Urban Water Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/nurw20

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Published online: 02 Apr 2015.

To cite this article: Maria Christina Fragkou, Teresa Vicent & Xavier Gabarrell (2015): An ecosystemic approach for assessing the urban water self-sufficiency potential: lessons from the Mediterranean, Urban Water Journal, DOI: 10.1080/1573062X.2015.1024686

To link to this article: http://dx.doi.org/10.1080/1573062X.2015.1024686

Urban Water Journal, 2015
http://dx.doi.org/10.1080/1573062X.2015.1024686

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RESEARCH ARTICLE

An ecosystemic approach for assessing the urban water self-sufficiency potential: lessons from the Mediterranean

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(*Received 4 November 2013; accepted 22 February 2015*)

Frequent water stress episodes affecting urban hubs have caused a shift in urban water management towards integrated approaches and motivated a search for alternative water resources. Large-scale rainwater harvesting on the municipal scale can overcome the disadvantages of climate dependence and the volume restrictions associated with small-scale collection facilities. In this paper, two tools based on the urban metabolism concept are used to determine the water self-sufficiency potential of urban systems from urban runoff: a simple water self-sufficiency potential indicator and a socioeconomic water flow accounting scheme, which includes water losses. Both tools are applied to a densely populated coastal area that exemplifies urban centres in the Mediterranean. This approach is useful for regions with restricted data availability on water use and facilitates information dissemination to policy makers. The results indicate a significant water self-sufficiency potential for the area of study, even under projections of reduced precipitation in the area.

Keywords: urban water management; rainwater harvesting; urban metabolism; indicators; climate change; Mediterranean

1. Introduction

In the summer of 2008, the Barcelona Metropolitan Region experienced prolonged droughts that led to an inevitable water shortage. The situation was intensified by the seasonal population increase in this popular tourist destination, which altered the region's water balance (Kanakoudis & Tsitsifli, 2013). The regional authorities adopted various compensatory measures, including shipping in drinking water from France and the controversial diversion of the mouth of the Ebro River in the region of Aragon for emergency water transfer. The latter project provoked social unrest, resulting in a popular protest against the diversion of the river and Barcelona's exploitation of the region's natural resources.

This case exemplifies predominant urban water management approaches: short-sighted supply management, constant attempts to satisfy an ever-growing demand, economic and conservation measures (Kanakoudis, 2002) and dependency on large infrastructures, such as water transfers between river basins. These long-established practices have a series of socio-environmental implications, including the depletion of natural reservoirs, typically beyond a city's hinterland, raising issues of vulnerability and urban resilience (Agudelo-Vera et al., 2012; Kanakoudis, 2004; Ludwig et al., 2011) and the tendency to provoke social conflicts (Kallis, 2008). The simultaneous urban exploitation of natural resources perpetuates a state of antagonism between cities and regional agriculture and industry for resource allocation for water-demanding activities (Ducrot et al., 2004).

Thus, the need has emerged for substantial policy modifications and new models for managing water resources to control urban water use and protect freshwater reserves (Gober, 2010; Huang et al., 2010). New strategies have been developed, reflecting a shift from a supply-oriented approach to a demand management approach (Burn et al., 2002; Gumbo & van der Zaag, 2002), along with use, water pricing policies and the paradigm of integrated water management, as regulated by the Water Framework Directive 2000/60/EC at the European Union level (Kanakoudis et al., 2011). A complementary and increasingly popular approach has involved identifying new technologies and strategies to increase water self-sufficiency in cities by exploiting unconventional, internal urban sources of water (Rygaard et al., 2009).

These new sources consist of reclaimed wastewater, desalinated seawater and harvested rainwater. Rygaard et al. (2011) conducted an extended case study review on

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the challenges related to the use of these new sources, showing that rainwater harvesting has greater public acceptance, minimises production prices and electricity consumption per m^3 of water produced before distribution, and has the lowest treatment intensity compared to the other alternatives. Rainwater harvesting can also reduce non-point source pollutant loads and prevent flooding (Helmreich & Horn, 2009; Sharma et al., 2008).

However, rainwater harvesting has two important drawbacks. Firstly, the source usually has a high climate dependency, precluding a stable and continuous water supply (Rygaard et al., 2011). Secondly, rainwater harvesting systems are predominantly small-scale, primarily being used in private households, public buildings and individual commercial units (Angrill et al., 2012; Farreny et al., 2011; Morales-Pinzón et al., 2014), with tank sizes that limit the harvested water volume (Mikkelsen et al., 1999; Morales-Pinzón et al., 2012; Zhang et al., 2009a, 2009b). Larger scale applications, such as for municipalities and entire cities, are limited to harvesting rainwater using water-sensitive urban design (Gabarrell et al., 2014; Morison and Brown, 2011; van Roon, 2007), i.e., the harvested water is essentially used for irrigation and stormwater retention to prevent urban floods caused by poor urban planning and deficient drainage systems (Llopart-Mascaró et al., 2014).

To address these limitations, city-scale rainwater harvesting is proposed as a basic element of sustainable urban water management. Climate dependence and limitations in the harvested volume can be tackled by collecting and storing rainwater in existing facilities used for stormwater retention. This solution can increase the volume of harvested rainwater up to all of the stormwater volume running off paved surfaces. The stored rainwater can simultaneously serve as a useful alternative source of water in dry periods. Therefore, city-level rainwater harvesting is presented as a socially acceptable, feasible option for water managers to complement or even provide all of the urban water required, thereby decreasing the pressure on local freshwater resource allocation.

To test this hypothesis, two methodological tools are presented in this paper; both are based on the concept of urban metabolism and can assess a city's potential for self-sufficiency. First, an urban water accounting scheme is suggested for the quantification of all of the flows of piped water, and losses at all stages of urban water management, from raw water abstraction to wastewater disposal. Second, an indicator is proposed that is suitable for assessing the potential of an urban or regional system to be water self-sufficient, which is calculated using easily obtainable climate and water demand data. Encouraging results are obtained by applying these tools to a case study comprised of 27 municipalities on the Mediterranean coast, suggesting that urban water self-sufficiency is a realistic goal for future urban water management agendas.

1.1 Water self-sufficiency in urban areas and the role of water metabolism

Ecological metaphors have been used in sustainability studies after the observation of similarities between ecosystems and socioeconomic systems, giving the latter organic qualities. Under this perspective, a city is viewed as a new type of open and interactive ecosystem, which helps to describe and better understand the complex interrelations between the elements and substructures of the city and its relationship with the natural environment (Alberti, 2008; Grimm et al., 2000; Newman, 1999). This perception has resulted in a circular material metabolism of natural ecosystems being proposed as a prototype in urban planning and natural resources management (Castán Broto et al., 2012), in contrast to the linear metabolic consumption patterns of urban centres (Sukopp, 1998).

These considerations are valuable contributions to the management of the urban water cycle for attaining water self-sufficiency. Urban water metabolism analysis, i.e., the accounting of the water inputs and outputs of a city (Thériault & Laroche, 2009), is a useful tool for describing the physical dimension of actual water management policies (Lemos et al., 2013) because it can connect the sources, the pathways and the intermediate and final sinks of the total flows within the system (Brunner & Rechberger, 2004). In this way, all the available water resources and actual needs can be identified and quantified to match supply with demand, a basic water management objective. The study of urban water metabolism also provides useful data for water management by enabling a comprehensive understanding of the physical processes in cities or regions and connecting urban water balances to temporal economic and social processes (Huang, 1998). Finally, urban water metabolism studies provide indicators based on an environmental balance of supply and demand, which can offer new insights into water resource use (Kennedy et al., 2007).

Despite the emergence of academic literature on urban water studies using a metabolic approach during the last decade (Baker, 2009; Gandy, 2004; Hermanowicz & Asano, 1999; Sahely & Kennedy, 2007; Sahely et al., 2003), relatively little research has been conducted in this field overall (Lemos et al., 2013; Zhang et al., 2010). The absence of a standardised methodology can be identified as a primary drawback (Daniels & Moore, 2001): thus far, researchers in the field have used various methodologies to quantify and analyse urban water metabolism, including ecological network analysis (Bodini & Bondavalli, 2002; Zhang et al., 2010), the water footprint approach (Jenerette et al., 2006) and urban water balance schemes, which have been used in a significant number of studies (Binder, 1997; Mitchell et al., 2003; Haase & Nuissl, 2007). Urban water balance schemes are typically used to calculate both socioeconomic and natural flows, thereby identifying the

Figure 1. Catalonia's location in Europe and the coastal system under study.

role of the entire urban water cycle in the global hydrologic cycle. Scholars usually account for all of the piped water flows, runoff, groundwater recharge, precipitation, evapotranspiration and change in water storage (Grimmond & Oke, 1991).

Kenway et al. (2011) formalised and applied an urban water mass balance scheme and reviewed the relevant literature, highlighting the importance of considering local conditions, such as urban density and land use, in such studies. The authors also concluded that it was important to examine the role of water reuse and the distribution losses in the water balance and to consider the rainfall volume in designing a city's water metabolism, emphasising the absence or underestimation of this issue in various previous studies.

In this paper, these recommendations are followed and are incorporated into a water accounting scheme that only considers the socioeconomic or artificial (Stanners & Bourdeau, 1995) components of the urban water metabolism, i.e., the piped water supply and the water disposal system. Therefore, the calculated actual water needs of a system include the water losses at all of the stages of catchment, treatment and distribution, in addition to the total consumption, providing a more representative overview of urban water needs. The developed self-sufficiency potential indicator accounts for the rainwater falling on the paved surfaces of the system and the urban land use factor.

2. Materials and methods

2.1 Coastal municipalities of the Barcelona Metropolitan Area

The case study in this paper consists of 27 municipalities along the coastline of Catalonia, an autonomous community in Spain located in the North-East corner of the Iberian Peninsula (Figure 1). The study area extends from the municipality of Malgrat de Mar in the North to that of Cubelles in the South, with an area of 478 km^2 and 118.6 km of coastline. The region serves 2.5 million residents at a density of more than 5000 inhabitants/km^2, whereas the average equivalent value for the European Union in 2004 was approximately 115 inhabitants/km^2. The area's economy heavily depends on the interrelated sectors of tourism, services and construction, which have replaced agricultural and industrial activities, that used to be the predominant ones in the area.

Water management in the area during the study period (i.e. between 1998 and 2003) was overseen by the Catalan Water Agency, a public organisation attached to the Ministry of the Environment and Housing of the Government of Catalonia that has complete authority over the water cycle in the inland basins of Catalonia. Until 2003, the main water sources for the region included the Tordera, Ter and Llobregat rivers, while the majority of municipalities augmented their supply with water obtained from local wells. The Tordera desalinisation plant started operating in 2003, providing seven of the studied municipalities with water; this plant is not considered in this study because it was in a start-up phase in 2003.

2.2 Methodological framework

The methodology developed in this study is based on Material Flow Analysis (MFA), which is a methodological framework provided by the European Statistical Office (Eurostat, 2001) for quantifying a socioeconomic metabolism. MFA is based on the metabolic aspects of the analogy between economies and natural systems (Ehrenfeld, 2004) and provides a framework within which to analyse the urbanisation process and the transformation of the earth's ecosystems by urban human activities (Huang & Hsu, 2003).

MFA studies basically provide an aggregate overview of the annual material inputs and outputs of an economy, in tonnes. Water flows are not accounted for because of their enormous mass, which is an order of magnitude greater than all of other materials in the economy. Eurostat recommends the separate accounting of water flows as an

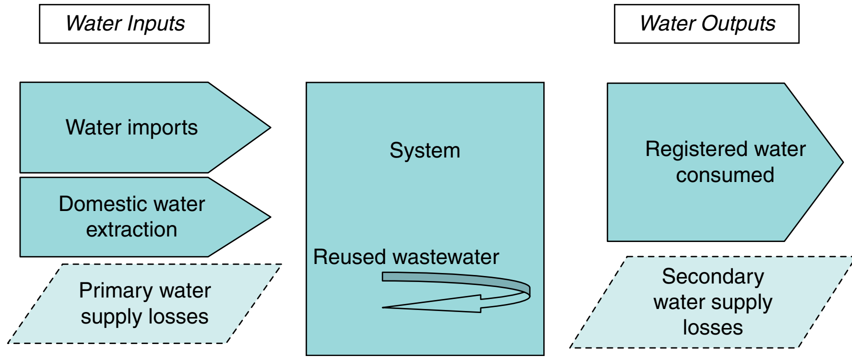

Figure 2. A general artificial water balance scheme, including inputs, outputs and associated indirect flows.

effective approach towards studying urban water metabolism (Hendricks et al., 2000; Suh, 2005). Here, a scheme is developed to account exclusively for all of the socioeconomic urban water flows, using the key concepts and flow categories suggested by Eurostat (2001). The water flow accounting is performed in a disaggregated manner at municipal level. The results for each municipality are summed to produce an aggregated view of the system.

2.3 *System boundaries*

Eurostat guidelines (Eurostat, 2001) define the system boundaries as follows:

1. by the extraction of primary materials from the environment and the discharge of materials to the environment; and
2. by the political borders that determine material flows to and from other economies (imports and exports).

In this study, these recommendations are followed, such that the water bodies, i.e., the sea, lakes, and rivers, crossing a system are considered to be outside its boundaries and representative of the natural environment. Therefore, all of the flows originating from or directed towards these bodies are counted as imports and exports. Precipitation and water evaporation are excluded from the water accounting scheme considered here.

2.4 *Main categories of water flows considered*

For a system boundary as defined above, Eurostat distinguishes three main categories of flows: *inputs* (flows that enter the economy, either as imported goods or extracted natural resources), *outputs* (flows that leave the economic system, either as exports or as "consumed" natural resources in the form of residues and emissions) and the *indirect* flows associated with the former two categories. The indirect flows represent the natural resources that are extracted from the environment but are not used at the end by the economy (for example, unused extraction in mining). In this study, the indirect flows are represented by the water losses occurring throughout the water distribution system of each system under study.

In accordance with this classification, for the purposes of the current study, the water input flows correspond to the volume of water used within the system boundaries. These flows are divided into water imports and domestic water extraction. Water imports originate from sources outside the system boundaries and include raw water treatment plants (RWTPs), bottled water imports and water transferred by vessels or container trucks. Water obtained from local wells is included in domestic water extraction. The indirect flows associated with the water inputs include the water losses in the primary distribution network that occur between water abstraction and water storage in the municipal water tanks.[1]

Water outputs correspond to the total volume of water leaving the system boundaries. This volume includes wastewater that is either directly discharged to the sea or rivers without prior treatment, or treated water leaving the waste water treatment plants (WWTPs). The water outputs consist of the total recorded water volume consumed in the secondary water supply networks of the system, together with the volume of bottled water consumed, less the reused water. The indirect flows associated with the water outputs are the secondary distribution network water losses of each municipality. The losses at this stage are primarily associated with distribution pipe leakages; however, recording errors, malpractices and users without a consumption measurement system inevitably increase this indicator. Indirect flows actually correspond to the volume of non-revenue water, according to IWA guidelines on terminology of urban water balance components (EPA, 2009). Although non-revenue water includes the volumes of water losses plus unbilled authorised consumption (IWA, 2000), in this work this shall be defined as *secondary distribution network water losses*. Figure 2 illustrates the aforementioned discussion

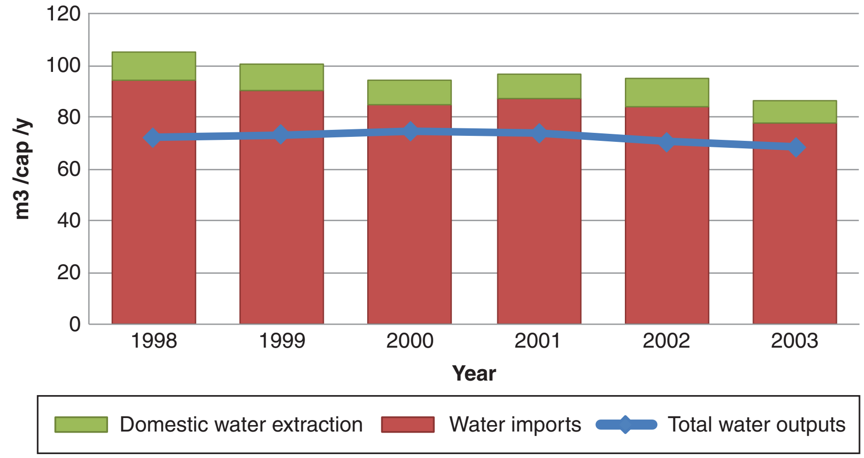

Figure 3. Total annual input and output flows for the regional system for 1998–2003.

by a water balance equation for a regional system, showing the inputs, outputs and the associated indirect flows.

3. The water self-sufficiency potential indicator

The most common water indicators typically measure consumption and recycling rates, whereas the most elaborate indicators reflect the stress put by human activities to available resources (Falkenmarck et al., 1989; Lallana & Marcuello, 2004; United Nations, 2003). Many of these indicators neglect temporal and spatial variations (WSM, 2004); however, the indicator developed here is simple to calculate and can be used for applications and comparisons over a wide range of temporal and spatial scales. This indicator is defined as the ratio of the water consumption by the system to the volume of rainwater falling on the paved surfaces of the system. The indicator is calculated for a system comprised of various municipalities as follows:

$$wsp_x = \sum_{m=0}^{n} [(I_{m,x} + IFP_{m,x}) \div RW_{m,x}], \qquad (1)$$

where

wsp_x denotes the water self-sufficiency potential indicator value for a system comprised of n municipalities in the year x;
$I_{m,x}$ denotes the total artificial water input flows for municipality m in the year x, m^3/y;
$IFP_{m,x}$ denotes the total indirect flows associated with the primary water distribution network for municipality m in the year x, m^3/y; and
$RW_{m,x}$ denotes the total renewable water inputs for municipality m in the year x, m^3/y.

The (I + IFP) term represents the actual needs of a system in terms of its water consumption, which corresponds to the total volume of piped water used by the system for both water imports and domestic extraction and the associated indirect flows corresponding to the water losses. The renewable water inputs (RW) are equal to the precipitation the system receives, which depends on the land use, i.e., only the volume of the rainwater that falls on the urbanised areas of the system is considered to be a renewable water resource, presupposing that the sewer's system presents no spills. The rainwater falling on urban non-paved surfaces is excluded from the scheme used here because it is directly used in nature through processes such as surface runoff and groundwater recharge.

The optimum value of the developed indicator is considered to be unity; this value corresponds to an urban system that can satisfy its water needs with the rainwater that it receives on its urban surface. It therefore indicates a self-sufficient city, in terms of water use, that can rely on locally harvested renewable water sources, and does not need to extract water from its hinterland. In general, an indicator value in the $0.75 < wsp < 1.25$ range indicates that the rainwater falling on the sealed surfaces in the system exceeds, and can therefore theoretically meet, the water needs of the area of study. This implies that urban centres that present these values are not depended on big infrastructure works for water provision, contributing this way in achieving integrated water management, while protecting natural reservoirs and avoiding social conflicts on access and control over water resources.

Concerning indicator values higher than unity, these correspond to systems that consume more water than the equivalent renewable water they receive; this implies dependence on water imports and/or extraction from local freshwater resources. The self-sufficiency potential of these systems then depends on their efforts to reduce water consumption, adapting it to the volume of rainwater they receive. Finally, low indicator values imply urban centres

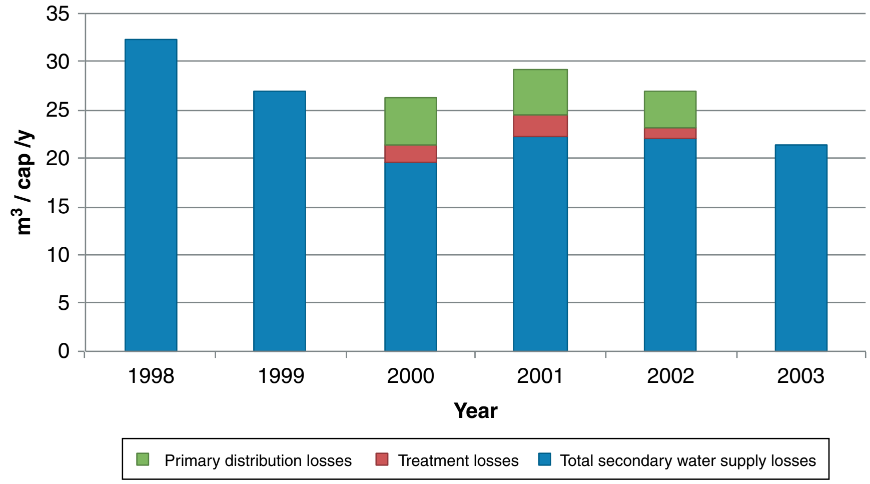

Figure 4. Water distribution losses in the regional system for 1998–2003, in m^3/cap/y.

with an excess of received rainwater, which could be attributed to extensive sealed surfaces.

4. Results

4.1 Water balance results

Water balance results were calculated for a series of 6 years, between 1998 and 2003, selected on demographic and climatic criteria. From one hand, the system presented elevated population during the period of study, whilst it has presented a decline in recent years, according to demographic data obtained from the Catalan Statistics Institute (http://www.idescat.cat/en/). On the other hand, the chosen time series is ideal due to the representative precipitation values it demonstrates, as explained in detail in Section 4.2.

Figure 3 illustrates the results for the direct flows of the entire regional system in this study. The total annual water inputs are shown together with contributions from the volumes of the imported water, domestic extraction and outputs. These data show a stable water balance pattern over the period of study; even though there is a steady decrease in the total water inputs, the system maintains a high dependence on water imports, with an average contribution of 10% from domestic water extraction. The total water outputs show a comparable overall reduction.

There is a general downward trend in the indirect flows for both the primary and secondary water supply because of the increased efficiency of the municipal distribution network (Figure 4). These figures also reveal that the annual per capita water losses associated with the secondary water supply are significantly higher than the losses during primary distribution. This result can be considered foreseeable since secondary supply losses occur during water distribution within the municipalities' extended distribution networks. From one hand, water losses are positively correlated to the pipes' length, and municipal networks are several kilometres long. On the other hand, municipal networks are usually very old and frequently present pipe leakages, due to poor maintenance and lack of monitoring.

On the contrary, primary distribution losses correspond to the volume of water being lost during the treatment process and during its transfer from the catchment point to the treatment plant and from there to the municipal water tanks; at this point, the total water pipe's length, through which water is transferred, is much shorter compared to the city's total distribution network pipe length. Consequently, in this latter stage, the losses during water transfer are up to 10 times higher than those during its treatment, a stage where water losses are almost negligible compared to the volumes of water consumed in urban hubs.

4.2 Water self-sufficiency potential assessment results

The water self-sufficiency indicator (wsp) is calculated for two different geographical levels in 2003: for each municipality in the case study, the wsp is first estimated at the regional level and then in a disaggregated manner. The aim of the latter analysis is to determine which municipalities exhibit the potential for water self-sufficiency and to correlate the indicator performance with water consumption patterns and urban characteristics, such as the population density and the degree of urbanisation.

As mentioned earlier, 2003 not only corresponds to a year with elevated population, and consequent population density, for the municipalities under study, but it also presents representative values with reference to rainfall. According to data obtained from the Meteorological Department of the Fabra Observatory (http://www.fabra.

Table 1. Relevant data for the water indicator for 2003.[a]

Municipality	Population density (inh/km^2)	Primary water distribution (L/cap·d)	Total rainfall (L/cap·d)	Urban area (%)	Water reuse (m^3/y)	Secondary supply network efficiency	Water indicator
Vilanova i la Geltrú	1685	245	940	62.1	0	79%	0.42
Sant Pere de Ribes	606	223	2614	56.4	0	77%	0.15
Sitges	517	247	3068	53.5	0	84%	0.15
Castelldefels	4062	294	421	89.9	2,267,870	76%	0.78
Gavà	1374	284	1245	88.2	1,766,490	76%	2.34
Viladecans	2909	207	588	77.6	1,803,060	76%	0.45
el Prat de Llobregat	2029	216	843	72.7	0	83%	1.24
Barcelona	15,764	261	99	89.6	0	76%	2.93
Sant Adrià de Besòs	8643	269	181	100.0	0	76%	1.48
Badalona	10,115	197	155	92.4	0	76%	1.38
Montgat	2925	223	627	84.3	0	76%	0.12
el Masnou	6177	299	297	77.4	1878	82%	0.14
Premià de Mar	13,012	172	141	90.0	1458	85%	1.36
Vilassar de Mar	4580	249	401	59.3	0	77%	1.05
Cabrera de Mar	430	801	4268	79.2	0	82%	0.24
Mataró	4972	232	369	87.7	0	91%	5.38
Sant Andreu de Llavaneres	716	254	2562	81.0	24,106	77%	0.12
Sant Vicenç de Montalt	534	392	3435	88.8	19,581	79%	0.13
Caldes d'Estrac	2567	376	715	97.8	10,397	82%	0.54
Arenys de Mar	1947	194	943	91.3	0	68%	0.23
Canet de Mar	2093	216	877	91.3	0	75%	0.27
Sant Pol de Mar	570	444	3218	19.2	0	72%	0.72
Calella	1925	364	953	89.6	0	72%	0.43
Pineda de Mar	2115	282	867	73.6	0	81%	0.15
Santa Susanna	190	924	9657	74.7	0	59%	0.13
Malgrat de Mar	1754	183	1046	86.2	0	77%	0.08
Entire system	5000	253	318	76.3	5,894,840	77%	1.04

[a]The municipality of Cubelles is not included because there is insufficient data for this system.

cat/meteo), the precipitation received by the city of Barcelona in 2003 was equal to 601 mm, considerably lower than the average value of precipitation in the city for the period 1991–2011, equal to 625 mm. What is more, and based on the same database, if we consider the last decade's average precipitation for the city of Barcelona, this coincides with 2003's value of 601 mm. Barcelona is the most important city in the entire system under study, covering 21% of its total surface and hosting 64% of its population, with an average population density of over 15,000 inhabitants/km^2.

Table 1 includes the parameters that control the water indicator value, i.e., the land use, precipitation and water consumption for each municipality. The regional system results show that the urban runoff is sufficient to satisfy all of the area inhabitants' water needs, despite the high population density.

The disaggregated results exhibit indicator values below unity for 20 out of the 27 municipalities, indicating a strong potential for using urban runoff to meet their water needs. The most interesting finding is the variation in the indicator values among municipalities from 0.4 (Malgrat de Mar) to over 5.0 (Mataró), even though these systems are situated in close proximity to each other in a Mediterranean area with similar precipitation conditions. This finding can be attributed to the differences in the urban models and the water consumption patterns among municipalities. This implies that urban features, such as population density and land use, may be more relevant factors in reaching water self-sufficiency, than precipitation.

These initial observations show that it is essential to examine the correlation between the indicator value and each of the parameters that influence indicator performance, which are given by the indicator formula in Equation (1), i.e., the urban surface, the total water consumption, including distribution losses, and the precipitation received by a system.

A potential drawback of the indicator is its positive correlation with the degree of urbanisation of the evaluated system because an increase in the amount of paved surfaces should enhance the water indicator. However, despite the effect of urbanisation on the indicator value, no correlation exists between the urban area of a system and the indicator value, either in terms of a percentage of the total municipal surface area (see Table 1) or as an absolute value in km^2 (see Figure 5a). The municipalities with indicator values below 0.50 have different degrees of

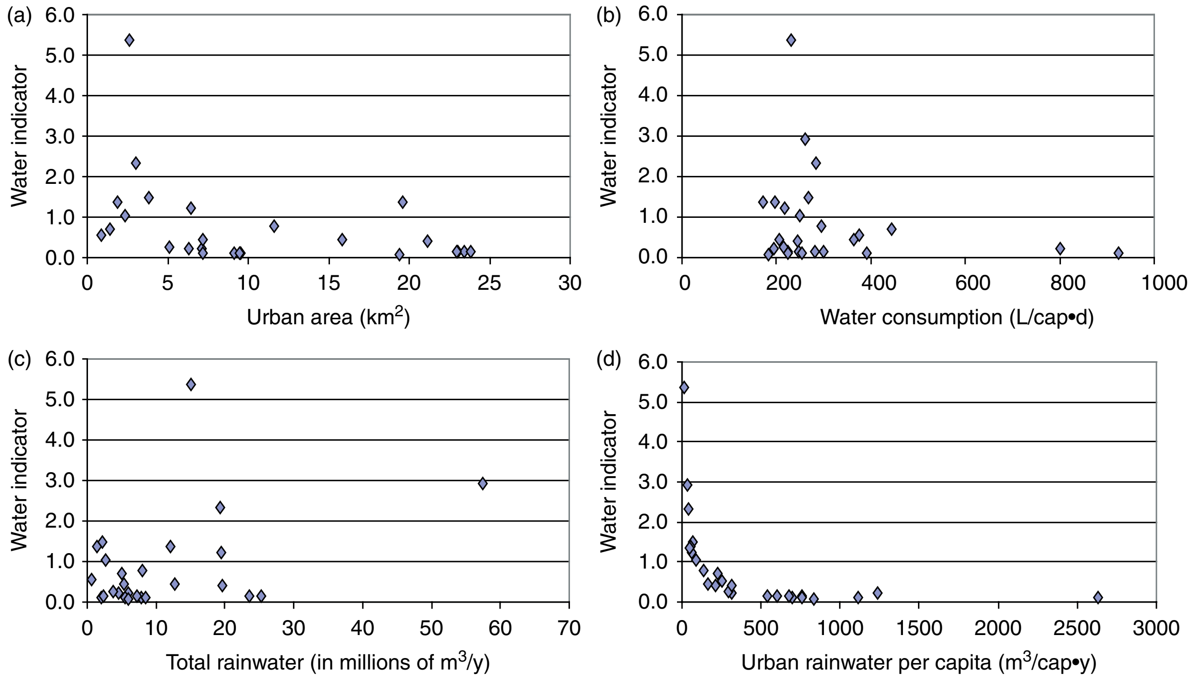

Figure 5. Correlation between the main factors affecting the water indicator value and the indicator value for each municipality in 2003, (a) variation in the indicator values with the urban area of each municipality, (b) variation in the indicator values with the water consumption, (c) variation in the indicator values with the total rainwater received and (d) variation in the indicator values with the per capita rainwater received on urbanised surfaces.

urbanisation with percentages of urban surface area that vary between 53.5% (Sitges) and 91% (Arenys de Mar and Canet de Mar). However, many systems with extensive urbanised surfaces of up to 100% of the total municipal surface area produce poor results: good examples are Premià de Mar, Badalona and Sant Adrià de Besòs, which have degrees of urbanisation of over 90% and exhibit high indicator values. The key common factor in these cases appears to be a high population density combined with low water reuse.

Figure 5 b shows that similar conclusions can be drawn regarding water consumption. The primary per capita water distribution values are not correlated with indicator performance. Figure 5c shows that higher rainfall does not necessarily increase the indicator values. In contrast, the per capita precipitation values for urbanised areas are clearly positively correlated with the indicator, showing the importance of the population density in a system (Figure 5d).

The correlation between the water indicator values and the population density confirms the significance of the

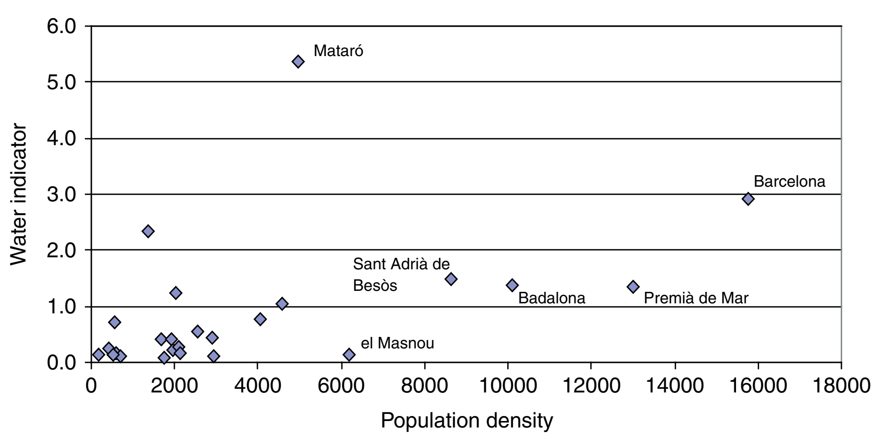

Figure 6. Correlation between the water indicator and the population density, in inhabitants per km^2, in 2003.

latter in achieving water self-sufficiency in cities. The representation of this correlation (Figure 6) depicts that all of the municipalities with population density superior to 5000 inhabitants per km^2 exhibit indicator values greater than 1, regardless of their per capita consumption and grade of urbanisation. The only exception to this observation is the municipality of el Masnou that demonstrates elevated per capita water consumption but has an extended urbanised surface that can collect a higher volume of rainwater. In fact, a high population density appears to be a common characteristic between poorly performing systems: Mataró, Sant Adrià de Besòs, Badalona, Premià de Mar and Barcelona are between the most densely populated municipalities.

5. Discussion

5.1 Proposal applicability and policy implications

Encouraging results are obtained for the potential of water self-sufficiency in the study area, showing that it can be attained in urban areas. These results must nevertheless be interpreted with caution because the feasibility and success of this proposal lies in the existence and appropriate use of an adequate infrastructure for rainwater retention and storage.

In an effort to develop a realistic water management strategy for the municipalities under study, it has to be noticed that only the city of Barcelona disposed of underground deposits for rainwater retention during the study period. However, according to the Sewerage of Barcelona Company, these underground deposits only retain rainwater for flood prevention purposes and gradually release this water to the sea. The authors recommend the use of urban runoff as an alternative water source by expanding and/or utilising existing facilities to capture rainwater. The use of urban runoff has been studied in depth by other scholars, who have suggested various schemes for collecting and using rainwater in urbanised areas for potable and non-potable purposes that demonstrate the viability of this proposal in the study area (see for example, Herrmann & Schmida, 1999; Kim et al., 2004; Villarreal & Dixon, 2005).

The indicator performance is affected by interrelated factors, including the degree of urbanisation of the system. Nevertheless, the authors do not propose the unrestrained expansion of sealed areas in urban systems to achieve water self-sufficiency or water management sustainability. Local strategies and policies can be used to develop sustainable water management solutions that increase self-sufficiency for the actual urbanisation rates and population density of the system. There is an imperative need for urban water demand management, and campaigns to change consumption habits and increase the efficiency of municipal water use can drastically reduce primary water supply needs. Increasing wastewater reuse and the efficiency of secondary water supply networks can also produce the same results.

Finally, despite the importance of municipal scale analysis for urban water management, two complementary views, in terms of scale, should be considered. The first one is the approach that emphasises the importance of analysis on the building or household level (Agudelo-Vera et al., 2012); second, the argument that there is an overemphasis on the local scale in the expense of the global water system's study and analysis should be taken into account (Alcamo et al., 2008). These two levels should supplement the city-scale approach in urban water management issues.

5.2 Methodological considerations

The methodology used in this work is a simple scheme for performing an urban water balance with easily obtainable data. Thus, the proposed tools can be used by countries and regions that are not members of the Organisation for Economic Co-operation and Development (OECD) and present low or restricted data availability on water use. In this study, the influence of local conditions, such as the population density, the distribution network efficiency and the land use, was also considered because of the importance of developing local solutions in addressing water management issues (Kenway et al., 2011).

Results validate the importance of including the distribution losses in studies on urban water balances. The total water losses of the municipalities considered averages of 34.5% of the water imports and 31% of the total water inputs over the study period. These flows influence the urban water balance as well as the entire material metabolism of a city. The inclusion of specific urban characteristics can further assist locally oriented decision-making and help to identify urban planning strategies for water self-sufficiency.

However, there are disadvantages associated with the omission of various parameters in this simplified approach to the urban water cycle. First, evapotranspiration is not typically excluded from the water balance in studies of this type. Evapotranspiration was neglected here to develop a simple description of the urban water cycle. The present approach represents an initial diagnosis of the water balance of a system, and evapotranspiration can be included within a more refined description. Another limitation is that losses are not considered in the capture and reuse of all of the urban runoff, which may be unrealistic in practice. Finally, city-specific volumetric runoff coefficients (Kenway et al., 2011) are not considered: instead, the paved surfaces are considered to be homogeneous. These omissions certainly affect the final water balance results; however, the developed

Table 2. Predictions for rainfall reduction and its impact on the urban water self-sufficiency potential indicator for 2003.

Source	Predicted reduction in precipitation	Comments	Corrected wsp value for the regional system	Corrected wsp value for Canet de Mar
IPPC (2007)	20%	Annual precipitation	1.30	0.34
Räisänen et al. (2004)	70%	Summer precipitation	3.47	0.90
Giorgi and Lionelo (2008)	30%	Summer precipitation	1.49	0.39
Stewart (2009)	15%	Winter precipitation	1.22	0.32

methodology simplifies complex water balances, and the computations are straightforward and can be easily applied to cities with low data availability. The methodology is also a tool that can be easily used by policy makers because few parameters are involved.

5.3 *Relevance of the methodology in the context of climate change*

This methodology should be reviewed within the context of current and anticipated global climatic changes (Iglesias et al., 2011; IPCC, 2007). According to some scholars who work on climate variability, the Mediterranean is one of the global "hot spots" that are expected to experience both increased temperatures and evaporation and reduced precipitation levels (Bates et al., 2008; Giorgi, 2006). These phenomena will affect freshwater availability and quality and are expected to increase agricultural and urban water demand (Döll, 2002).

The degree of alteration of these two climatic parameters (i.e. temperature and rainfall) is not expected to be homogeneous over the entire Mediterranean (García-Ruiz et al., 2011), and the projected precipitation shows greater spatial variability than the projected temperature (López-Moreno et al., 2008). Relevant studies also predict seasonal variations in the climatic conditions in the region. Rainfall reduction is generally predicted; however, some studies project increased winter precipitation for areas in the Northern Mediterranean (Giorgi et al., 2004; Hertig and Jacobeit, 2008), and other scholars have predicted an increased precipitation density over the entire region (Goubanova & Li, 2007; López-Moreno & Beniston, 2009).

Despite these uncertainties and spatiotemporal variations, the viability of the presented methodology was further studied by using a series of predictions on rainfall reduction to apply a corrective coefficient to the indicator values in 2003 over the entire region of study and the municipality of Canet de Mar (Table 2). The results show that most of the predictions drastically affect the self-sufficiency potential of urban systems. The regional system, for which the original indicator value is 1.04, still exhibits a considerable degree of water self-sufficiency under the 30% reduction scenario. In contrast, Canet de Mar, which had one of the lowest wsp value (0.27) of all the municipalities, can maintain its self-sufficiency potential even for a 70% reduction in precipitation.

This overview identifies a considerable potential for urban water self-sufficiency, even under pessimistic precipitation scenarios and especially for cities that demonstrate a strong self-sufficiency potential under current climatic conditions. These results are also encouraging for systems with lower self-sufficiency potentials that are expected to improve their urban water infrastructure (to reduce losses) and advance demand management over the next few years. The resulting reduced urban water needs of such systems will increase their water self-sufficiency potential.

6. Conclusions

In this paper, the hypothesis that urban centres can become water self-sufficient through city-scale rainwater harvesting was tested. Two simple methodological tools are developed using the concept of urban water metabolism and are applied to a case study of 27 coastal municipalities on the Mediterranean coast. Our results validate the feasibility of the methodologies; most of the municipalities studied receive enough rainwater to meet all of their water needs, including the water losses from all of the water treatment and distribution stages. Promising results are also obtained when correction coefficients are used to incorporate predictions of precipitation reduction for the wider Mediterranean region.

The simplified water accounting scheme and the indicator presented in this paper are useful tools for an initial diagnosis of the viability of urban water self-sufficiency. The omission of various parameters from the water balance is compensated for by two important advantages. First, the required data are easily obtained, making this an ideal approach for countries with limited statistical information. Second, these quantitative tools are easily applied, thereby simplifying information transfer from water resource experts to policy makers.

The analysis of the impact of urban characteristics on the indicator shows the complexity of urban sustainability issues, which combined with the importance of spatial and temporal climate variability supports the need for locally oriented approaches to urban water management. Overall, the findings of this paper indicate the need for a holistic approach to urban water management that includes the following actions: (i) increasing the efficiency of the current infrastructure, (ii) reinforcing demand management policies, and (iii) exploiting alternative urban water resources. The combination of these strategies can result in matching urban water demands with the internal supply of water resources, thereby guiding cities to a future state of water self-sufficiency. These strategies also indicate the possibility of designing urban futures with lower environmental impacts.

Acknowledgements

Financial support was provided by the *Fondecyt Iniciación* project 11130631, and the European Union Interreg project (ECOTEC_SUDOE SOE/P2/E377).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Note

1. In the Catalan municipalities under study, the water network is divided in two parts, categorised as primary and secondary (of water supply and distribution respectively); the primary network includes the stages of water extraction, treatment and transfer to the municipal water tanks. The secondary network bares the responsibility to carry the water from the municipal water tanks to the tap of each user.

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