing/Urinals and Garden irrigation | Toilet flushing/Urinals and Garden irrigation |
| Characteristics of the rainwater harvesting system | Rainwater catchment area | 158 $m^2$ | 3 087,66 $m^2$ | 5 900 $m^2$ | 3 074 $m^2$ |
| | Type of coverage | Impermeable coverage (0,9) | Impermeable coverage (0,9) | Flat with gravel coverage (0,7) | Flat with gravel coverage (0,7) |
| Characteristics of the greywater system | Greywater production equipment | Wash basins, Showers/Tubs and bidets. | Wash basins, Showers/Tubs and bidets. | Wash basins | Wash basins |

## 3.2 Precipitation Records

For rainfall records a study period of, at least, 10 years, should be used (Santos, 2012). The longer the simulation period, the best the representation of the system operation. To this end, updated data from the SNIRH - National Water Resources Information System (APA, 2022) were collected for meteorological stations in the study areas. The selected weather stations were: Ermesinde and Leça da Palmeira for the Oporto area; Espargo (Feira) and Barragem de Castelo Burgães stations for the region of Esmoriz.

The data from SNIRH system had failures, due to technical malfunctions. For the region of Oporto, the missing data was about 40%, and for Esmoriz 20%. Those failures of the SNIRH system were filled with data collected by NASA (National Aeronautics and Space Administration) satellites, namely the Global Precipitation Measurement (GPM) immersive (Integrated Multi-satellitE Retrievals for GPM) - Final Precipitation L3 (IRI, 2021) and Tropical Rainfall Measuring Mission (TRMM) 3 Products (IRI, 2019). The GPM satellite has data from June 2000 to September 2021, with a resolution of (0.1° × 0.1°) (NASA, 2022a). The TRMM satellite provides daily precipitation data from March 2000 to October 2016 from tropical and subtropical regions, with a resolution of (0.25° × 0.25°) (NASA, 2022b).

The data collected by SNIRH were compared with the two NASA databases, in order to select the one that was closer to the data obtained by SNIRH. For the region of Oporto and Esmoriz, the total monthly precipitation value was calculated for the three databases. Based on this analysis, the SNIRH data for the Oporto region were completed with data from the TRMM satellite and to the Esmoriz region with the GPM satellite. Since the TRMM satellite ceased operating in 2016, the daily rainfall figures for the period 2005–2015 were collected for the two regions. The distance between the observation station and the observation satellite, for the studies in Oporto, was 6,4 km for the educational building and 6 km for the multifamily building. For the study in Esmoriz the distance was 909,5 m.

### 3.3 Volumes of Water Collected and Consumed

The volume of daily rainwater ($V_{RW}$) collected was obtained from the following equation:

$$V_{RW} = P \times A \times C$$

P - Daily precipitation data (mm).

A - Catchment Area (m2).

C – Runoff coefficient.

The runoff coefficient is the ratio between the collected volume and the total volume. Predefined values were used, obtained from ANQIP (National Association for quality of building installations) (ANQIP, 2021).

The volume of greywater collected depends on the selected treatment system, varying according to the pre-defined treatment flow rate. The required non-potable water volume is obtained thought the following equation:

$$V_{non-potablewaterrequired} = V_{Tf/U} + V_{Ir} + V_{Wm} + V_{Tp}$$

$V_{Tf/U}$ – Volume of non-potable water required for use in toilet flushing/Urinals;

$V_{Ir}$ – Volume of non-potable water required for garden irrigation;

$V_{Wm}$ – Volume of non-potable water required for use in washing machines;

$V_{Tp}$ – Volume of non-potable water required for use in Washing Taps.

The calculation of the volume of non-potable water for use in toilet flushing/Urinals, washing machines and washing taps considered the number of occupants and the distribution of non-potable water consumption according to the building under study. The calculation of the non-potable water demand for garden irrigation was made considering the area for garden and the irrigation needs, depending on the type of grass (ANQIP, 2021).

### 3.4 Performance Analysis

In the performance analysis of the system, the average volume of non-potable water consumed ($m^3$/year) is calculated, as well as the volume of rainwater harvested and greywater reused ($m^3$/year). The average volume of potable water inserted into the system ($m^3$/year) is also determined. From these values, the effectiveness of the system is obtained by dividing the volume of non-potable water used (rainwater and greywater) and the volume of non-potable water necessary for the considered final uses.

### 3.5 Economic Study

SAPRA also conducts an economic analysis, by calculating the estimated return period, obtained by the ratio between the costs (initial installation and maintenance) and the annual savings.

In estimating investment costs, all costs involved in the execution of the project are considered. The maintenance cost is estimated by assigning a maintenance percentage against the investment cost. The estimated annual savings result from the sum of the average savings in each month, which is obtained by reducing the consumption of potable water compared to the conventional system. The monthly savings are calculated by the difference in costs of water consumption of the building without and with the hybrid system, according to the rates of the municipality under study.

### 3.6 Performance Indicators

SAPRA, for each system under study, determines the volume of the storage tank ($V_S$), the average volume of water consumed in non-potable uses ($V_{NP}$), the average volume of rainwater used ($V_{RW}$), the average volume of greywater reused ($V_{GW}$) and the average volume of potable water inserted in the system ($V_{POT}$). In addition, it calculates the costs of installation and maintenance of the system, the savings relative to the volume of non-potable water consumed and, finally, the return period (RP). For the calculation of the return period, in the initial year, SAPRA considers the installation cost as an expense and that there is still no savings. From year 1, the annual maintenance cost of the system is added to the expense and the accumulated annual savings are considered. The result of the return period is obtained when the savings are greater than the expense.

From the values calculated by SAPRA it is possible to define other performance indicators. In terms of the effectiveness of HRGS, the systems will be evaluated for the consumption of non-potable water in the building and its production. The effectiveness of non-potable water consumption is determined by the ratio between the volume of non-potable water used in the building [$m^3$/day] and the volume of non-potable water required [$m^3$/day] (Eq. 1).

$$\mathrm{Ef}_{\mathrm{non-potable\,consumption}}(\%) = \frac{\mathrm{V_{RW}} + \mathrm{V_{GW}}}{\mathrm{V_{NP}}} \tag{1}$$

The effectiveness of the production of non-potable water is calculated by Eq. 2 and results from the ratio between the volume of non-potable water used in the building [$m^3$/day] and the total volume of rainwater produced ($V_{RW\ Produced}$) and the total volume of greywater produced ($V_{gw\ Produced}$) [$m^3$/day].

$$\mathrm{Ef}_{\mathrm{non-potable\,production}}(\%) = \frac{\mathrm{V_{RW}} + \mathrm{V_{GW}}}{\mathrm{V_{RW\,produced}} + \mathrm{V_{GW\,produced}}} \tag{2}$$

This indicator allows us to evaluate the amount of non-potable water that is being used against the production potential of non-potable water in the building. Similarly, the effectiveness of rainwater production (Eq. 3) and greywater production (Eq. 4) can be determined.

$$\mathrm{Ef}_{\mathrm{RW\,produced}}(\%) = \frac{\mathrm{V_{RW}}}{\mathrm{V_{RW\,produced}}} \tag{3}$$

$$\mathrm{Ef}_{\mathrm{GW\,produced}}(\%) = \frac{\mathrm{V_{GW}}}{\mathrm{V_{GW\,produced}}} \tag{4}$$

The total volume of rainwater produced ($V_{RW\ Produced}$) was calculated considering the total volume of rainwater that precipitates, considering the coverage area of the building and the runoff coefficient. The total volume of greywater produced ($V_{GW\ Produced}$) results from the annual flow of treated greywater.

In terms of the performance evaluation, indicators will be defined as: potable water saved, reduction of wastewater and cost reduction in the water bill. The volume of potable water saved is obtained through Eq. 5, and results from the ratio between volume of rainwater and greywater used [$m^3$/day] and the volume of potable water required ($V_{PW}$) [$m^3$/day] (Eq. 5).

$$\text{Potable water savings}\,(\%) = \frac{V_{RW} + V_{GW}}{V_{PW}} \tag{5}$$

The volume of potable water required was obtained by the sum of the daily unitary consumption values for a week, multiplied by the number of weeks in one year (52 weeks) and by the number of occupants in the building. The reduction in the volume of wastewater (WW) is obtained through the ratio between the volume of reused greywater ($V_{GW}$) [$m^3$/day] and the total volume of wastewater produced ($V_{WW}$) [$m^3$/day] (Eq. 6).

$$\text{Reduction of WW}\,(\%) = \frac{V_{GR}}{V_{WW}} \tag{6}$$

The volume of wastewater produced was obtained considering 80% of the volume of potable water consumed in the building. The reduction in water bill is calculated by Eq. 7, using the cost of water consumption (€) with and without the hybrid system (results provided by SAPRA).

$$\text{Reduction in water bill}\ (\%) = \frac{\text{cost water}_{\text{without HRGS}} - \text{cost}_{\text{with HRGS}}}{\text{cost water}_{\text{without HRGS}}} \tag{7}$$

## 4 Results and Discussion

The decision support tool, SAPRA determined the parameters referred in 3.4. With those values, the results of the effectiveness and performance indicators were determined for the four case studies.

### 4.1 Dwelling

For the dwelling case study (Table 4) (Fig. 2), the five scenarios led to effectiveness values in relation to the “consumption of non-potable water”, between 67.2 and 100%, which means that, among the final uses of non-potable water considered, about 67% can be supplied by rainwater and greywater if toilet flushing and garden irrigation were considered, rising to the whole of the final uses if only the toilet flushing were supplied. This indicator is essentially influenced by two parameters: the final uses of non-potable water considered and the storage volume. In more detail, it was found that:

**Table 4** Dwelling: results of the indicators (for a 10 years simulation)

| Indicators | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|---|
| | | Tf/U | Tf/U, Ir | Tf/U, Wm | Tf/U, Ir, Wm | Tf/U, Ir, Wm, Tp |
| **Effectiveness** | Effectiveness related to non-potable consumption | 100.0% | 67.2% | 99.8% | 68.7% | 69.3% |
| | Effectiveness related to non-potable production | 14.8% | 19.7% | 20.0% | 23.7% | 25.8% |
| | Effectiveness related to RW production | 0% | 3.6% | 0.3% | 4.2% | 5.2% |
| | Effectiveness of GR production | 66.7% | 76.0% | 88.7% | 91.9% | 97.8% |
| **Performance** | Potable water savings | 28.1% | 37.3% | 37.8% | 44.9% | 48.8% |
| | Reduction of wastewater discharged | 35.1% | 40.0% | 46.7% | 48.4% | 51.5% |
| | Reduction of water bill | 32.7% | 43.1% | 44.1% | 51.8% | 56.3% |
| **Economic** | Average annual savings (€/year) | 76 | 100 | 102 | 120 | 130 |
| | Return Period (years) | 227 | 176 | 160 | 143 | 133 |

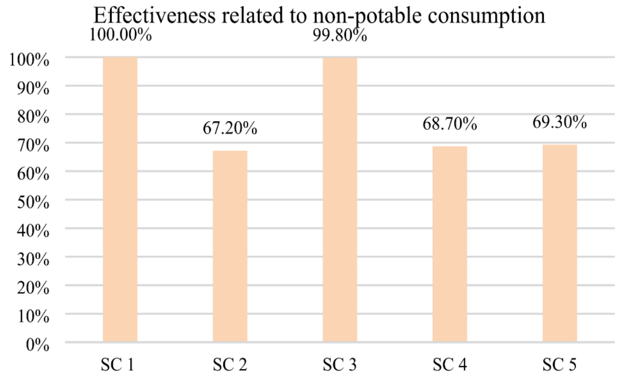


**Fig. 2** Dwelling: results of effectiveness related to non-potable consumption (for a 10 years simulation)

- Scenarios 1 and 3 show the highest non-potable consumption effectiveness values, covering all non-potable water needs for the defined end-uses.
- In scenarios 2, 4 and 5, effectiveness related to consumption of 67.2%, 68.7% and 69.3%, respectively, were obtained. These scenarios have in common the supply of non-potable water to the garden irrigation network, thus presenting, in the summer months, higher non-potable water demand. However, in these months, the potential for the use of rainwater is lower, due to low rainfall, and since greywater is constantly produced, the potential for the use of non-potable water will be smaller, hence lower consumption effectiveness.
- It is also verified that the potential for "use of rainwater and greywater" is limited by the volume of storage. Thus, for scenarios 2, 4 and 5, increasing the storage volume, higher effectiveness values in relation to the "consumption of non-potable water" would be obtained, allowing to mitigate the impact of seasonal variations in the production of non-potable water.

Comparing the effectiveness values in relation to the "consumption of non-potable water", with those consulted by the bibliography, the present study obtained higher effectiveness: Ghisi & Mengotti de Oliveira (2007) obtained an effectiveness of 33.8–36.4% for an analysis similar to Scenario 3, while for the same scenario, an effectiveness of 99.8% was obtained in the present study; Marinoski and Ghisi (2019) studied a scenario similar to scenario 5, considering the supply for garden irrigation, washing of floors and vehicles and use for washing in clothes machines, and obtained an effectiveness of 41.9%, while for scenario 5 (garden irrigation, washing in clothes machines, washing floors and flushing of toilets), in the present study, the resulting effectiveness was 69.3%.

As for the effectiveness of "non-potable water production", it is concluded that:

- It will obviously be as greater as much rainwater and greywater is collected. For the scenarios under study in the dwelling case, values between 14.8 and 25.8% were obtained, resulting from the low need for non-potable water in the building, when compared to the high production of rainwater and greywater;
- The effectiveness of greywater production is higher than rainwater because SAPRA first considers the reuse of greywater, and as housing has low need for non-potable water, those end-uses are almost all fulfilled with greywater.

In relation to the performance indicators, it was found that:

- The greater the volume of potable water saved, the greater the reduction in water bill costs and the greater the reduction of the wastewater sent for the public drainage networks, as expected;
- These indicators depend on the volume of non-potable water used, and the higher this value is, the better the system will perform.

From an economic point of view, the results are not very favorable. The high investments in the construction of the hybrid system in the face of low consumption of non-potable water result in very high periods of return, in the order of 150 years. The high costs are mainly from the treatment unit for greywater reuse and the cost of the storage tank.

As for the cost of drainage and supply networks, this will depend on the materials used and the configuration selected. The construction of a joint network for the drainage of rainwater and grey will reduce the cost associated with these, however it will be necessary to implement a combined treatment for the two waters.

In environmental terms, the main benefit resulting from the implementation of a hybrid system is the reduction of potable water consumption and the reduction of wastewater produced and sent to the wastewater treatment plant. For this dwelling and similar, the implementation of a hybrid system can provide reductions in potable water consumption between 28.1 and 48.8%, and a reduction in wastewater discharged between 35.1 and 51.5%.

### 4.2 Multifamily Building

For the multifamily building, in terms of the effectiveness related to "non-potable water consumption", the results obtained for the two scenarios were very different (Table 5) (Fig. 3):

**Table 5** Multifamily Building: results of the indicators (for a 10 years simulation)

| Indicators | | Scenario 1 | Scenario 3 |
|---|---|---|---|
| | | Tf/U | Tf/U, Wm |
| **Effectiveness** | Effectiveness related to non-potable consumption | 100.0% | 8.0% |
| | Effectiveness related to non-potable production | 44.5% | 95.6% |
| | Effectiveness related to RW production | 0% | 88.0% |
| | Effectiveness of GR production | 70.4% | 100.0% |
| **Performance** | Potable water savings | 30.1% | 64.7% |
| | Reduction of wastewater discharged | 37.6% | 53.4% |
| | Reduction of water bill | 30.5% | 65.8% |
| **Economic** | Average annual savings (€/year) | 13 359 | 28 816 |
| | Return Period (years) | 5 | 3 |

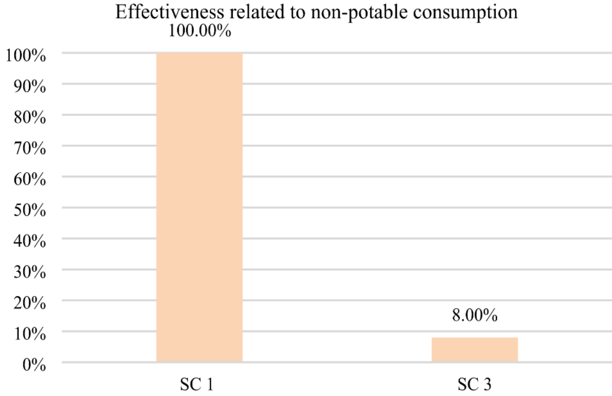


**Fig. 3** Multifamily Building: Results of Effectiveness related to non-potable consumption (for a 10 years simulation)

- For scenario 1, considering only the supply of toilet flushing, the system obtained an effectiveness of 100%, only through the reuse of greywater;
- Scenario 3, considering the supply of toilet flushing and washing machines, obtained an effectiveness of only 8%. The low water savings for scenario 3 results from the high need for non-potable water when compared to the volumes of grey and rainwater that can be used in the building.

In terms of effectiveness of the "production of non-potable water" the picture is reversed, with scenario 3 presenting higher values than scenario 1:

- Despite the low effectiveness of the non-potable consumption of scenario 3, this system has a high use of the non-potable water produced in the building, 95.6% resulting from all the greywater produced and 88% of all rainwater that can be collected;
- Scenario 1 shows an effectiveness in the production of non-potable water of 44.5%, resulting only from the reuse of greywater.

Regarding the performance indicators, as well as for the previous study case, they all depend on the volume of non-potable water used, and the higher this value is, the better performance the system will have. In more detail, it was found that:

- In terms of potable water saved, scenario 1 achieved a reduction of 30.1% and scenario 3 of 64.7%, resulting in reductions in water cost of 30.5% and 65.7%, respectively;
- The hybrid system of the multifamily building would allow a reduction of the wastewater sent for the public drainage networks, of 37.6% for scenario 1 and 53.4% for scenario 3.

In economic terms, despite the high investment for the implementation of the hybrid system, both scenarios obtained low return periods: five years for scenario 1 and three years for scenario 3. The low return period makes the investment profitable, even for scenario 3, that obtained lower effectiveness related to non-potable consumption, allowing to obtain profits soon after the implementation of the system.

Regarding environmental benefits, the implementation of the hybrid system allows achieving savings of potable water compared to the conventional system of 30.1% for scenario 1 and 64.7% for scenario 3 and reduction of the volume of wastewater produced and sent to the wastewater networks of 37.6% for scenario 1 and 53.4% for scenario 3.

### 4.3 Educational Building

Building B obtained effectiveness values for "non-potable water consumption" between 42.8 and 65.6% (Table 6) (Fig. 4). From the analysis it is possible to highlight the following aspects:

- When considering the supply for toilet flushing and urinal discharges, effectiveness of 50.1% were obtained, but adding as final use the supply to the garden irrigation system, the effectiveness decreased to 42.8%. This is due to the fact that the period of operation of the garden irrigation system is between April and September, corresponding to the period with the lowest rainwater production, resulting in low consumption effectiveness;
- For the scenario considering only the supply to the garden irrigation system, an effectiveness related to consumption of 65.6% was obtained, higher than that achieved in the other scenarios. This is because, when only considering the use to supply the garden irrigation system, the volume of non-potable water required is lower, and despite the low use of rainwater in the summer months, there is a high potential for reuse of greywater, resulting in higher effectiveness.

**Table 6** Building B - Results of the indicators (for a 10 years simulation)

| Indicators | | Scenario 1 | Scenario 2 | Scenario 6 |
|---|---|---|---|---|
| | | Tf/U | Tf/U, Ir | Ir |
| **Effectiveness** | Effectiveness related to non-potable consumption | 50.1% | 42.8% | 65.6% |
| | Effectiveness related to non-potable production | 57.8% | 59.8% | 16.0% |
| | Effectiveness related to RW production | 31.5% | 34.7% | 1.8% |
| | Effectiveness of GR production | 98.8% | 99.1% | 38.2% |
| **Performance** | Potable water savings | 19.9% | 20.7% | 5.5% |
| | Reduction of wastewater discharged | 16.7% | 16.7% | 6.4% |
| | Reduction of water bill | 19.9% | 20.6% | 5.5% |
| **Economic** | Average annual savings (€/year) | 19 814 | 20 531 | 5 494 |
| | Return Period (years) | 4 | 4 | 12 |

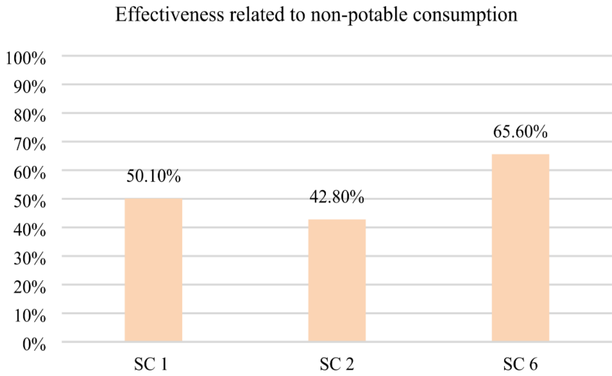


**Fig. 4** Building B - Results of Effectiveness related to non-potable consumption (for a 10 years simulation)

In terms of effectiveness regarding the "production of non-potable water", this value is higher for scenario 2, taking advantage of 59.8% of the total non-potable water produced in the building. This value, besides depending on the volume of non-potable water used in the building, is also influenced by the non-potable water demand. Thus, for scenario 6, an effectiveness related to production of 16.0% was obtained, due to the low consumption of non-potable water for the considered end-uses.

Regarding the performance indicators, it is shown that the performance of the system depends on the volume of non-potable water used, and the higher this value is, the better the performance of the system, in terms of potable water savings. As expected, the volume of non-potable water used is also directly connected to reduction of the wastewater discharged to the public networks and to the reduction of costs in the water bill.

In economic terms, despite the high investment costs, the high water savings provide low return periods. Scenarios 1 and 2 obtained return periods of four years and scenario 6, of twelve years, due to lower needs of non-potable water. With regard to environmental benefits, these systems allow for a significant reduction in potable water consumption and a reduction in the volume of wastewater produced.

Together with the economic and environmental benefits, the implementation of this type of system in a higher education institution such as FEUP, transmits to society and stakeholders a message of concern for the environment and responsibility in the sustainable management of water resources.

### 4.4 Investigation Building

Finally, considering the results obtained for FEUP building H (Table 7) (Fig. 5) in terms of effectiveness in relation to "consumption of non-potable water", the following aspects can be highlighted:

- Scenario 1 obtained effectiveness values of 93.6%;
- The remaining scenarios had effectiveness of 12.9% and 17.5%. The low effectiveness values for scenarios 2 and 6 are the result of the low volumes of non-potable water used when comparing to the demand, due to the supply to the garden irrigation system.

**Table 7** Building H - Results of the indicators (for a 10 years simulation)

| Indicators | | Scenario 1 | Scenario 2 | Scenario 6 |
|---|---|---|---|---|
| | | Tf/U | Tf/U, Ir | Ir |
| **Effectiveness** | Effectiveness related to non-potable consumption | 93.6% | 17.5% | 12.9% |
| | Effectiveness related to non-potable production | 6.9% | 12.0% | 7.9% |
| | Effectiveness related to RW production | 4.9% | 9.3% | 6.5% |
| | Effectiveness of GR production | 94.4% | 96.1% | 52.0% |
| **Performance** | Potable water savings | 37.3% | 65.4% | 42.9% |
| | Reduction of wastewater discharged | 20.1% | 20.5% | 11.1% |
| | Reduction of water bill | 37.2% | 60.8% | 38.3% |
| **Economic** | Average annual savings (€/year) | 936 | 1 530 | 964 |
| | Return Period (years) | 78 | 50 | 71 |

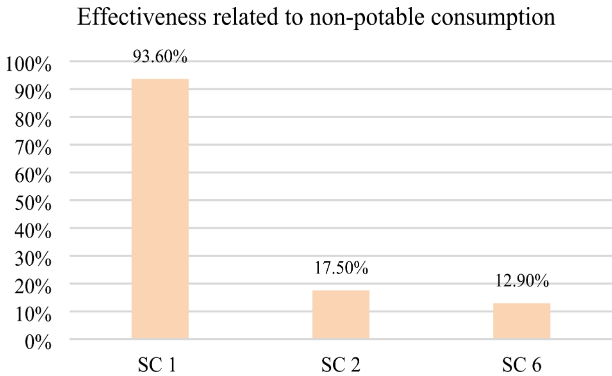


**Fig. 5** Building H - Results of effectiveness related to non-potable consumption (for a 10 years simulation)

Building H has a high potential for the use of non-potable water, mainly rainwater, due to the high catchment area. In the studied scenarios, regarding the effectiveness of "non-potable water production", the analysis describes the following aspects:

- Low values were obtained, between 6.9 and 12%, which means that there is still a high potential for non-potable water to be used;
- The potential for rainwater use is higher than that of greywater, and it is verified that, for all scenarios, the volume of rainwater used was higher than greywater reuse, because in building H the production of greywater is conditioned by low occupation.

In terms of performance indicators, there was a reduction in potable water between 37.3 and 65.4%, increasing according to the volume of non-potable water used. The reduction in the amount of wastewater discharged in the public networks and the reduction in water bills is proportional to the volume of non-potable water used, so the higher this volume, the better the system will perform.

From the economic viability point of view, there were high periods of return, between 50 and 78 years, resulting from high investment costs and low water savings. The high investments are mainly resulting from the treatment unit and the storage tank. The feasibility of implementing a hybrid system in a building such as FEUP building H will depend on the intended end uses. If the consumption of non-potable water is high, the building cannot provide sufficient water, as the production of greywater is conditioned by the low frequency of people. Besides, the use of rainwater is conditioned by the collection areas and climatic conditions, resulting in low effectiveness and high return periods.

Regarding environmental benefits, these systems reduce potable water consumption by up to 65.4% (scenario 2) and wastewater production by 11.1 to 20.5%. In addition to the environmental benefits, as well as for building B, issues of environmental concern and responsibility in the management of water resources, may be the incentive for the implementation of a hybrid system.

### 4.5 Comparison

Figures 6 and 7 present the results obtained for the four cases. The Dwelling and the Multifamily building have similar results for the first scenario, where toilets are supplied by the non-potable water provided by the hybrid system. The best results are presented by the Multifamily building with potable water savings and water bill reduction rounding 65%. Even though the dwelling presents lower results, they are not distant from Multifamily ones, and this similarity can be explained by the same type of consumption pattern in the two cases: a typical domestic water use. This fact also explains the differences between the results obtained for the two Buildings of FEUP. Despite belonging to the same institution and being close to each other, the use made by the occupants is distinct. In building B water is used mainly for toilet/Urinals flushing and in building H a significant amount of water is also used to the support of lab work and people tend to stay in the building more time throughout the day. More use of water leads to more savings when a hybrid system is implemented and it is possible to see that building B only saves 20% of potable water with the system, while building H almost doubles the value for Scenario 1, reaching 65% if garden irrigation is also considered.

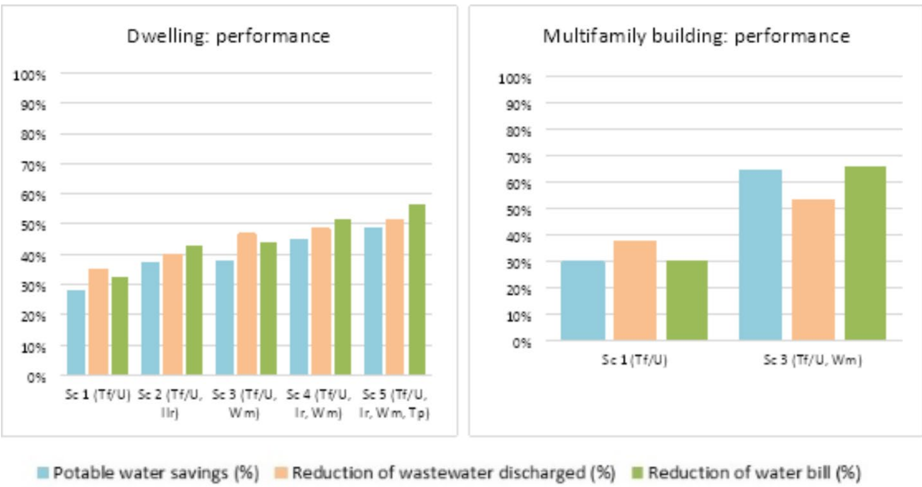


**Fig. 6** Performance results for the studied dwelling and Multifamily building

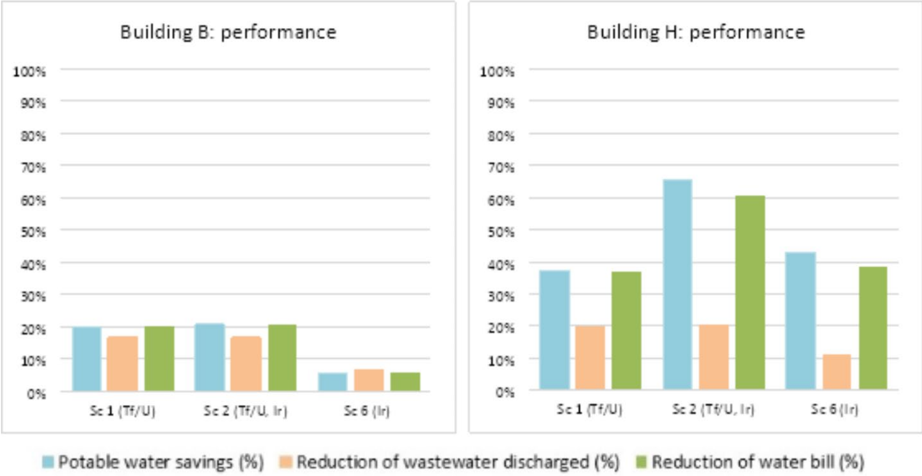


**Fig. 7** Performance results for the studied Building B and Building H

## 5 Conclusions

This performance and effectiveness analysis of hybrid systems showed that, in most of the study cases, more than 50% of non-potable water demands can be supplied by them, except for some scenarios in which the consumption of non-potable water was of such a magnitude that the maximum use of rainwater and greywater was not sufficient to meet the non-potable water demand. The analysis carried out allows to present the following conclusions:

- For domestic buildings, such as dwellings and multifamily buildings, the production of non-potable water allows to meet all water needs for the supply of toilet flushing, achieving consumption effectiveness of 100%. This indicator is influenced by two factors: the final uses considered for non-potable supply and the storage volume. When garden irrigation is considered as a final use, the effectiveness related to consumption decreases due to the high water needs during the summer months.
- In general, the effectiveness related to the non-potable water produced was low, which means that there is a high potential for non-potable water to be used. This indicator is influenced by the non-potable water demand in the building and by the non-potable water production. In all the studied cases, the reuse of greywater was superior to the use of rainwater, with the exception of FEUP building H, which is due to its more regular production.

Regarding potable water savings, this value is dependent on the volume of non-potable water used in the building. However, this depends on the selected storage volume and the availability of rainwater and greywater. Consequently, the reduction in water bills depends on the volume of potable water saved, so this will be greater with the biggest storage volume available for the building.

The reduction in the volume of wastewater produced will be greater when the fraction of greywater used in the building is higher. For the dwelling and for the multifamily building, reductions in the volume of wastewater between 35.1 and 53.4% were obtained, resulting from the reuse of the greywater produced in washing basins, showers and bidets. For the two FEUP buildings under study, reductions between 6.4 and 20.5% were obtained, which are lower than domestic buildings, as only greywater from washbasins were considered for reuse.

Based on the effectiveness values, in all scenarios of the studies cases, it is possible to see that, in general, the effectiveness depends on the end uses of non-potable water: the more end uses the higher the effectiveness. However, it may decrease when considering garden irrigations, because for this activity the water necessity will be more significant during the warmer months, when less precipitation occurs, and less non-potable water is available.

Nevertheless, when evaluating only the effectiveness, a wrong interpretation of the performance of the system can be made. When comparing the scenarios of the case studies, it was verified that some scenarios had higher effectiveness, but lower potable water savings, when compared to scenarios with lower effectiveness. To evaluate the performance of hybrid systems, different indicators that assess the different aspects of the system must be considered such as effectiveness related to non-potable water consumption, effectiveness related to non-potable water production and potable water savings.

The best performance of hybrid systems is achieved when the volume of non-potable water used in the building is maximized, represented in a greater volume of potable water saved and in reducing in the water bill. To this end, all rainwater collection areas and all greywater-producing equipment in the building shall be considered. In addition, the larger the fraction of greywater reused, the lower the volume of wastewater produced and sent directly to the wastewater network.

In environmental terms, the main advantage of these systems results in the reduction of potable water consumption and the reduction of the volume of wastewater produced, providing a sustainable management of water resources.

From an economic point of view, it was found that the implementation of these systems in larger buildings is more cost-effective, achieving high economic savings that quickly outweigh the initial investment and this finding matches with the findings of Shanableh et al. (2012). For housing, low consumption of non-potable water and high investment, results in very high periods of return, and that can lead to the unfeasibility of implementing the system.

The results obtained from this article allowed a step forward in the perception of the functioning of this type of systems. It was possible to conclude that hybrid systems perform better, when more final uses of non-potable water are selected and that the use of these systems to supply irrigation system may not be advantageous. Even so, there are other aspects, also relevant, that should be considered in further developments in order to assess their impact on the effectiveness of the system, namely the number of occupants, the coverage area and type of coverage, the production sites of greywater, volume of the tank, as well as the type of treatment selected.

**Author Contributions** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ana Ferreira and Cristina Santos, and both Monzur Imteaz and Cristina Matos performed the work structure, editing and revisions. The first draft of the manuscript was written by Cristina Santos and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** Open access funding provided by FCT|FCCN (b-on). The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

## Declarations

**Competing interests** The authors have no relevant financial or non-financial interests to disclose.



## References

ANQIP (2011) ETA 0905 - Sistemas Prediais de Reutilização e Reciclagem de Águas Cinzentas (SPRAC) - Versão 2. Associação Nacional Para a Qualidade nas Instalações Prediais (ANQIP). https://www.anqip.pt/images/stories/eta%200905%20v.2.pdf

ANQIP (2021) ETA 0701 – Sistemas de Aproveitamento de Águas Pluviais em Edifícios (SAAP) – Versão 11. Associação Nacional Para a Qualidade nas Instalações Prediais (ANQIP). https://anqip.pt/images/stories/comissoes/0701/eta%200701%20v.11.pdf

APA (2022) Sistema Nacional de Informação de Recursos Hídrico (SNIRH). Agência Portuguesa do Ambiente. https://snirh.apambiente.pt/indexphp?idMain=2&idItem=1&objCover=920123704&objSite=920685506

Chen W, Gao W, Jiang J, Wei X, Wang R (2021) Feasibility analysis of decentralized hybrid rainwater-graywater systems in a public building in Japan. Sustainable Cities and Society 69. https://doi.org/10.1016/j.scs.2021.102870

Chen W, Gao W, Wei X, Jiang J, Wang R, Fang X (2022) Dimensionless parameter method for evaluating decentralized water reuse systems in buildings. Sustainable Cities and Society 76. https://doi.org/10.1016/j.scs.2021.103391

EN 16941-1 (2018) On-site non-potable water systems-Part 1: Systems for the use of rainwater. In Norma Europeia

EN 16941-2 (2021) On-site non-potable water systems - Part 2: Systems for the use of treated greywater. In Norma Europeia

Ghafourian M, Nika C-E, Mousavi A, Mino E, Al-Salehi M, Katsou E (2022) Economic impact assessment indicators of circular economy in a decentralised circular water system — case of eco-touristic facility. Sci Total Environ 822:153602. https://doi.org/10.1016/j.scitotenv.2022.153602

Ghisi E, de Mengotti S (2007) Potential for potable water savings by combining the use of rainwater and greywater in houses in southern Brazil. Build Environ 42(4):1731–1742. https://doi.org/10.1016/j.buildenv.2006.02.001

IRI (2019) NASA GES-DAAC TRMM_L3 TRMM_3B42RT v7. http://iridl.ldeo.columbia.edu/SOURCES/.NASA/.GES-DAAC/.TRMM_L3/.TRMM_3B42RT/.v7/

IRI (2021) NASA GES_DISC GPM_L3 v06 IMERG_Final daily precipitationCal: Daily accumulated precipitation (combined microwave-IR) estimate data. http://iridl.ldeo.columbia.edu/SOURCES/.NASA/.GES_DISC/.GPM_L3/.v06/.IMERG_Final/.daily/.precipitationCal/

Leong JYC, Oh KS, Poh PE, Chong MN (2017) Prospects of hybrid rainwater-greywater decentralized system for water recycling and reuse: A review. In Journal of Cleaner Production (Vol. 142, pp. 3014–3027). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2016.10.167

Leong JYC, Chong MN, Poh PE, Vieritz A, Talei A, Chow MF (2018) Quantification of mains water savings from decentralised rainwater, greywater, and hybrid rainwater-greywater systems in tropical climatic conditions. J Clean Prod 176:946–958. https://doi.org/10.1016/j.jclepro.2017.12.020

Leong JYC, Balan P, Chong MN, Poh PE (2019) Life-cycle assessment and life-cycle cost analysis of decentralised rainwater harvesting, greywater recycling and hybrid rainwater-greywater systems. J Clean Prod 229:1211–1224. https://doi.org/10.1016/j.jclepro.2019.05.046

Marinoski AK, Ghisi E (2019) Environmental performance of hybrid rainwater-greywater systems in residential buildings. Resour Conserv Recycl 144:100–114. https://doi.org/10.1016/j.resconrec.2019.01.035

Matos C, Pereira S, Amorim EV, Bentes I, Briga-Sá A (2014) Wastewater and Greywater reuse on irrigation in centralized and decentralized systems- an integrated approach on water quality, energy consumption and CO2 emissions. Sci Total Environ 493:463–471. https://doi.org/10.1016/j.scitotenv.2014.05.129

NASA (2022a) The Global Precipitation Measurement Mission (GPM). National Aeronautics and Space Administration. https://gpm.nasa.gov/missions/GPM#imerg:twodecadesofglobalprecipitationdata

NASA (2022b) The Tropical Rainfall Measuring Mission (TRMM). National Aeronautics and Space Administration. https://gpm.nasa.gov/missions/trmm

Santos C (2012) Otimização Ambiental do Uso de Água em Edifícios [PhD Thesis]. Faculdade de Engenharia de Universidade do Porto (FEUP)

Santos C, Taveira-Pinto F (2013) Analysis of different criteria to size rainwater storage tanks using detailed methods. Resour Conserv Recycl 71:1–6. https://doi.org/10.1016/j.resconrec.2012.11.004

Santos C, Taveira-Pinto F, Cheng C-Y (2011) Otimização do consumo de água em edifícios. Implementação de sistemas de aproveitamento de águas pluviais e reutilização de águas cinzentas. 6o Jornadas de Hidráulica, Recursos Híbridos e Ambiente [FEUP]. https://paginas.fe.up.pt/~shrha/publicacoes/pdf/JHRHA_6as/8_CSantos_Optimiza%C3%A7%C3%A3oDoConsumo.pdf

Shaikh IN, Ahammed MM (2020) Quantity and quality characteristics of greywater: A review. In Journal of Environmental Management (Vol. 261). Academic Press. https://doi.org/10.1016/j.jenvman.2020.110266

Shanableh A, Imteaz MA, Merabtene T, Ahsan A (2012) A Framework for Reducing Water Demand in Multi-Storey and Detached Dwellings in the United Arab Emirates, 7th International Conference on Water Sensitive Urban Design, Melbourne, February

Silva CM, Sousa V, Carvalho NV (2015) Evaluation of rainwater harvesting in Portugal: application to single-family residences. Resour Conserv Recycl 94:21–34. https://doi.org/10.1016/j.resconrec.2014.11.004

Valente Neves M, Bertolo E, Rossa S (2006) Aproveitamento e Reutilização da Água para Usos Domésticos. 1a Jornadas de Hidráulica Recursos Hídricos e Ambiente. https://paginas.fe.up.pt/~shrha/publicacoes/pdf/JHRHA_1as/RevistaHRHA6_AproveitamentoReutilizacao_VERFINAL.pdf

Zhang Y, Grant A, Sharma A et al (2010) Alternative Water Resources for Rural Residential Development in Western Australia. Water Resour Manage 24:25–36. https://doi.org/10.1007/s11269-009-9435-0