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Research article

Modeling for sustainability: Life cycle assessment application to evaluate environmental performance of water recycling solutions at the dwelling level

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ABSTRACT

The reduction in drinking water consumption, also through the reuse and recycling of unconventional sources of water, has been identified as one of the goals of the sustainable development. This study focuses on evaluating and comparing the environmental impacts attributable to the use of source of water supply, such as rainwater harvesting and greywater recycling, alternative to the traditional one. The environmental impacts of both positive (reduction of the potable water consumption, stormwater runoff mitigation, wastewater reduction, etc.) and negative factors (system complexity, double network, tank, pump system, etc.) have been evaluated through the combined use of two models. The first is a Life Cycle Assessment (LCA) model, developed by means of Simapro software and based on Recipe 2008 method. The second is a hydrological model, realized with the EPA SWMM software. Models have been used to estimate the environmental impact of the following scenarios: (i) Business-As-Usual; (ii) rainwater harvesting system; (iii) greywater recycling system. Those scenarios have been applied to several configuration of single dwellings and apartment buildings. The Life Cycle stages evaluation showed how energy consumption for distribution system plays a critical role in the overall environmental performance of the solutions proposed, as well as use intensity of the technology. For greywater recycling system, the application of 1 m^3 storage and treatment system serving thirty population equivalent results in a net positive impact, while for rainwater harvesting system, the high use intensity should be combined with an alternative reuse for recycled water, i.e. washing machine supply, to obtain an overall environmental benefit.

1. Introduction

Water scarcity is widely recognized as one of the most challenging consequence of the climate change, already afflicts 40% of the world population and is destined to grow in the coming years (WWAP, 2015). Its correlation with environmental degradation, biodiversity loss and human rights threat made it a strategic element in the Sustainable Development Agenda for United Nations, where "ensuring availability and sustainable management of water and sanitation for all" has been listed as sixth sustainable development goal (WWAP, 2015). The full commitment to this issue is a milestone of 2030 agenda and a "universal and equitable" access to drinking water, increased efficiency in water use and supply, improving capacity-building support of local communities in order to decrease water scarcity through the application of sustainable techniques (e.g. water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies), are the main objectives.

The concept of sustainable solutions can be defined, in accordance with the definition of sustainable development, as technologies and techniques meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). Therefore, assessing the global impact of a local solution for water saving and recycling must be regarded, in this sense, as a crucial decision support step for designer and decision-makers.

Although Italy may not be considered a water-poor country, there are many regional differences in the water supply and consumption, with local water stresses and stormwater management issues. For this reason, the evaluation of rainwater harvesting,

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and greywater recycling solutions may be strategic to improve the sustainability of urban areas, as suggested by several studies (Stephan and Stephan, 2017; Angrill et al., 2011, 2017). Within this framework, the GST4Water project (Green-Smart Technology for Water) has been developed, with the main objective of creating hardware and software solutions for the sustainable use of water and promote rain and grey water reuse. The new instruments and technologies are, then, disclosed to encourage social change and improve awareness into water consumers. Moreover, smart and green solutions would be available for building and construction industry, supporting the establishment of smart, sustainable and resilient environments at building and urban scale.

1.1. GST4 W project presentation

The GST4Water project consists of four work-packages (WPs); the first two pertain to the development of: (a) a real time monitoring system of the mains water supply consumption at household; (b) a software cloud platform to manage and process information from the monitoring system; and (c) a user-friendly software interface to transfer information to users and water companies. WP1, in particular, analyzes the information from outdoor flow meters, while WP2 analyzes the indoor devices (showers, toilet flushing, washing machine, etc.). The third work package (WP3) is aimed to develop models and strategies for the optimal reuse of the grey and rainfall water at building level, while WP4 is focused on the elaboration of methods and tools to assess the economic and environmental sustainability of urban water systems at different scales, in particular household and urban. On one hand, a water sustainability tool is provided at household level along with environmental and economic performance indexes; on the other hand, the urban metabolism model is focused on the definition of different scenarios and strategies to limit the emissions and energy fluxes associated with the water consumption. Life Cycle Assessment (LCA) has been selected, as comprehensive impact assessment tool, to support water saving solution proposed, especially at household level.

This study, developed within the WP3 and WP4, fits this framework with a research activity devoted to assessing the sustainability of solutions proposed at a building scale, with the application of a Life Cycle Assessment tool.

Within the framework of GST4Water project, the main reuse option for recovered and recycled water has been identified in toilet flushing and garden irrigation (for rainwater only).

1.2. Decentralized system for water recycling and reuse

Two classes of technological solutions for water recovery in urban systems have been evaluated: Greywater Recovery Systems (GRS) and Rainwater Harvesting Systems (RHS).

1.2.1. Greywater recovery systems

A Greywater System (GRS) collects the gently used water from bathtubs, showers, handwashing basins and sometimes washing machines, and reuse it for non-potable uses. The volume of greywater produced by a households (Dwumfour-Asare et al., 2017; Yu et al., 2013) typically range between 43.6 and 117 $l/p/d$ (liters per person per day) due to living habits and to plumbing fixtures (standard vs low consumption). These value are 70%–75% of the total household sewage water production in terms of volumes, despite corresponding to a rather limited portion of the pollution load (Noutsopoulos et al., 2017) A greywater system includes three major components (Fig. 1): a collection system with a coarse filter (1), which conveys greywater to the storage tank (2), where volumes are equalized, and (3) the treatment train who guarantees the quality requirements mandatory by law. The tank is usually equipped with an overflow and a mains water top-up system regulated by level controllers (Leong et al., 2017). A pump system delivers treated non-potable water to the users (7). Greywater systems have had a limited uptake in Italy compare to other European countries, due to significant plant costs, low prices of freshwater, and the perceived long-term risk of contamination.

1.2.2. Rainwater harvesting systems

Systems aimed to capture and store rainwater have been generally used since 3rd millennium BC in the Near East and the Mediterranean regions (Mays, 2014). Ever since, rainwater-harvesting systems have evolved, and nowadays may still represents a valid technology to reduce the increasing demand for mains water supply.

A Rainwater Harvesting System (RHS), as illustrated in Fig. 2, includes four main elements: a catchment surface (1); a convey systems (2), which comprises gutters and some coarse filters to remove large solids (e.g. leaves and twigs); a storage tank (3), and a pump system (4) from which water is sent into the building or elsewhere (gardens, green roofs, etc.). Any excess of water, respect to the storage capacity of the tank, is delivered into the sewer system with a tank overflow (5), while a mains water top-up (6) system with level controller (7) ensures that the level of rainwater inside the tank does not go below a certain threshold level during periods without rainfall. Frequently, rainwater undergoes further treatment (additional filtration and disinfection) immediately before reuse (4) in order to lower health risks (Leong et al., 2017).

The non-potable water demand supplied by rainwater harvesting systems depends on the precipitation patterns, the volume of the tanks, and the demand for non-drinking water (Campisano et al., 2017). In California, due to the arid climate, the water saving efficiency does not exceed 10% (Loux et al., 2012), in Brazil due to tank size limitation it ranges from 14.7–17.7% (Ghisi and Mengotti de Oliveira, 2007). In Europe there is a marked improvement (Palla et al., 2011), and in Italy several studies show that water saving efficiencies of 70%–80% can be achieved with modest tank volumes (Liuzzo et al., 2016; Palla et al., 2011).

1.3. Life cycle assessment applied to water treatment

LCA, as defined with UNI EN ISO 14040 (2006), is generally applied for the assessment of eco-efficiency of product and processes. This analytical tool supports the quantification of environmental impacts generated throughout the whole life cycle, with each phase (production, use and end-of-life) carefully modeled and investigated (JRC, 2010). Thus including: extraction and transportation of raw materials, manufacturing process, distribution, use and maintenance, reuse (where possible) and waste treatment.

LCA applied to water recycling solutions offers an innovative perspective for most appropriated technique selection, considering technologies required to obtain the same level of environmental matrices quality, environmental benefit offered and possible criticality.

Several studies have been performed to evaluate the overall environmental impact of GRS, performed with different technologies (Dominguez et al., 2018), implemented into different residential zones (Jeong et al., 2018) and with different outline, i.e. with centralized treatment plant and re-distribution toward households or with small-scale treatment plant at building level (Opher and Friedler, 2016). Conclusions suggests that the decentralized approach offers the major environmental benefits. Moreover, the sizing of the system appears to play a significant role in the environmental performance of the solution.

As shown by Ghimire et al. (2017), literature available on LCA application on RHSs present quite different perspective and results on the issue, strongly depending on methodological approach toward the case studies proposed (Crettaz et al., 1999; Angrill et al., 2011; Ghimire et al., 2014; Devkota et al., 2015; Morales-Pinzón et al., 2015; Petit-Boix et al., 2018; Yan et al., 2018).

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