Ecological Indicators 69 (2016) 165–175

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Methodological proposal to assess the water footprint accounting of direct water use at an urban level: A case study of the Municipality of Vicenza

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ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form 9 February 2016
Accepted 5 April 2016
Available online 27 April 2016

Keywords:
Water management
Water footprint accounting
Urban environment
Water use of buildings

ABSTRACT

Climate change, world population growth and industrialization have placed considerable stress on the local availability of water resources. Considering that most of the world's population currently resides in cities, this issue has particular relevance in an urban environment. One of the methods that is recognized to support better water management is water footprint accounting. However, due to the requirement of large amounts of data and their limited availability, applications of this method at an urban scale use national or regional water use data. The goal of this study is to develop a methodological proposal to assess the water footprint accounting of direct water use at an urban level to support the local management of water resources by using local data, by adopting a bottom-up approach and by verifying its applicability in a real case study. The water footprint accounting approach was modified by adopting a modular approach in the definition of boundaries and by adapting the blue, green and gray water footprint accounting formulations. The proposed method was successfully tested in the municipality of Vicenza (north east Italy) and provided interesting responses in terms of water management. Herein, we also discuss the latest developments in impact assessments related to water based on a life cycle assessment, which should be used as a framework for the future development of the model that is presented.

1. Introduction

Freshwater use and management has become central to the international debate (Rudd and Fleishman, 2014). The main reason for this interest is that a growing number of countries are faced with the issue of limited freshwater availability and have limited access to high-quality water resources (UN, 2012; Dong et al., 2013). Currently, one-third of the world's population lives in regions facing water scarcity (WWAP, 2014), and statistics show that by 2025, this value will increase to over two-thirds of the population (IPCC, 2008). Improving the management of this resource is therefore a major challenge that affects users, policymakers and businesses (WBCSD, 2006).

In Europe, there is unequivocal evidence of this significant issue; recent estimates show that 10% of the European population and 20% of the territory are suffering the consequences of limited water availability. Considering that 75% of European citizens live in cities, the correct management of this resource at an urban level is recognized as a priority in Europe (EC, 2009).

The scientific community has worked intensively in recent years to develop tools and methodologies to understand and evaluate the consequences of water use and to develop suitable water management policies and strategies (Mazzi et al., 2014; Paterson et al., 2015). One of the tools that has been extensively applied is water footprint (hereafter WF) accounting (Postle et al., 2011). This tool was initially introduced by Hoekstra (2003) and developed into the WF assessment method (Hoekstra et al., 2011). According to this reference, a WF is defined as a multidimensional indicator that measures freshwater use by showing water consumption volume by source and polluted volume by type of pollution. Recently the international organization for standardization released a new standard, i.e., ISO 14046 (ISO, 2014), wherein a WF is defined as a metric(s) that quantifies the potential environmental impacts related to water and is approached from a life cycle assessment methodology perspective (ISO, 2006). Boulay et al. (2013) state that both of these references can be used to define solutions to reduce

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http://dx.doi.org/10.1016/j.ecolind.2016.04.016
1470-160X/

anthropogenic effects on water resources but also recognize that the WF accounting method developed by Hoekstra et al. (2011), i.e., the analysis of sustainable, efficient and equitable allocation and use of freshwater in both a local and global context, has a clear water management focus.

Even if WF methodologies are recognized as being useful and have several applications in products and processes (Chapagain and Orr, 2009; Nicolucci et al., 2011), experiences at urban level are limited to the use of national or state/province level water use averages that do not show unique consumption patterns of the city (Paterson et al., 2015). The main reasons are the vast quantities of data required and their limited availability in a local context (Hoekstra et al., 2011). Hoff et al. (2013) studied indirect water use of the cities of Berlin (Germany), Delhi (India) and Lagos (Nigeria) starting from regional data. Wang et al. (2013) compared the WF of Beijing for the years 2002 and 2007 using sector level data. Feng et al. (2011) assessed the WF of London using national data on water use. To use the WF concept to assist decision makers at urban scale local data on water use are needed (Paterson et al., 2015).

The urban water system is complex and is characterized by several water flows (e.g., evaporation, wastewater), water users (e.g., domestic, industrial) and sources (e.g., groundwater, surface water) (Agudelo-Vera et al., 2011; Gessner et al., 2014). Moreover, when focusing at an urban level, both direct and indirect uses can be identified: the former, which refers to water use and the treatment of wastewater, is directly managed by the local community; the latter accounts for the water content and supply chain used to deliver products purchased by citizens (Hoekstra et al., 2011). Traditional (engineered) urban water management is only concerned with direct water use.

The objective of this study is to develop a methodological proposal to assess the WF accounting of direct water use at an urban level to support local management of water resources by

- Adapting the WF accounting method presented by Hoekstra et al. (2011), and
- Verifying its applicability in a real case study.

This paper presents part of the results of the European project referred to as the Introduction of the WF Approach in Urban Areas to Monitor, Evaluate and Improve Water Use (Fiałkiewicz et al., 2014). Founded within the central Europe Program, this project started in 2012 and involved nine partners from five European countries. The objective of the project was to develop a central, common European approach to guarantee better water use and management in urban areas (Scipioni et al., 2014). The developed approach was applied in three cities: Vicenza in Italy, Innsbruck in Austria and Wroclaw in Poland.

In this study, urban areas are defined as locations with over 50% constructed surfaces, according to Mertes et al. (2015). The research is focused only on this area of a city, and therefore excludes agricultural use. The focus of this paper is on direct water use; modeling of indirect water use at an urban level will be presented in future work by the authors.

2. Materials and methods

2.1. Adaptation of the WF accounting approach for urban areas

The method presented by Hoekstra et al. (2011) was used as the framework for the WF accounting of the urban area. Two phases were considered in the research and were adapted to be applicable to urban areas with limited local data availability: the setting of the goals and scope, and the WF accounting. The developed approach is presented in Fig. 1 where dashed blocks represent the proposed integrations/modifications to the original approach presented by Hoekstra et al. (2011).

In the setting of the goals and scope, the purpose of the study was determined. Consequently, the inventory boundaries were defined; this step consisted of the identification of all of the relevant processes to be included in the study. According to Hoekstra et al. (2011), the basic processes to be considered in the inventory boundaries are referred to as "building blocks". Considering the complexity of urban systems (Gessner et al., 2014) and the considerable number of building blocks that can be identified, it was decided to adopt a bottom-up perspective based on the modular approach

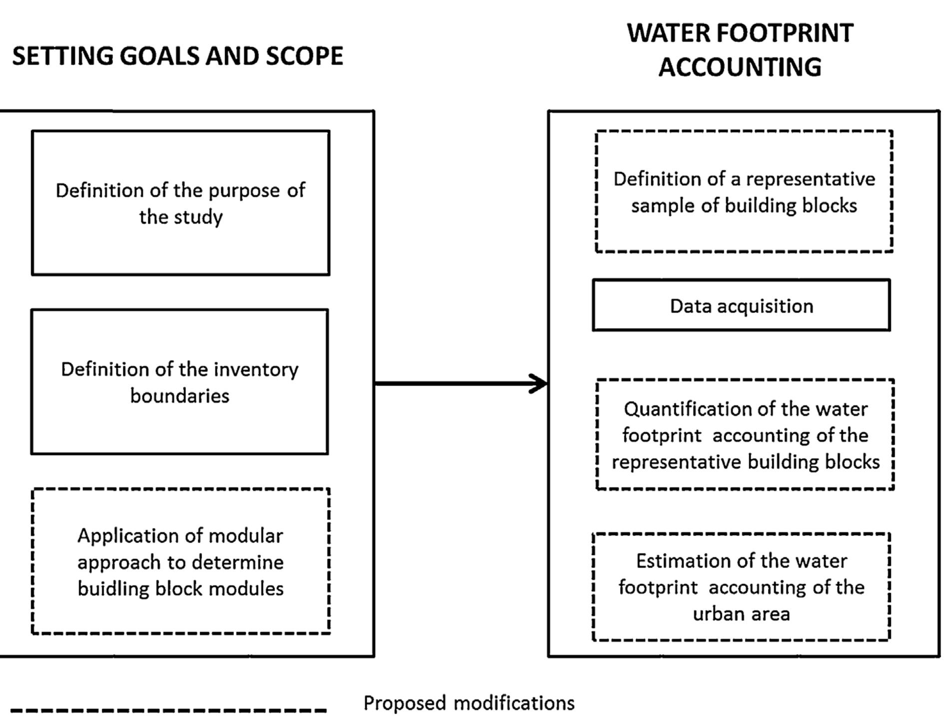

Fig. 1. Model for WF accounting in an urban area.

Table 1
Module classification.

Category	Sub-category	Module
Buildings: residential	Household buildings	Single houses
		Duplex
		Multifamily houses
		Condominiums
Buildings: non-residential	Commercial buildings	Offices
		Hotels
		Restaurant/bars
		Shops
		Shopping centers
	Public buildings	Schools and Universities
		Sport facilities
		Municipal buildings
		Military buildings
		Hospitals and health care buildings
	Industrial buildings	Industrial installations
Other units		Roads
		Public green areas
		Other impervious surfaces (e.g., car parks)
		Water storage
		Water and wastewater distribution system
		Water surface

presented by Mackay and Last (2010) and Mitchell et al. (2001) to simplify the representation of the inventory boundaries. This was based on the assumption that a complex system can be divided into basic modules with homogeneous characteristics; in the proposed methodology, each module consists of a group of building blocks with similar functions, similar needs and behavior and therefore, in our case, with similar WF accounting performances.

To determine the modules and therefore to group the building blocks located in the urban area, it was decided to follow the classification reported in Table 1, which was adapted from Mitchell et al. (2001). This classification categorizes water uses according to the types of buildings and other structures where water is used. Each module can have green surfaces and impervious surfaces. In the case of residential buildings, a building block is considered to be a housing unit for a single family. The actual "dimension" of a family is based on the average number of persons per housing unit in the city under study.

In the WF accounting phase, the quantification of the blue, green and gray WF accounting indicators is performed. The first step in the proposed approach consists of the identification of a representative sample of building blocks for each module to avoid the issue of limited data availability. Here, the approach of Mamade et al. (2014) was considered. This method suggests focusing on a neighborhood where most of the modules can be identified.

The second step of the WF accounting phase consists of the collection of relevant quantitative and qualitative water data for each building block included in the representative sample. Based on these data and by applying the adapted equations presented in the following chapters, the blue, green and gray WF accounting of the urban area was estimated.

2.2. Adaptation of the blue, green and gray water accounting in urban areas

According to Hoekstra et al. (2011), blue WF accounting is defined as the amount of water withdrawn from surface and groundwater that is not returned to the same water basin because of evaporation, product incorporation or discharge into a different water basin. In the proposed methodology, this definition has been extended to include the part of rainwater that either evaporates due to impervious surfaces (such as roads and car parks) and therefore does not enter the water basin or infiltrates the ground. To account this, the following equations were applied to the building blocks belonging to the selected representative sample. The general formulation of a blue water mass balance is the following:

$$\mathrm{WF}_{\mathrm{Blue\_i,j}} = V_{\mathrm{in\_i,j}} - V_{\mathrm{out\_i,j,t}} + V_{\mathrm{rainwater}} * (k_{\mathrm{evaporation\_i,j}} + \alpha * k_{\mathrm{infiltration\_i,j}}) * X_{\mathrm{i,j}} \quad (1)$$

where WF $_{\mathrm{Blue\_i,j}}$ is the blue WF accounting of the i-esime building block of the j-esime module that is located in the urban area, expressed in [m^3]; $V_{\mathrm{in\_i,j}}$ is the volume of freshwater withdrawn from surface and groundwater resources to supply the i-esime building block of the j-esime module, expressed in [m^3]; $V_{\mathrm{out\_i,j,t}}$ is the volume of wastewater discharged from the i-esime building block of the j-esime module treated in the t-esime wastewater treatment plant, expressed in [m^3]; $V_{\mathrm{rainwater}}$ is the volume of water that falls per unit of surface in the urban area during a one-year period, expressed in [m^3/m^2]; $k_{\mathrm{evaporation\_i,j}}$ is the percentage of rainwater that evaporates from the specific module impervious surfaces, expressed in %; $k_{\mathrm{infiltration\_i,j}}$ is the percentage of rainwater that falls on the specific module impervious surfaces and infiltrates into the ground; α is a coefficient $\in$ [0,1]; α is equal to 1 in the case where the specific module impervious surface is located in an area where hydrological conditions prevent groundwater recharge; $X_{\mathrm{i,j}}$ is the impervious surface of the i-esime building block of the j-esime module that is located in the urban area, expressed in [m^2].

It must be noted that runoff that is directly discharged into the groundwater is not needed in the accounting because it recharges the groundwater resources.

Considering potential data constraints, in the case no data on water outputs of building blocks are available, the following equation can be used

$$\mathrm{WF}_{\mathrm{Blue\_i,j}} = V_{\mathrm{in\_i,j}} * t_{\mathrm{losses\_i,j}} + V_{\mathrm{rainwater}} *(k_{\mathrm{evaporation\_i,j}} + \alpha * k_{\mathrm{infiltration\_i,j}}) * \overline{X_{\mathrm{i,j}}} \quad (2)$$

where $t_{\mathrm{losses\_i,j}}$ is a coefficient that represents the percentage of water that once withdrawn is not returned to the same basin of origin because of water use of the i-esime building block of the j-esime module, expressed in %; $\overline{X_{i,j}}$ is the average impervious surface of the i-esime building block of the j-esime module that is located in the urban area, expressed in [m^2].

Note that in the mass balance above, the discharge of wastewater from the building block to the treatment device contributes to gray water.

The total blue WF accounting of the urban area can therefore be assessed using the following equation:

$$\mathrm{WF}_{\mathrm{Blue}} = \sum_{\mathrm{j}} (n_{\mathrm{j}} \overline{\mathrm{WF}_{\mathrm{blue\_j}}}) \quad (3)$$

where $\mathrm{WF}_{\mathrm{blue}}$ is the total blue WF accounting of the urban area, expressed in [m^3]; n_{j} is the number of building blocks that belong to the j-esime module; $\overline{\mathrm{WF}_{\mathrm{Blue\_j}}}$ is the average blue water accounting of the building blocks belonging to the j-esime module, expressed in [m^3].

The green WF accounting according to Hoekstra et al. (2011) is defined as total rainwater evapotranspiration from fields and plantations of green areas plus the water incorporated into the harvested crop or wood. In the case of urban areas, it is assumed that no significant crop production occurs and therefore green water accounting is supposed to be limited to green areas, such as for private or recreational use (public parks). In the case of massive plant growth at a unit level due to e.g., roof gardens and green walls, this assumption should be questioned. Eq. (4) represents the formulation of green water in the case of an urban area.

$$\mathrm{WF}_{\mathrm{Green\_i,j}} = (V_{\mathrm{rainwater}} * k_{\mathrm{green\_evaporation\_i,j}} * Y_{\mathrm{i,j}}) \tag{4}$$

where $\mathrm{WF}_{\mathrm{Green\_i,j}}$ is the green WF accounting of the i-esime building block of the j-esime module that is located in the urban area, expressed in [m^3]; $k_{\mathrm{green\text{-}evaporation\_i,j}}$ is the percentage of rainwater that evaporates from specific module surfaces, expressed in %; $Y_{\mathrm{i,j}}$ is the green area surface of the i-esime building block of the j-esime module that is located in the urban area, expressed in [m^2].

$$\mathrm{WF}_{\mathrm{Green}} = \sum_{\mathrm{j}} (n_{\mathrm{j}} \overline{\mathrm{WF}_{\mathrm{Green\_j}}}) \tag{5}$$

where $\mathrm{WF}_{\mathrm{Green}}$ is the total gray WF accounting of the urban area, expressed in [m^3]; n_{j} is the number of building blocks that belong to the j-esime module; $\overline{\mathrm{WF}_{\mathrm{Green\_j}}}$ is the average green water accounting of the building blocks belonging to the j-esime module, expressed in [m^3].

The gray WF accounting according to Hoekstra et al. (2011) is defined as the volume of freshwater that is required to assimilate the load of pollutants of wastewater discharged from each building block given natural background concentrations and existing ambient water quality standards. According to Franke et al. (2013) the gray WF is assessed for each contaminant calculated separately. The overall gray WF of each building block is equal to the largest GWF found when comparing the contaminant-specific gray WFs. In the case of urban areas, two different wastewater flows can be identified: wastewater from water used in buildings, and wastewater resulting from the runoff or infiltration of rainwater from other structures and buildings surfaces, i.e., runoff that is discharged into the sewer system.

The general formulation of gray water related to wastewater discharge is provided by the following:

$$\mathrm{WF}_{\mathrm{Gray,wastewater\_i,j,t}} = (\mathrm{DF}_{\mathrm{out\_i,j,t,p}} * V_{\mathrm{out\_i,j,t}}) \tag{6}$$

where $\mathrm{WF}_{\mathrm{Gray,wastewater\_i,j,t}}$ is the gray WF accounting resulting from wastewater discharges of the i-esime building block of the j-esime module treated in the t-esime wastewater treatment plant that is located in the urban area, expressed in [m^3]; $\mathrm{DF}_{\mathrm{out\_i,j,t,p}}$ is the dilution factor of the p-esime pollutant selected, according to Hoekstra et al. (2011), related to the wastewater discharged from the i-esime building block of the j-esime module in the t-esime recipient water body. This factor is dimensionless. It is assessed at the output of the t-esime wastewater treatment plant.

In the case that the DF factor is not available for the i-esime building, the following formulation can be used:

$$\mathrm{DF}_{\mathrm{i,j,t,p}} = \chi_{\mathrm{i,j,t,p}} * \mathrm{DF}_{\mathrm{out\_t,p}} \tag{7}$$

where $\mathrm{DF}_{\mathrm{out\text{-}t,p}}$ is the dilution factor of the p-esime pollutant selected, according to Hoekstra et al. (2011), of the wastewater treated in the t-esime wastewater treatment plant assessed at the output of the plant.

$\chi_{\mathrm{i,j,t,p}}$ is the contribution of the i-esime building block of the j-esime module to the concentration of the pollutants of the wastewater treated by the t-esime wastewater treatment plant; this factor is assessed using the following equation:

$$\chi_{\mathrm{i,j,t,p}} = \frac{C_{\mathrm{out\_i,j,p}} * V_{\mathrm{out\_i,j,t}}}{C_{\mathrm{in\_t,p}} * V_{\mathrm{in\_t}}} \tag{8}$$

where $C_{\mathrm{out\text{-}i,j,p}}$ is the concentration of the p-esime pollutant selected to determine the dilution factor, according to Hoekstra et al. (2011), of the water discharged from the i-esime building block of the j-esime module, expressed in [mg/l]; $C_{\mathrm{in\_t,p}}$ is the concentration of the p-esime pollutant selected to determine the dilution factor, according to Hoekstra et al. (2011), of the wastewater that enters the t-esime wastewater treatment plant, expressed in [mg/l]; $V_{\mathrm{in\text{-}t}}$ is the volume of wastewater that enters the t-esime wastewater treatment plant, expressed in [m^3]; in the case where there are no available data on the water outputs related to the building blocks, $V_{\mathrm{out\text{-}i,j,t}}$ in Eqs. (7) and (8) can be expressed by the following equation:

$$V_{\mathrm{out\_i,j,t}} = V_{\mathrm{in\_i,j}} * (1 - t_{\mathrm{losses\_i,j}}) \tag{9}$$

The general formulation of gray water related to rainwater is provided by the following:

$$\mathrm{WF}_{\mathrm{Gray,rainwater\_i,j,t}} = Z_{\mathrm{i,j,t,p}} * [(\mathrm{DF}_{\mathrm{out\_t,p}} * V_{\mathrm{rainwater,treatment\_t}}) + (\mathrm{DF}_{\mathrm{in\_t,p}} * V_{\mathrm{rainwater,bypass\_t}})] \tag{10}$$

$\mathrm{WF}_{\mathrm{Gray,rainwater\_i,j,t}}$ is the gray WF accounting resulting from rainwater that is treated and bypassed at the t-esime wastewater treatment plant located in the urban area, expressed in [m^3]; $V_{\mathrm{rainwater,treatment\_t}}$ is the volume of rainwater collected by the wastewater network and treated in the t-esime wastewater treatment plant, expressed in [m^3]; $\mathrm{DF}_{\mathrm{in\_t,p}}$ is the dilution factor of the p-esime pollutant selected, according to Hoekstra et al. (2011), of the wastewater treated in the t-esime wastewater treatment plant assessed at the input of the plant.

$V_{\mathrm{rainwater,bypass\_t}}$ is the volume of rainwater that, due to intense rain events, bypasses the t-esime wastewater treatment plant (e.g., via a combined sewer overflow) and goes directly into the recipient water body, expressed in [m^3]; $Z_{i,j,t,p}$ is the contribution of the i-esime building block of the j-esime module to the rainwater treated or bypassed by the t-esime wastewater treatment plant; this factor is assessed using the following equation:

$$Z_{\mathrm{i,j}} = \frac{X_{\mathrm{i,j}}}{\sum_{\mathrm{j}} \sum_{\mathrm{i}} X_{\mathrm{i,j}}} \tag{11}$$

The total gray WF is assessed using the following equation:

$$\mathrm{WF}_{\mathrm{Gray}} = \sum_{\mathrm{j}} (n_{\mathrm{j}} * \overline{\mathrm{WF}_{\mathrm{Gray,wastewater\_j,t}}}) + \sum_{j} (n_{\mathrm{j}} * \overline{\mathrm{WF}_{\mathrm{Gray,rainwater\_j,t}}}) \tag{12}$$

$\mathrm{WF}_{\mathrm{Gray}}$ is the total gray WF accounting of the urban area, expressed in [m^3]; n_{j} is the number of building blocks that belong to the j-esime module; $\overline{\mathrm{WF}_{\mathrm{Gray,wastewater\_j,t}}}$ is the average gray water accounting resulting from wastewater discharges of the building blocks belonging to the j-esime module, expressed in [m^3]; $\overline{\mathrm{WF}_{\mathrm{Gray,rainwater\_j,t}}}$ is the gray WF accounting of rainwater defined above.

3. Results

To test the applicability of the proposed WF accounting approach, the city of Vicenza (north east Italy) was chosen as a case study. The choice of this city is related to its territorial characteristics, where the entire module reported in Table 1 is represented, and to the opportunity to directly acquire primary data on urban water use from the municipality of Vicenza, which was involved as partner in the Central European project that funded this study. Due to local hydrological conditions, no groundwater recharge takes place where the city is located. The city's population is approximately 115,675 inhabitants. Its citizens live within an area of 80.48 km^2 and the settlements are located along three rivers: Bacchiglione, Retrone and Astichello. The urban area extension considered in the study is 28.08 km^2. There are no large reservoirs of surface water nearby and the main water sources that feed the urban area are

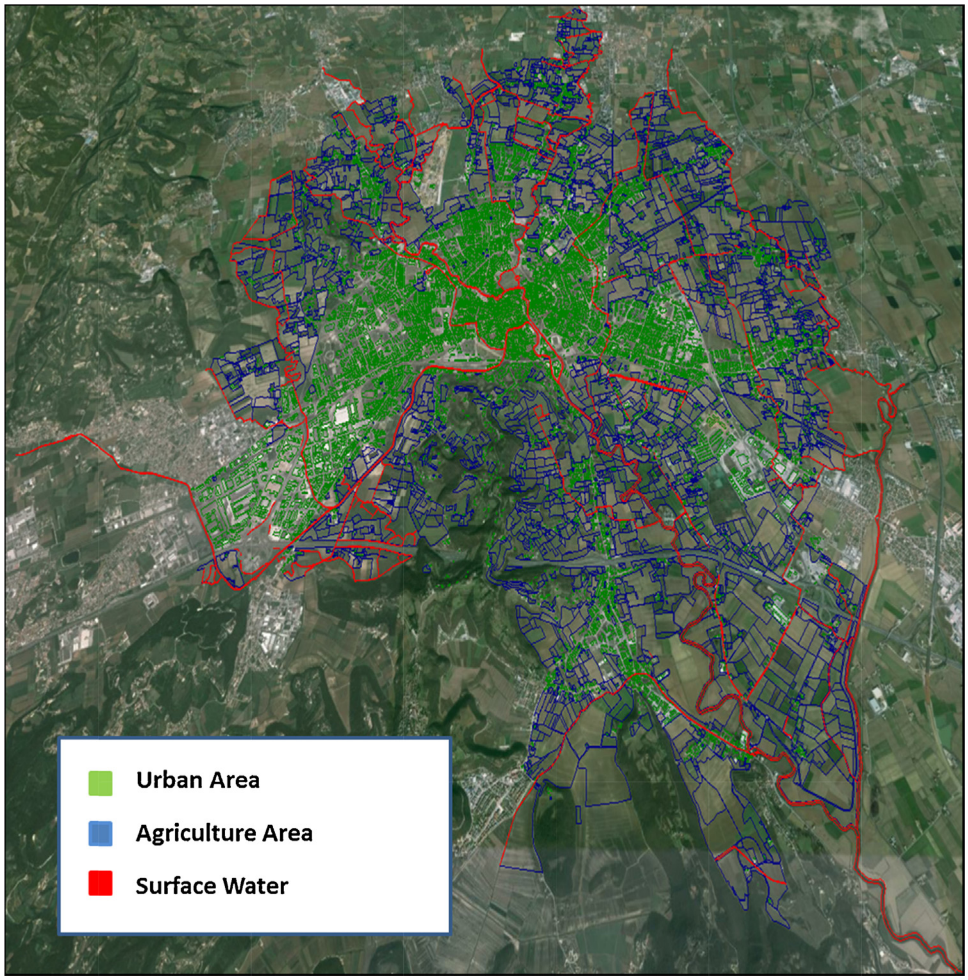

Fig. 2. Map of Vicenza and the boundaries of the analysis. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

aquifers. A water supply and sewage system is available for most of the Vicenza inhabitants. In 2011, 98% of the Vicenza population used water from the public water network, and 92% was connected to the public wastewater network. A total of 85% of the sewer system is combined. In this application, it was assumed that the total sewer system was combined. The wastewater volumes produced within the urban area of Vicenza are treated in three different wastewater treatment plants that also serve other nearby towns.

According to the approach presented in Section 2.1, the first step is the definition of the purpose of the study: quantify the WF accounting indicators for the urban area of Vicenza considering the different modules located in the city. The inventory boundaries correspond to the urbanized area of the city represented by the green color in Fig. 2.

In the specific case of the wastewater that goes into the public wastewater systems, the inventory boundaries to quantify gray water were set at the output of the wastewater treatment plants that serve the city of Vicenza.

Considering the modular approach adopted and the classification reported in Table 1, primary data on the quantity of the building blocks of each module were acquired from the municipality of Vicenza (Table 2). Considering the characteristics of the inhabited buildings of Vicenza, it was estimated that single houses comprised one housing unit, duplex houses comprised two building units, multifamily houses comprised four and condominiums comprised eight housing units; a housing unit corresponded to one building block in the case of residential buildings. In the case of roads, public green areas, other impervious (e.g., car park) and water surfaces, a building block is assumed to correspond to a unit covering a surface of 1000 m^2. In the case of water storage, a building block corresponds to a unit of storage of 1 m^3. In the case of the water and wastewater distribution system, a building block is considered a 1-km water or wastewater distribution network.

The urban areas were analyzed to determine which one had the widest variety of modules. In the case of Vicenza, this was the San Bortolo neighborhood where most of the different modules, except for industries, are located. Then, a representative sample was selected for each module. When available, data on the total number of building blocks were used. This was the case of industrial buildings, roads, public green areas, other impervious surfaces and water surfaces. The dimensions of the significant samples identified in the San Bortolo neighborhood are reported in Table 3.

Data related to water use of each building block are either primarily referred to as 2013 or secondary data based on literature references.

$V_{\text{in\_i,j}}$ data are primary data made available by the municipality of Vicenza.

$V_{\text{out\_i,j,t}}$ data were provided only with reference to industrial buildings from local water management authorities.

Local rainfall $V_{\text{rainwater}}$ data were provided by the local Agency for the Environment (ARPAV) and are data measured directly in Vicenza and normalized over a 30-year period.

The $t_{\text{losses\_i,j}}$ parameter, in the case of residential buildings, public buildings, offices, shops and shopping centers, was estimated by summing the leaks and irrigation percentages presented by Beal et al. (2013), which resulted in a value of 0.075.

Table 2
Number of building blocks per module.

Module	Number of building blocks	Unit	Data source
Single houses	5975		Primary data from the Municipality of Vicenza related to 2013
Duplex houses	6790		
Multifamily houses	16,468		
Condominiums	28,392		
Offices	68		
Hotels	50		
Restaurants/bars	968		
Shops	3726		
Shopping centers	2		
Schools and Universities	147		
Sport facilities	21		
Municipal buildings	98		
Military buildings	13		
Hospitals and health care buildings	33		
Industrial installations	224		
Roads	5.340	1000 m^2	
Public green areas	4.534	1000 m^2	
Other impervious surfaces	11.307	1000 m^2	
Water storage	18.800	m^3	
Water and wastewater distribution system	470	km	
Water surfaces	1.453	1000 m^2	

A value of 0.43 was used for the $t_{losses\_i,j}$ parameter in the case of hotels, restaurants and bars, according to Zhang and Anadon (2014). Finally, the $t_{losses\_i,j}$ parameter for hospitals and health care buildings was retrieved from the European Commission (EC, 2009). Having the volumes in the input and output of each industrial building, $t_{losses\_i,j}$ was not assessed in the case of industrial buildings.

A value of 0.10 was used for $k_{evaporation\_i,j}$ in the case of residential and non-residential buildings, according to Ragab et al. (2013); in the case of roads and impervious surfaces a value of 0.15 was used, according to Da Deppo and Datei (2005). For the other modules, $k_{evaporation\_i,j}$ was considered to be negligible. The $k_{green\_evaporation\_i,j}$ parameter was applied in the case of public and private green areas located in the other modules and was considered to be 0.35 according to the US Environmental Protection Agency (EPA, 1999). Considering the land characteristics of Vicenza, α was set equal to 1; however, $k_{infiltration}$ was considered to be negligible.

$X_{i,j}$ and $Y_{i,j}$ were primary data acquired from the municipality of Vicenza.

$DF_{out-t,p}$ and $DF_{in-t,p}$ were determined based on primary data considering the total nitrogen concentration at the output and input of the different wastewater treatment plants; these values were acquired from the local water management authority and the legal concentration limits set by local regulation.

$C_{in\_t,p}$ were primary data acquired from the local water management authority.

$DF_{i,j,t,p}$ values were available only in the case of industrial buildings and were determined based on primary data from the local water management authority. For all other modules, it was necessary to estimate $DF_{i,j,t,p}$ starting from the quantification of the $\chi_{i,j,p}$ values. In the case of residential and commercial buildings, $C_{out\_i,j,p}$ values acquired from Almeida et al. (1999) were used; in the case of the $C_{out\_i,j,p}$ resulting from runoff over impervious surfaces, data from Llopart-Mascarò et al. (2010) were used; for all other modules, $C_{out\_i,j,p}$ values were acquired from Beal et al. (2013).

The values of the $\chi_{i,j,p}$ and $Z_{i,j}$ parameters for different modules and $DF_{out\_t,p.}$ and $DF_{in\_t,p}$ for different wastewater treatment plants (WWTPs) are reported in Tables 4 and 5, respectively.

By applying the equations presented in Section 2.2, the WF accounting of each module was estimated (Table 6).

The total WF accounting of the urban area of Vicenza in the year 2013 is therefore the sum of the WF accounting performances of each module considered (Table 7)

The contribution of the different modules to the total WF accounting of the urban area of Vicenza is presented in Fig. 3

Focusing on the blue WF accounting results, the other units category was the most relevant one, with a contribution of 59.36%,

Table 3
Number of building blocks considered in the representative sample.

Module	Number of building blocks
Household buildings	579
Commercial buildings	74
Public buildings	41
Industrial buildings	914
Roads	5.340
Public green areas	4.534
Other impervious surfaces	11.307
Water storage	18.800
Water distribution system	470
Water surfaces	1.453

Table 4
Values of $\chi_{i,j,p}$ and $Z_{i,j}$.

Module	$\chi_{i,j,t,p}$	$Z_{i,j}$
Single Houses	0.05597	0.01497
Duplex	0.07713	0.02064
Multifamily	0.12721	0.10503
Condominiums	0.26596	0.01762
Offices	0.00089	0.00047
Hotels	0.00065	0.00035
Restaurants/bars	0.01262	0.00673
Shops	0.04859	0.02592
Shopping centers	0.00003	0.00001
Schools and Universities	0.02242	0.01464
Sport facilities	0.00320	0.00209
Municipal buildings	0.01495	0.00976
Military buildings	0.00214	0.00139
Hospitals and health care buildings	0.00503	0.00329
Industrial installations	0.08663	0.04030
Roads	0.11969	0.23295
Public green areas	–	–
Other impervious surfaces	0.11716	0.50385

Table 5
Values of $DF_{out\_t,p}$ and $DF_{in\_t,p}$ for the different WWTPs.

WWTP	$DF_{out-t,p}$	$DF_{in-t,p}$
Plant 1	0.166	0.423
Plant 2	0.233	0.633
Plant 3	0.580	0.447

Table 6
WF accounting of each module.

Module	Blue WF accounting [m^3]	Green WF accounting [m^3]	Gray WF accounting [m^3]
Single houses	3.52E+05	1.00E+06	5.23E+05
Duplex houses	4.85E+05	1.38E+06	7.21E+05
Multifamily houses	9.37E+05	7.95E+05	1.19E+06
Condominiums	4.83E+05	1.78E+05	2.07E+06
Offices	1.51E+03	6.50E+03	6.89E+03
Hotels	2.03E+04	7.90E+04	5.07E+03
Restaurants/bars	3.13E+05	3.01E+05	9.81E+04
Shops	8.43E+04	1.01E+04	3.78E+05
Shopping centers	4.19E+03	1.22E+04	2.03E+02
Schools and Universities	4.69E+04	2.73E+05	1.74E+05
Sport facilities	1.89E+04	4.87E+05	2.49E+04
Municipal buildings	3.17E+04	0.00E+00	1.16E+05
Military buildings	3.87E+04	1.44E+04	3.25E+05
Hospitals and health care buildings	2.63E+04	1.70E+05	3.91E+04
Industrial installations	8.74E+05	0.00E+00	6.73E+05
Roads	9.60E+05	0.00E+00	9.30E+05
Public Green areas	1.97E+04	1.90E+06	0.00E+00
Other impervious surfaces	2.07E+06	0.00E+00	9.10E+05
Water storage	18800.00	0.00E+00	0.00E+00
Water and wastewater distribution system	2.36E+06	0.00E+00	0.00E+00
Water surfaces	0.00E+00	0.00E+00	0.00E+00

Table 7
Total WF accounting.

	Blue water Footprint accounting [m^3]	Green water Footprint accounting [m^3]	Gray water Footprint accounting [m^3]	Urban area WF accounting [m^3]
Urban area	9.14E+06	6.60E+06	8.18E+06	2.39E+07

followed by residential building with a contribution of 24.67% and non-residential building with a contribution of 15.97%. The total volume of withdrawn water is considered to contribute to the blue WF because the city is located in an area where no groundwater recharge takes place. However, this aspect needs to be questioned in other situations where different local hydrogeological conditions exist.

The highest water use in the other units category was related to the water lost in the water distribution system, which contributed to 25.81% of the total blue WF accounting; Within the other units category, a significant volume of blue water depended on the water evaporated from other impervious surfaces, with a contribution of 22.64%. In this case, the $K_{evaporation}$ factor that consider 15% rain-water evaporation, was estimated based on the runoff coefficients

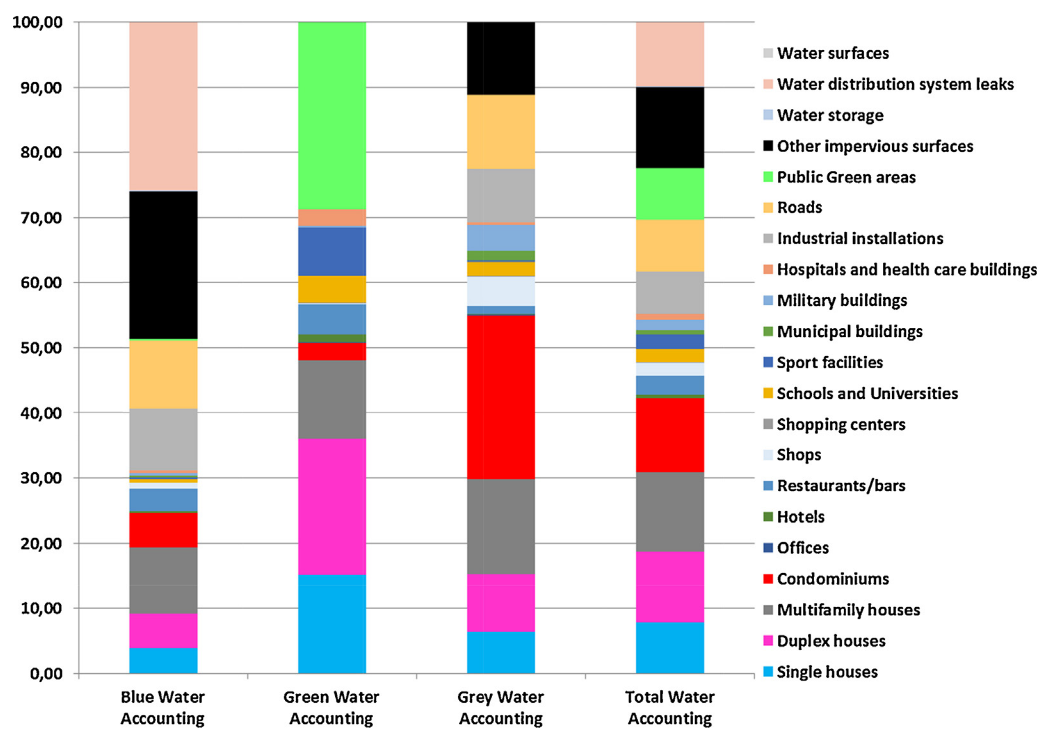

Fig. 3. Contribution of the different building blocks to the total WF accounting indicators results.

proposed by Da Deppo and Datei (2005). Water used to clean roads, which subsequently evaporates, and rainwater evaporated from road surfaces contributed to 10.49% of the total blue water accounting. The water evaporated from roads was determined considering the same $K_{\text{evaporation}}$ factor used for impervious surfaces. The blue water used for the public green areas and water storage was limited, i.e., a 0.22% contribution. Water storage was considered to contribute to blue water accounting because even if this water is not lost from the system, it is stored all year long to guarantee the correct functioning of the potable water distribution in the urban area. The contribution of evaporation from water surfaces, considering the limited extension of surface water, was considered negligible. To reduce the blue water accounting of this category, the municipality should work to reduce $K_{\text{evaporation}}$ of the impervious surfaces from which rainwater evaporates, along with the installation of rainwater collection and reuse technologies.

The highest water use in the residential building category was related to the water used in multifamily houses, with a contribution of 10.24%, followed by duplex houses, condominiums and single houses with an average contribution of 4.81% each. In these modules, blue water mainly depends on the water withdrawn for domestic use, followed by gardening and evaporation from the impervious building surfaces based on the $K_{\text{evaporation}}$ from Ragab et al. (2013). Most of the water in residential buildings is withdrawn from treated groundwater and is distributed through the water distribution system; in the case of single houses, it must be considered that many building blocks withdraw water directly from private wells without discharging it into the wastewater network. The total volume of this water therefore contributes to the final blue WF accounting. A deeper analysis of the results, which considered the number of building blocks per module, indicated that condominiums exhibited better water use performance. The main reasons are related to the higher density of housing units per m^2 of surface, which limits the evaporation of rainwater, and to the smaller extent of private green areas compared with other residential modules. The module with the worst performance was the single houses. The results for this category suggested focusing on the management of private wells to reduce blue water accounting and to manage the way water is used by citizens for domestic use and gardening.

The highest water use in the non-residential building category was related to the water withdrawn from public water distribution systems and used in industrial buildings, with a contribution of 9.41%, followed by restaurants/bars, with a contribution of 3.42%. The remaining modules considered in this category contributed less than 1% each to the total WF accounting. The blue water of industrial buildings is related to the water used in two main industrial sectors: the steel and food industries.

Focusing on the green WF accounting results, the residential building category was the most relevant one, with a contribution of 50.77%, followed by other units, with a contribution of 28.73%, and non-residential buildings, with a contribution of 20.05%. The highest green water use in the residential building category was related to duplex houses, with a contribution of 20.87%, followed by single houses, with a contribution of 15.15%, multifamily houses (12.05%), and condominiums (2.70%). This distribution of green water use depended on the average extension of the green areas in the different modules as well as the number of building blocks per module. The total green water use of the other units category was related to the public green area module. The contribution of the other modules of this category was negligible because of the limited extension or absence of green areas. In the non-residential building category, the highest green water use was related to sport facilities, with a 7.83% contribution, followed by schools and universities, with a contribution of 4.53%, and restaurants and bars, with a contribution of 4.14%. The other modules belonging to this category had limited green water use.

Focusing on the gray WF accounting results, the residential building category was the most relevant one, with a contribution of 55.01%, followed by non-residential building, with a contribution of 22.50% and other units, with a contribution of 20.49%. The assessment of gray water was based on total nitrogen because it resulted to be the pollutant with the highest dilution factor (Franke et al., 2013); this choice was influenced by the assumption that the natural concentration in the receiving body was considered to be null (Hoekstra et al., 2011), and the maximum allowed concentration was set equal to the legal limits. It must be noted that the choice of nitrogen as an indicator substance has a huge impact on the gray water assessment. In the residential building category, condominiums had the highest gray WF accounting, with a contribution of 25.26%, followed by multifamily houses, with a contribution of 14.54%, duplex houses, with a contribution of 8.81%, and single houses, with a contribution of 6.40%. These results mainly depend on the number of building blocks per module. Focusing on the module performances, condominiums, which have a smaller impervious surface per unit block, are responsible for less runoff and therefore lower gray water contribution related to rainwater interception.

In the non-residential building category, industrial installation had the greatest contribution to gray WF, accounting for 8.39%. It must be considered that most of the water from industrial facilities in the city is treated in private wastewater treatment plants before being discharged into the public wastewater network. Shops contributed 4.61%, followed by the remaining modules of this category, with an average contribution of 1.07% each. In the other units category, the gray water volumes were determined by the pollutants contained in the water that runs off from road surfaces (contribution of 11.37%) and other impervious surfaces (contribution of 11.13%). The total gray water performance was significantly influenced by the $V_{\text{rainwater,bypass}}$. This volume of water, commonly generated during intense rainwater events when the capacity of treatment plants is exceeded, reaches the recipient water body without being treated.

To reduce the effect of this water, the municipality should work to improve the permeability of impervious surfaces and roads, in addition to rainwater collection and reuse technology to manage this water differently (e.g., making it available for local water use). In the specific case study, the blue and gray water accounting results produced consistent responses in terms of an intervention strategy to reduce the WF accounting.

Focusing on the total WF accounting results, the residential building category was the most relevant one, with a contribution of 42.24%, followed by other units, with a contribution of 38.30%, and non-residential buildings, with a contribution of 19.45%. The results for total WF accounting showed that duplex houses, multifamily houses, condominiums, other impervious surfaces and water leaks from the water distribution systems had similar performances, with an average contribution of 11.35% each.

4. Discussion

The methodological proposal developed in this research, was applicable and allowed the quantification of the WF accounting indicators in the urban area. The introduction of the modular approach used by Mackay and Last (2010) and Mitchell et al. (2001) allowed better organization of the data collection and simplification of the analysis of the results by assigning each building block with similar characteristics to the same category. This also allowed a better understanding of which modules contributed the most to the total WF accounting of Vicenza. The introduction of the sampling method used by Mamade et al. (2014) allowed a significant reduction in the quantity of data that needed to be collected by focusing on a limited number of building blocks. However, in the specific case study, we also had to consider modules outside of the representative neighborhood as in the case of industrial buildings.

The formulation of blue WF accounting was integrated to consider the part of rainwater that either evaporates due to impervious surfaces (such as roads and car parks) and therefore does not discharge into the water basin, according to Hoekstra et al. (2011), or infiltrates the ground. In the specific case of Vicenza, it must be considered that not all of the rainwater that falls on the ground recharges the groundwater reservoir because of the local conditions of the land, but it does recharge the surface watercourses. The consideration of rainwater evaporation is lively debated in the literature (Berger et al., 2014; Pfister and Ridoutt, 2014). Therefore, the formulation of blue water according to Eqs. (1) and (2) could be revised, once consensus on this issue is found. To determine rainwater evaporation volumes from impervious surfaces, the parameter $K_{evaporation}$ was estimated based on the runoff coefficient proposed by Da Deppo and Datei (2005). Considering the data availability in the urban area under study, Eq. (2) was introduced to allow for the quantification of blue WF accounting in the case where no $V_{out\_i,j,t}$ data were available. This was the case, for example, for residential buildings. To determine the water outputs, the parameter $t_{losses\_i,j}$ was introduced. The value of this parameter varied in the literature, for example, in the case of residential buildings, a value of 7.5% was estimated considering losses from water leaks and evaporation (Beal et al., 2013). This parameter is influenced by various aspects such as the local climate condition, geographical location, household life style and technologies installed in buildings. The collection of primary data, through the installation of flow meters in input and output areas of a representative sample of residential buildings, could improve the accuracy of the estimate.

Some assumptions were introduced to address the influence of green water in the urban area. Green areas can exhibit different evapotranspiration factors, which are related to the specific vegetation that is located in the city. In the proposed approach, specific evapotranspiration factors were substituted by a $K_{green\_evaporation\_i,j}$ parameter acquired from the EPA (1999) that was considered to be an average representation of the conditions in public and private green areas. The function of this parameter can vary with respect to local climate conditions, geographical location and morphological characteristics of the soil and the green area in general.

In addition, considering that this parameter is based on the concept of rainwater evaporation, the same considerations related to the debate on rainwater evaporation from impervious surfaces are valid (Berger et al., 2014; Pfister and Ridoutt, 2014). Therefore, the green WF accounting formulation could also change when consensus is reached.

It is relevant to highlight that in the proposed methodology, the direct link between blue and green WF, related to the contribution of rainwater volume, can place a burden on the definition of WF accounting improvement strategies. This can be the case, for example, for land use management: a reduction of green water determined by the conversion of a green area into an impervious surface (e.g., roads of car parks) can result in an increase in blue WF and vice versa.

The definition of the gray WF has not been changed from that proposed by Hoekstra et al. (2011); however, different formulations are proposed. Two components of the gray WF accounting were identified in the urban area: one related to the wastewater treatment, $WF_{Grey,wastewater\_i,j,t}$, and one related to rainwater that runs off over impervious surfaces and enters the public wastewater system, WF $Gray_{,rainwater-t}$.

Focusing on the WF $Gray_{,wastewater\_i,j,t}$, if primary data on $DF_{out\_i,j,t,p}$ are not available, Eq. (7) can be used in the proposed methodology. In this case, the dilution factor of the specific building block can be determined using $DF_{out\_t,p}$ and a contribution factor $\chi_{i,j,t,p}$ (Eq. (8)). Without adopting the contribution factor, it would not have been possible to determine the contribution of some modules, such as the residential building one. The data on the concentration of the different pollutants of the residential building modules were acquired from Almeida et al. (1999). It was assumed that public buildings and commercial buildings released the same quantity of pollutants per m^3 of discharged water.

In the case where no $V_{out-i,j,t}$ data are available, Eq. (9) can be used. In Vicenza, this allowed, for example, the quantification of the contribution of residential buildings where data availability was limited. The results of the estimation of $V_{out-i,j,t}$ are in line with the results of Almeida et al. (1999).

Focusing on the WF $Gray_{,rainwater\_t}$, two contributions were identified and are represented by Eq. (9): a component of water that runs off and is treated in the different wastewater treatment plants, $V_{rainwater,treatment\_t}$, and the quantity of rainwater that, even if collected in the wastewater system, bypasses the wastewater treatment plants, $V_{rainwater,bypass\_t}$. In the former, the gray water was assessed at the output of the t-esime wastewater treatment plant that can be either public or private, such as the case of private houses not connected to the public wastewater system. In the latter, gray water was assessed assuming that $V_{rainwater,bypass\_t}$ has the same quality characteristics of the water that enters the t-esime treatment plant. To determine the contribution of the different modules, the factor $Z_{i,j,t,p}$ was introduced (Eq. (10)); this parameter is based on the extension of the impervious surface of the i-esime building block compared with the total extension of the impervious surface of all of the building blocks considered in the study.

It was assumed that 100% of the sewer system was combined. This assumption may affect the results of the contribution of rainwater to the gray water accounting results. In fact, in a separate system, $V_{rainwater,bypass\_t}$ could either be reduced or nulled, and the gray water volumes resulting from rainwater discharges could be significantly reduced.

The proposed methodology is based on the WF accounting method presented by Hoekstra et al. (2011); therefore, no impact or sustainability assessment was performed. Recently, as mentioned in the introduction, WF methodological developments have been made within the life cycle assessment framework (Kounina et al., 2013). The application of these methodologies in the present case study would most likely lead to different results and conclusions (Berger and Finkbeiner, 2012). Considering the characteristics of the territory of Vicenza and its water use, impact assessment methodologies should focus more on the impacts relevant to degradative water use that can be significant in urban areas (EC, 2009). The application of methodologies, such as WF according to ISO 14046 (ISO, 2014), and full life cycle assessment according to ISO 14040 (ISO, 2006), would lead to the integration of WF accounting as presented in this study, by also including the effects of air emissions on water quality.

In the past, several urban water balance (Bach et al., 2014) and urban water footprint models (Paterson et al., 2015) have been published in the literature. The proposed methodology, if compared with these models, allows the determination of additional information that can be used to improve the water management capacities in urban areas; in fact, its main difference is that the spatial scope is detailed at the level of a single building block. This can be particularly useful for an initial estimation and monitoring over time of the effects that technological (e.g., water reuse solutions), regulatory (e.g., land use in spatial planning) and management solutions have on the water use of a single building block.

Moreover with specific reference to traditional urban water balance mode, another important difference is related to the way the model results are presented; consumptive water use is presented through the blue and green WF accounting metrics. Blue WF is used to consider water volumes that are not returned to the local system and can be considered an inventory indicator to be used in environmental impact assessments (Boulay et al., 2013). In the case of Vicenza, where most of the withdrawn water does not return to the original water basin, blue WF accounting results are consistent with results of traditional water balance model. Green WF accounting clearly focuses on the way the green area interacts with rainwater flows. Qualitative water use is presented through the gray water footprint accounting, which in addition to providing a measure of the way that urban wastewater uses the carrying capacity of the receiving water bodies, can also be regarded as a general midpoint environmental impact assessment indicator (Berger and Finkbeiner, 2010).

5. Conclusions

In this paper, the method presented by Hoekstra et al. (2011) was adapted for WF accounting in an urban area to provide information to support water management in a local context and was successfully tested in the case of the municipality of Vicenza.

The results of the WF accounting demonstrated the utility of the specific modifications applied to the method of Hoekstra et al. (2011). Compare to previous urban water footprint studies (Paterson et al., 2015), the proposed adapted methodology allowed a detailed representation (single module) of WF accounting results starting from a limited number of local data.

From the analysis of the WF accounting results, water related hot-spots and management strategies to improve water use in the urban area were identified. Firstly, the municipality should work on its urban infrastructure by limiting the water losses in the water distribution system and by limiting the rainwater bypass volume. These solutions would help reducing the blue and gray WF accounting.

Secondly, the municipality should work at regulatory level by setting rules on the extension of impervious and green surfaces per building block and by recommending the installation rainwater collection and reuse technologies. This could be particularly relevant when planning the construction of new buildings and neighborhoods. Another important action is to inform citizens on the correct management of private wells.

The results of the proposed adapted methodology also highlighted a link that exists in urban areas between green and blue WF accounting. Effective strategies to reduce the total WF accounting should therefore take into consideration the effect of land use changes in urban areas.

This could be particularly relevant when the municipality plans new neighborhoods constructions or the modification of existing ones.

Considering the results of the study, future development can be identified. It would be interesting to revise and integrate the proposed methodology once consensus is reached on the issue of rainwater and surface permeability. Therefore, the relationships between the proposed method, local hydrological conditions and the effects of land use change should be studied in greater detail. To do so, it may be useful to study the WF accounting of a pristine condition and evaluate the effect of urbanization. It would also be interesting to quantify the effect of a separate versus a combined sewer system. From an environmental impact assessment perspective, it would be interesting to integrate the water use accounting with an assessment of the impacts within a framework of recent methodological developments (ISO, 2014). This would allow a better comprehension of the consequences of water use from a different perspective, including air and soils emissions that affect water quality. Moreover, it would be interesting to extend the study by introducing social and economic indicators (Manzardo et al., 2014a) to address potential risks such as resource accessibility and availability for different users in a more comprehensive WF sustainability assessment (Hoekstra et al., 2011; Pizzol et al., 2013; Manzardo et al., 2014b; Manzardo et al., 2016).

Based on the overall results of the European project referred to as the Introduction of the WF Approach in Urban Areas to Monitor, Evaluate and Improve Water Use (Fiałkiewicz et al., 2014), the future work of the authors will focus on benchmark of WF accounting among Vicenza in Italy, Innsbruck in Austria and Wroclaw in Poland under different planning scenario.

Acknowledgments

This paper presents part of the results of the project referred to as the Introduction of Water Footprint Approach In Urban Area to Monitor, Evaluate and Improve The Water Use. This project was implemented through the Central Europe Programme co-financed by ERDF.

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