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Review

A systematic review of factors influencing spatiotemporal variability in urban water and energy consumption

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ABSTRACT

Understanding which factors influence urban metabolism is a prerequisite for designing policies and plans that effectuate sustainable resource management. A growing number of publications is concerned with these factors. Yet, this emerging field of research lacks a common framework that supports researchers in interpreting their findings, such as generalizability to other cities, and making informed decisions on their research design. Aiming to contribute to building such a framework, we systematically reviewed urban metabolism literature. This review paper presents an overview of factors influencing urban water and energy consumption and their effect on consumption, and it describes the interconnectedness of these factors for six different types of relationships. Results disclose fourteen *drivers*, changes in societal context that shape consumption patterns, and twenty-one *facilitators/constraints*. The latter type of factors include consumer, resource and urban landscape characteristics that affect resource consumption by facilitating or constraining specific activities. Findings indicate commonalities between primary studies in terms of prevalent observed effect direction for a given factor. However, the interconnections between different factors can influence the direction and magnitude of effects and thereby result in case-specific variability in consumption patterns. Future research should enhance the understanding of these interconnections, strengthen the evidence for the factors presented here and provide insight in additional factors of influence. It is essential to align these studies in terms of a common terminology, transparent quality assessment and a unified approach to measuring and expressing factors of influence. Connecting with related disciplines working on a common systems approach is key to realize the full potential of urban metabolism research to advance our understanding of cities.

Contents

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1. Introduction

Cities have become focal areas for sustainable resource management due to the concentration of human activities in urban areas. These activities transform and consume the majority of global resources (Pulido Barrera et al., 2018), thereby generating waste and emissions that contribute to environmental issues such as climate change, air pollution and water contamination (Dijst et al., 2018). Yet, realising sustainable resource management is complicated due to feedback effects, non-linearity and interactions between multi-scale processes that characterize social-ecological-technological systems[1] (McPhearson et al., 2016a; Pahl-Wostl, 2007). Moreover, resource flows in urban ecosystems are strongly shaped by human induced mechanisms such as the organization of urban space, societal priorities, management methods and urban practices at hand (Broto et al., 2012; Pincetl et al., 2014). Just like ecological processes, these mechanisms continuously influence the urban landscape (Grimm et al., 2008), which is heterogeneous with respect to environmental, demographic, cultural and socio-economic characteristics as well as urban forms and functions. As a result, the distinctive heterogeneity of urban ecosystems dynamically develops over time (Alfsen et al., 2011). This "dynamic heterogeneity" (Pickett et al., 2017) shows both in variation between cities and within cities. Namely, in inter-city differences in terms of size and political, economic and social organization but also in intra-city differences, such as functional specialisation of neighbourhoods (Pincetl et al., 2012; Pulido Barrera et al., 2018).

The need to understand how these dynamic and heterogeneous characteristics affect urban resource flows, generating spatial variations and changes in resource flows over time, is increasingly recognized in the field of urban metabolism (UM) (Zhang et al., 2015). UM refers to the processes whereby cities transform raw materials, energy, and water into the built environment, human biomass, and waste (Decker et al., 2000). Various scholars argue that UM analyses should better capture the complex nature of cities by providing insight in how different factors influence consumption patterns and how they are interlinked and operated at different spatial and temporal scales (Golubiewski, 2012; Metzger et al., 2016; Voskamp et al., 2018). Researchers particularly advocate these adjustments to UM assessment methods to enhance the suitability of UM analyses to support resource-conscious design, planning and management of urban areas (Cui, 2018; Perrotti and Stremke, 2018). Understanding the factors that influence resource consumption, is a prerequisite for designing policies and plans that map out the route to sustainable management of urban resources (Broto et al., 2012). After all, formulating effective policies and plans requires not only insight into *what* a city's metabolism looks like – 'how much resource consumption occurs where and when?' –, but also, *why* the metabolism looks the way it does – 'which are the mechanisms behind the resource flow patterns?'. For example, if a city aims to reduce its natural gas usage, it is not only relevant to know the quantity of gas used per neighbourhood. It is also essential to understand what underlies these consumption patterns. This knowledge can support the identification of the most effective strategy to realize reduction goals: retrofitting the building stock, upgrading the heating appliances in place, increasing the natural gas price or starting educational campaigns. Recently, new approaches in UM studies are emerging that pay attention to informing urban planning practice and aim to investigating the spatiotemporal dynamics of UM and the relationship between so-called 'drivers' and UM (Bai, 2016).

This emerging field of UM analyses requires a common framework that supports researchers in designing their research and that enables interpretation of their findings, such as the generalizability of their findings to other cities. Hitherto, studies on factors influencing UM are generally limited to selected factors of influence and they are incomplete in motivating why these factors are the appropriate ones to study. An overview of potential factors of influence enables researchers making an informed decision which factors are the relevant ones to assess in their case. At the same time, it supports interpretation of their findings by showing which additional factors, that are excluded from their analysis, could still affect their results. The framework should thus also provide insight into whether factors are connected and how they can influence one another. Aiming to support building such a framework, we conducted a systematic literature review that synthesizes the scientific understanding on factors that influence the spatiotemporal variability of the UM generally and water and energy consumption specifically.[2] The aim of this review was thus to provide an overview of the factors influencing urban water and energy consumption and their effect on consumption; and to give insight in the interconnectedness of these factors over spatial and temporal scale

[1] According to Bai et al. (2016), conceptualising cities as social-ecological-technological systems relies upon acknowledging the following system characteristics. Cities constitute of physical/built, social-economic and ecological subsystems that encompass multiple and diverse actors. Across these subsystems, causally interlinked urban processes result in intended and unintended consequences. Likewise, cities are open systems, that are influencing and influenced by the broader structures they are embedded in. They are self-organizing, dynamic and evolving, and have non-linear pathways.

[2] In this review we focus on final water and energy consumption because of the relevance for resource-conscious design, planning and management of urban areas. Water and energy are key resources when it comes to implementing spatial and technical interventions in the urban landscape in support of urban climate adaptation, climate mitigation and/or resource efficiency (Mitraka et al., 2014; Pincetl et al., 2012).

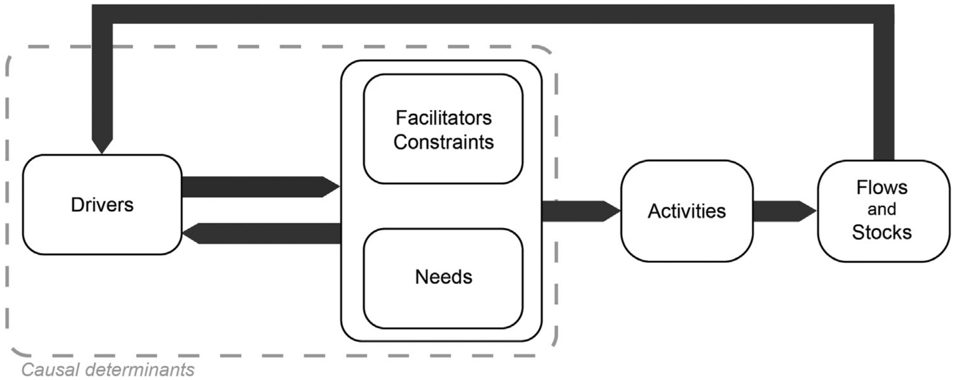


Fig. 1. The five interrelated elements of urban metabolism (Dijst et al., 2018).

Table 1
Categorization of factors affecting resource consumption in relation to the elements needs, facilitators/constraints and drivers. Elaborated on the work of Dijst et al. (2018) and Poças Ribeiro et al. (2019).

Elements	Needs	Facilitators/constraints			Drivers
		Consumer characteristics	Resource characteristics	Urban landscape characteristics	
Categories of factors	Individual survival Individual aspirations Satisfaction Social Practical Political	Personal Psychological Social context Cultural context Decision making	Quality Price Availability	Spatial Infrastructural	Demographic Economic Political Cultural Technological Geographical

levels. In addition, the aim was to describe the characteristics of this body of UM literature to interpret the validity of findings and to identify relevant directions for future research.

2. Conceptual framework

2.1. Drivers, needs, facilitators and constraints

The basis of this review is a conceptual framework that portrays: (I) what kind of factors influence the spatiotemporal variability of urban water and energy consumption, and (II) in what way. Thereby, this framework facilitates the categorization, interpretation and comparison of findings from different studies. At present, such an elaborated conceptualisation is absent in UM literature, but the work by Dijst et al. (2018) proved a valuable starting point to build on. Dijst et al. (2018), identified five interrelated elements of urban metabolism (Fig. 1). Resource flows through and stocks in a city are the effect of activities that are undertaken within the urban environment. The causal determinants of those activities constitute three elements: needs, facilitators/constraints, and drivers (Dijst et al., 2018). We classified these elements further into different categories of factors to facilitate the categorization of our findings, using the cross-disciplinary review by Poças Ribeiro et al. (2019). We took their review as point of departure, which is focused on the factors that influence consumption of goods and services rather than resources, because the UM literature lacks such a comprehensive and coherent overview. In line with Dijst et al. (2018), we thus distinguish three elements that affect the spatial and temporal characteristics of urban energy and water consumption patterns: needs, facilitators/constraints, and drivers (see Table 1).

First, the *needs* of individuals and communities prompt particular activities (Dijst et al., 2018). For example, thirst (need) might trigger drinking (activity) and accordingly result in water consumption (flows and stocks). *Needs* are thus an attribute of consumers. Poças Ribeiro et al. (2019) found that these *needs* can be very diverse and can be categorised as factors related to individual survival, individual aspirations, satisfaction as well as social, practical and political purposes (Table 1). As UM analyses generally do not assess these factors, we did not consider needs in our review.[3]

Second, there are *facilitators/constraints* that increase or decrease the probability or degree to which specific activities are triggered, and in doing so they shape particular consumption patterns. They are "two sides of the same coin, depending on whether a given factor is present in a positive or negative sense" (Dijst et al., 2018). In case of the example above, the health conditions of the consumer, the quality of available water or distance to a tap with potable water can influence the drinking of tap water. *Facilitators/constraints* can thus relate to either the consumer, the resource or the physical urban landscape (Table 1). With regard to the consumer; the personal and psychological characteristics as well as social and cultural context of consumers influence his/her consumption patterns, along with his/her way of decision making (Poças Ribeiro et al., 2019). Consumer behaviour also depends on the product consumed and its so-called "marketing mix" (Poças Ribeiro et al., 2019), which translate in the categories resource quality, price, and availability in the context of resource consumption. With *facilitators/constraints* related to the urban landscape, we refer to urban patterns that facilitate or constrain particular activities to occur, comprising both spatial and infrastructural factors.

Third, *drivers* can influence and set the context for needs, facilitators/constraints, activities and resource flows and stocks at the

[3] Analyses within the UM field that investigate the factors that influence urban resource consumption are generally not concerned with factors at the level of individuals, except for key descriptive characteristics of consumers such as income (see facilitators/constraints, table 1). Rather, characteristic of the urban system, such as those describing the societal context and spatial set-up of the city at hand, are within the scope of those studies. Note that our results confirm that predominantly those kind of factors are studied.

level of an individual or a community. We define *drivers* as large scale developments in the societal context in which the physical urban landscape is embedded, that cause a particular activity to occur. Without (a) driver(s), facilitators/constraints will not result in activities (Dijst et al., 2018). In line with Poças Ribeiro et al. (2019), we distinguish *drivers* related to the demographic, cultural, economic, political/institutional, technological, and geographical context (Table 1). *Drivers* intrinsically have a temporal characteristic as they comprise local up to global processes. It should be noted that although Dijst et al. (2018) explicitly refer with '*drivers*' to macro developments that can be either endogenous or exogenous to a system, other scholars also commonly use the term '*driver*' in the UM literature, but without providing a definition of the term. Consequently, it remains unclear whether they consider '*drivers*' as the only type of causal determinants or that they also acknowledge the influence of facilitators/constraints and needs.

3. Methods and materials

The method underpinning this paper is a systematic review of the literature. This involves searching, selecting as well as critically appraising the literature in a systematic manner and synthesizing the findings into a coherent statement (Gough et al., 2012). By closely adhering to a set of scientific methods, such a review explicitly aims to limit error (bias) (Petticrew and Helen, 2005). Accordingly, our review consisted of three steps, as described below: (I) search strategy development and implementation; II) relevance and quality assessment; (III) data extraction and synthesis. A detailed description of these steps is provided as supplementary material S1.

3.1. Search strategy development and implementation

The first step of the review process was to develop and implement a search strategy to identify studies eligible to answer the research questions. Three study types were considered: (I) Case studies discussing temporal variation in urban water and/or energy consumption, (II) Case studies discussing spatial variation in urban water and/or energy consumption, and (III) Review studies that mention case studies focussing on the temporal or spatial variation of the UM. A Boolean search string was formulated, using keywords based on two inclusion concepts and several exclusion terms (see Table 2). Then, this search string was applied to the databases Scopus and Web of Science, yielding 474 unique items.

An additional search strategy that was employed, was 'reference list checking' the selected review papers (see 3.2), by scanning the titles of citations in the reference lists of those papers (Gough et al., 2012). Non-review papers were not considered for this strategy to avoid that the number of irrelevant items in the sample would extensively grow, a known issue associated to this strategy that can be prevented this way (Gough et al., 2012).

3.2. Relevance and quality assessment

The second step of the review process entailed screening the retrieved publications and deciding which ones to examine in detail. This is also known as critical relevance and quality appraisal (Gough et al., 2012; Petticrew and Helen, 2005). For this, criteria were formulated to either ex- or include publications for further review based the relevance of the publications and their appropriateness in answering our research questions and drawing conclusions. A detailed description of our process and the eligibility criteria used is provided in supplementary material S1.2.

The 474 unique items that were obtained were screened in several steps to judge their eligibility using exclusion criteria (Fig. 2). First, all items were screened on title and abstract and appraised on the criteria: publication year, topic, scope, resource flow, and study design. Each item was coded accordingly in the EPPI-Reviewer software (Thomas et al., 2010). Based on this first screening 75 items were directly included for full text screening. Another 75 items were additionally screened on the introduction, methods and/or conclusion section, because screening of the abstract and title of these items did not provide sufficient information on the scope and study design to decide whether these articles should be included for full text screening or not. Through this second screening phase, twenty-three items were additionally included, giving a total of 98 items for full text screening. During the full text screening, the same exclusion criteria as in the earlier screenings were employed. In addition, publications were excluded when they did not discuss factors influencing resource consumption and case studies were also excluded when the scale level of analysis was less detailed than the metropolitan level. Based on this final screening step, forty-three items remained. Finally, reference list checking of the four included review studies identified an additional six eligible items. Accordingly, in total forty-nine items were to be considered for further quality assessment.

After the relevance assessment, the next step was quality assessment. Inclusion criteria were used to evaluate whether the forty-nine publications that remained met quality requirements on the basis of which they should be included in the final sample. Accordingly, reviews were only included if they discuss how factors are related to consumption, thus mentioning their effect. Case studies were evaluated on two characteristics of the quality of the data used: reliability and resolution (see also supplementary material S1.3). After this final step of quality assessment the final sample totalled thirty publications.

3.3. Data extraction and synthesis

The next step in the review process was data extraction from publications and finally synthesizing these data. Two types of data were extracted: (I) descriptive characteristics of the research and (II) data on the relationship between spatiotemporal variability of water and/or energy consumption and the factors that generate these geographical variations and changes over time. The elements of data extraction are described in more detail in S1.4. Both types of data were recorded in a Microsoft Excel spreadsheet because tabulation was identified as a valuable tool for data synthesis. It can be used to "develop an initial description of the included studies and to begin to identify patterns across studies" (Popay et al., 2006),

Table 2
Elements of the search string.

Search string elements		Keywords
Inclusion concept 1	"Urban metabolism/ecology"	Urban, Metropol*, Neighbourhood, City, Cities Metaboli*, Ecology
Inclusion concept 2	"Water/energy use"	Water, Energy, Resource*, Material Use, Usage, Consum*, Flow*, Demand*
Exclusion terms		Modelling, Disease, Water quality, Species, Plant*, Bee*

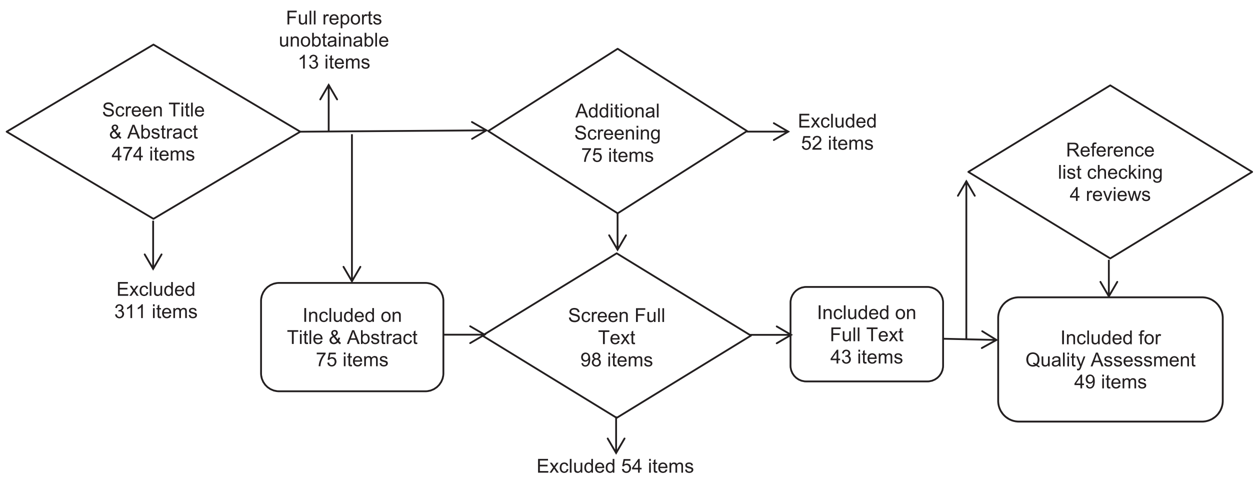


Fig. 2. The steps of relevance assessment.

thereby informing our narrative synthesis. This is an approach to the "synthesis of findings from multiple studies that relies primarily on the use of words and text to summarise and explain the findings of the synthesis" (Popay et al., 2006).[4] Narrative synthesis is suitable to synthesize studies that have a wide range of research designs and yield both quantitative and qualitative findings (Popay et al., 2006)– which is the case for our review. We followed the narrative synthesis approach as described by Popay et al. (2006) and describe this in detailed in the supplementary material S1.5.

4. Results

4.1. Descriptive characterization of the body of literature

UM research on the factors that influence urban water and/or energy consumption is growing and diversifying in terms of research design (Fig. 3). The oldest publication reviewed is from 2001 and most research dates from recent years, with half of the publications from the period 2014–2018 (see Fig. 3a). This sample composition reflects the general development in the UM field that empirical case studies have become more frequent since 2000 (Beloin-Saint-Pierre et al., 2017; Cui, 2018). Moreover, the sample shows a diversification of research designs in recent years. The oldest half of the sample, up to 2014, consists for two-thirds of flow analyses and environmental history studies. These type of studies are not specifically designed to establish quantitative correlations between consumption figures and factors explaining them. Since 2014 UM research has been published that is specifically designed with this aim, namely 'regression analyses' and 'trend analyses', i.e. multi-year flow analyses using indicators to explain temporal differences, that specifically aim to establish those correlations (see Fig. 3b).

Mapping the case studies on the geographic location of their embedded case(s) reveals that this body of literature is dominated by case studies of mature cities in the global north and in temperate climates (Fig. 3c). Sixteen publications, 57% of the case studies, research one or several cities in Europe. For North America, Asia and Australia this is respectively six, four and one publication(s). In addition, one publication covers several cities in Europe, North-America, South America and Africa (see supplementary material S2). These twenty-eight case studies cover in total thirty-one unique cities: fourteen European cities, six cities in North America, six cities in Asia, three cities in Australia, one city in Africa and one city in South America (see Fig. 3b). Twenty-two of those cities are located in a temperate climate, seven in a continental climate and two in a tropical climate zone (see also supplementary material S2). Most frequently studied urban areas are Los Angeles, covered by four case studies and one meta-study, and Barcelona, covered by four case studies. Four of these five publications of Los Angeles present results from the same research project (Pincetl et al., 2016, 2014; Pincetl and Newell, 2017; Porse et al., 2016), as do the three trend analyses covering the three biggest Swedish cities (Kalmykova et al., 2016, 2015; Rosado et al., 2016).

A further breakdown of the case studies according to spatio-temporal resolution revealed five clusters within the sample (see Fig. 4), with each cluster having another focus when it comes to understanding the factors influencing consumption. Clusters 1 and 2 include research that assesses the temporal variation in consumption across decades or even centuries, namely 'environmental history studies' (cluster 1) and multi-year 'material flow analyses' and 'trend analyses' (cluster 2). These type of studies discuss primarily the effect of drivers and the facilitating or constraining role of infrastructure on consumption. Cluster 3 includes research aimed at explaining differences in consumption between cities. Some publications have one focal city of research that is compared with other cities to bring context related effects into view (e.g. Voskamp et al., 2017a), whereas other research is aimed at assessing and comparing several cases from the start (e.g. Renouf et al., 2018). Both this cluster of 'city comparisons' and that of 'intra-urban comparisons' (cluster 4) focus on the influence of urban spatial characteristics. Only two studies in these clusters provide spatially explicit data of consumption patterns, namely the publications by Ariza-Montobbio et al., (2014) (#1) and Mehta et al., (2013) (#14). Furthermore, research in cluster 4 also considers the effect of consumer characteristics, as do 'high-resolution studies' (cluster 5). This latter research cluster also provides insight in the spatial facilitators/constraints on building and plot level, and three publications support their findings with spatially explicit consumption data (Pincetl et al., 2014, 2016; Porse et al., 2016; #16–18). The role of resource characteristics is addressed by research from all five different clusters.

[4] Narrative synthesis refers to a specific approach to combining the findings of multiple studies as part of a systematic review process in order to draw conclusions based on the body of evidence. It should not be mistaken for a narrative review.

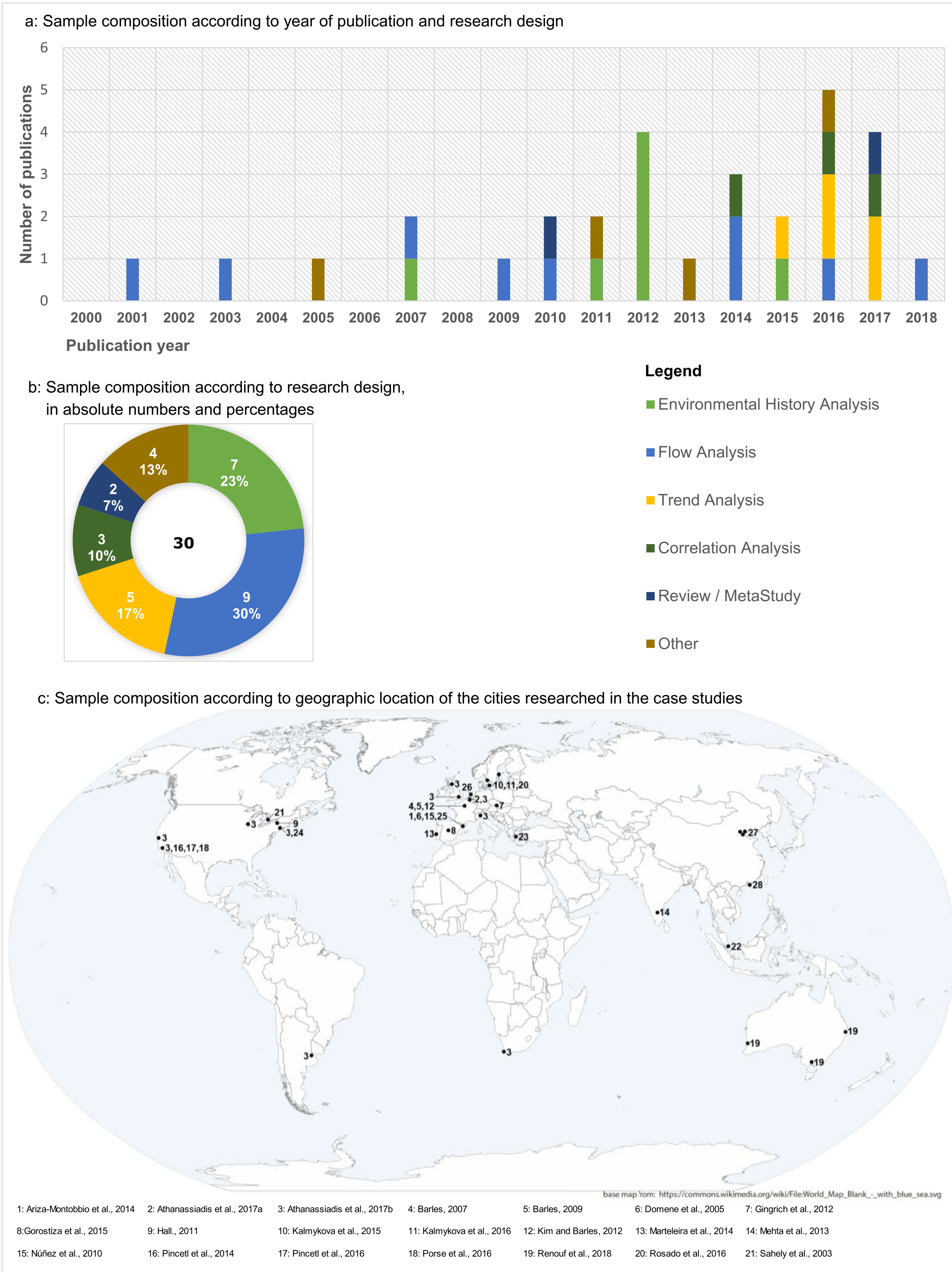


Fig. 3. Sample composition according to year of publication, research design and geographic location of embedded case(s).

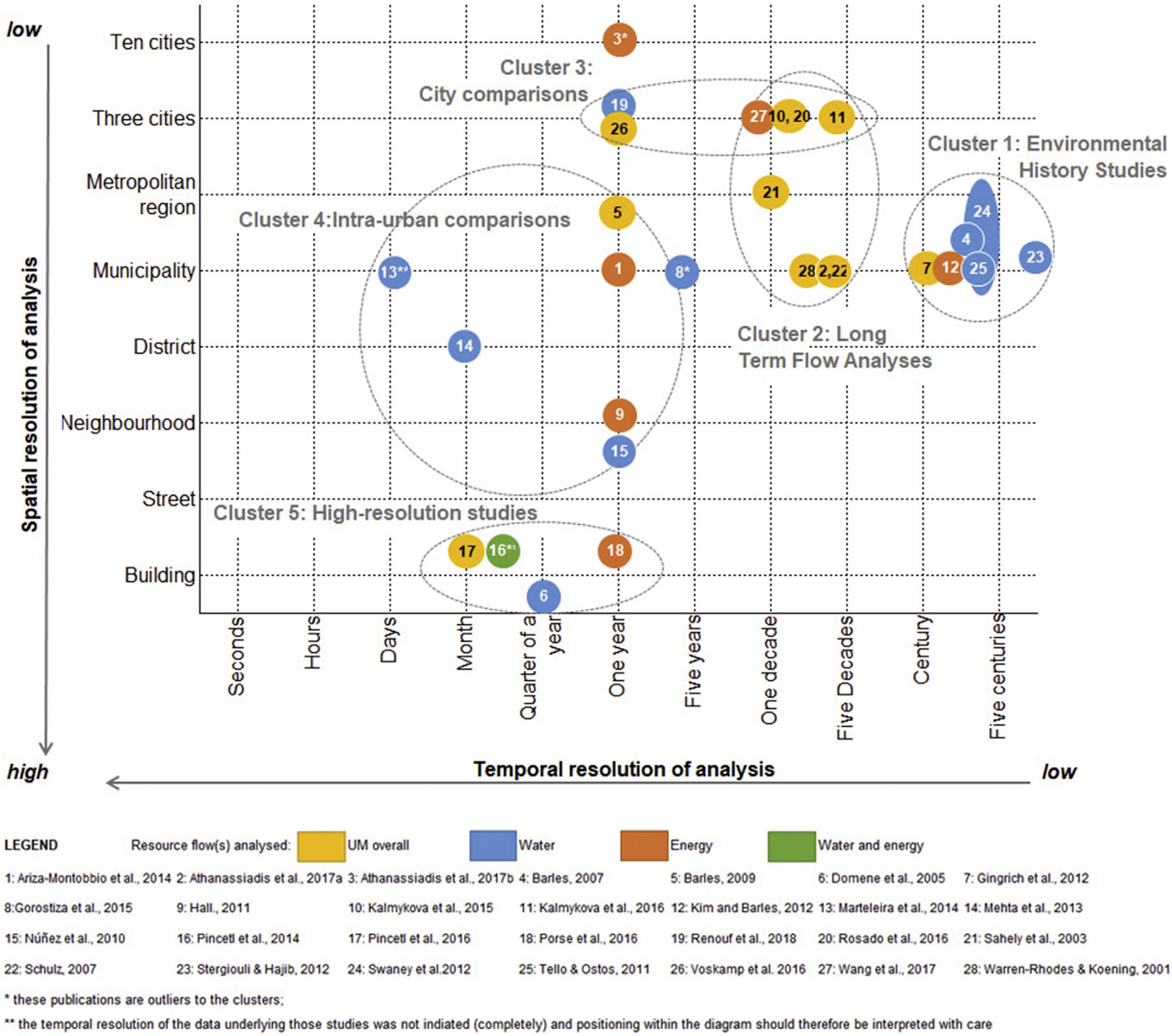


Fig. 4. Sample composition according to spatiotemporal resolution of analysis.

4.2. *Determinants of urban water and energy consumption*

In the following two sections we present an overview of the factors that influence water and/or energy consumption and what this effect is. These findings are summarized in Table 3 and further explored in section 4.2.1, where we discuss all drivers, and section 4.2.2, focussing on facilitators/constraints. Note that each factor mentioned in Table 3 is indicated in bold in the text.

4.2.1. *Drivers*

4.2.1.1. Demographic drivers. Demographic drivers comprise changes in the overall characteristics of the urban population that affect resource consumption patterns. Population size was the only factor found to represent such a driver. The most frequent finding is increasing total consumption of both water and energy with increasing population size (Barles, 2007; Gingrich et al., 2012; Gorostiza et al., 2015; Kim and Barles, 2012; Stergiouli and Hadjibiros, 2012; Swaney et al., 2012; Tello and Ostos, 2012; Warren-Rhodes and Koenig, 2001). Yet, Athanassiadis et al., 2017a show that this is not always the case, as evidenced by absolute water and energy consumption in Brussels neither following the evolution of the population nor the evolution of consumption per inhabitant between 1970 and 2000. The findings of Athanassiadis et al., 2017b suggest that with increasing population size, consumption of natural gas and electricity per capita actually decreases.

4.2.1.2. Economic drivers. Economic drivers include changes in the economic domain of a city, namely in its system of production and exchange of goods and services, that influence resource consumption patterns. Three economic drivers were identified: level of economic development and economic specialisation both signify more or less gradual changes in economic activities, while the third driver, crises, denotes disruptive events or periods. Five studies mention that consumption increases with an increasing level of economic development, for the UM in general, water and energy.

Table 3
Overview of factors influencing water and/or energy consumption.

Category	Factors influencing consumption	References for water	References for energy
Drivers			
Demographic	Population size	Athanassiadis et al., 2017a; Barles (2007); Gorostiza et al. (2015); Stergiouli and Hadjibiros (2012); Swaney et al. (2012); Tello and Ostos (2012); Warren-Rhodes and Koening (2001)	Athanassiadis et al., 2017a; Athanassiadis et al., 2017b; Gingrich et al. (2012); Kalmykova et al. (2016); Kim and Barles (2012); Warren-Rhodes and Koening (2001)
Economic	Level of economic development	Tello and Ostos (2012)	Gingrich et al. (2012); Kalmykova et al. (2016); Wang et al. (2017); Warren-Rhodes and Koening (2001)
	Economic specialisation	Athanassiadis et al., 2017a; Tello and Ostos (2012)	Ariza-Montobbio et al. (2014); Athanassiadis et al., 2017a; Sahely et al. (2003); Warren-Rhodes and Koening (2001)
	Crises	Tello and Ostos (2012); Stergiouli and Hadjibiros (2012)	Kim and Barles (2012); Athanassiadis et al., 2017a
Political	Educational campaigns	Gorostiza et al. (2015); Pincetl et al. (2014); Pincetl and Newell (2017); Renouf et al. (2018); Stergiouli and Hadjibiros (2012)	Kim and Barles (2012)
	Rules and regulations	Gorostiza et al. (2015); Pincetl et al. (2014); Pincetl and Newell (2017); Renouf et al. (2018); Swaney et al. (2012)	–
	Policy and planning	–	Kalmykova et al. (2016); Kim and Barles (2012); Pincetl et al. (2014); Warren-Rhodes and Koenig, 2001
Cultural	Standard of living	Barles (2007); Stergiouli and Hadjibiros (2012)	Athanassiadis et al., 2017a; Kim and Barles (2012); Warren-Rhodes and Koenig, 2001
	Environmental awareness	Swaney et al. (2012); Tello and Ostos (2012)	Warren-Rhodes and Koenig, 2001
Technological	Conversion efficiency	–	Gingrich et al. (2012); Kalmykova et al. (2015); Kim and Barles (2012); Sahely et al. (2003)
	Transition in energy system	–	Athanassiadis et al., 2017a; Kalmykova et al. (2015)
	Technological inventions	Swaney et al. (2012)	Gingrich et al. (2012); Kim and Barles (2012)
Geographical	Natural resource availability	–	Gingrich et al. (2012); Kim and Barles (2012); Voskamp et al. (2017)
	Climate	–	Athanassiadis et al., 2017a; Weisz and Steinberger (2010)
Facilitators/Constraints			
Spatial	Population density	Athanassiadis et al., 2017a; Marteleira et al. (2014)	Ariza-Montobbio et al. (2014); Athanassiadis et al., 2017a; Athanassiadis et al., 2017b; Barles (2009); Hall, 2011; Porse et al. (2016); Weisz and Steinberger (2010)
	Spatial distribution of functions	–	Barles (2009)
	Presence of a port	–	Kalmykova et al. (2015); Schulz (2007); Voskamp et al. (2017); Warren-Rhodes and Koenig, 2001
	Amount of productive tree canopy	–	Hall, 2011
	Garden typology	Domene et al. (2005); Pincetl and Newell (2017)	–
	Building size	–	Ariza-Montobbio et al. (2014); Hall, 2011; Pincetl et al. (2014); Porse et al. (2016)
	Building type	Núñez et al. (2010)	Ariza-Montobbio et al. (2014); Porse et al. (2016); Pincetl and Newell (2017); Pincetl et al. (2016)
	Building age	–	Pincetl et al. (2014); Porse et al. (2016); Pincetl and Newell (2017)
Infrastructural	Size of the supply network	Barles (2007); Gorostiza et al. (2015); Stergiouli and Hadjibiros (2012); Swaney et al. (2012); Tello and Ostos (2012)	Kim and Barles, 2012; Gingrich et al. (2012)
	Condition of the supply network	Swaney et al. (2012)	Kim and Barles, 2012; Gingrich et al. (2012)
	Sanitary fittings	Núñez et al. (2010); Swaney et al. (2012)	–
	Metering	Swaney et al. (2012)	–
	Presence of a pool	Núñez et al.; Tello and Ostos (2012)	Pincetl et al. (2014)

Table 3 (*continued*)

Category	Factors influencing consumption	References for water	References for energy
	Home appliances	–	Pincetl et al. (2014)
Resource characteristics	Price	Stergiouli and Hadjibiros (2012)	Athanassiadis et al., 2017a; Gingrich et al. (2012); Kim and Barles (2012); Sahely et al. (2003)
	Availability	Gorostiza et al. (2015); Mehta et al. (2013); Renouf et al. (2018); Tello and Ostos (2012)	–
	Quality	Gorostiza et al. (2015)	–
Personal consumer characteristics	Income level	Domene et al. (2005); Pincetl et al. (2014); Pincetl and Newell, 2017	Ariza-Montobbio et al. (2014); Athanassiadis et al., 2017b; Hall, 2011; Pincetl el at., 2014; Pincetl and Newell (2017); Porse et al. (2016); Weisz and Steinberger (2010)
	Lifestyle	–	Ariza-Montobbio et al., (2014); Hall (2011); Kalmykova et al. (2016); Weisz and Steinberger (2010)
Social & cultural context	Household size	–	Ariza-Montobbio et al., (2016); Weisz and Steinberger (2010)
Decision making	Behaviour	Renouf et al. (2018)	–

Note that "–" indicates the sample does not provide evidence for a direct influence of that factor on the consumption of that resource.

Rosado et al. (2016) point this out for the UM in general with their analysis of three Swedish cities. They found that urban areas in a mature development stage, i.e. Stockholm and Gothenburg, consume fewer resources than urban areas in transition such as Malmo. Tello and Ostos (2012) found increasing water consumption with economic development. Likewise, three studies indicate increasing final energy consumption with increasing GDP (Gingrich et al., 2012; Wang et al., 2017; Warren-Rhodes and Koenig, 2001). The findings of Kalmykova et al. (2016) indicate quite the opposite. In Stockholm fuel consumption decreased to 63% of the 1996 fuel consumption level in 2011, despite population increase of 20% and GDP growth, hence concluding that decoupling of resource consumption and economic growth took place.

Changes in economic specialisation do not have a univocal effect on overall water and/or energy consumption. Rather, shifts in economic sector composition can be observed in altering consumption *profiles*. Hence, although European and North-American cities that experienced de-industrialization in the last quarter of the 20th century decreased their industrial resource consumption (e.g. Athanassiadis et al., 2017a; Tello and Ostos, 2012; Sahely et al., 2003), overall consumption did not necessarily decrease in these cities. The tertiarization process that took place simultaneously implied an increasing consumption by the service sector resulting in stable total consumption. Athanassiadis et al., 2017a indicate those changes in consumption profile for water in the case of Brussels, and Warren-Rhodes and Koenig (2001) for energy consumption in Hong Kong. Ariza-Montobbio et al. (2014) identify the relationship between economic sector composition and consumption profiles specifically for electricity consumption. They found high electricity consumption levels among different municipality types in Catalonia, including “industrial cities” with industry as a major consumer and “service cities”, which have a high consumption due to service activity and a high population density (see 4.2.2).

Different kinds of crises are mentioned in relation to declining consumption. Stergiouli and Hadjibiros (2012) illustrate for example the influence of war, indicating that Athens experienced a substantial reduction in water use during the second world war and the Greek civil war that followed (1939–1949). Two more recent examples of economic crises are the oil crisis in the 1970’s (Kim and Barles, 2012) and the recent financial crisis (Athanassiadis et al., 2017a), both of which are associated with declining consumption of petroleum products in Paris and Brussels, respectively.

4.2.1.3. Political drivers. Political drivers comprise changes in governmental policy, effectuated by different sorts of policy instruments, that influence consumption patterns. Literature reveals that different types of policy instruments are being employed to target either consumption of water or of energy. Educational campaigns as well as rules and regulations are mentioned by six studies as intervention in response to drought, resulting in reduced water consumption (Gorostiza et al., 2015; Pincetl et al., 2014; Pincetl and Newell, 2017; Renouf et al., 2018; Stergiouli and Hadjibiros, 2012; Swaney et al., 2012). Pincetl et al. (2014) and Pincetl and Newell (2017) found that restricting irrigation to specific days and times, i.e. mandatory conservation, was more effective in reducing water use than a voluntary program. The only example of educational campaigns with regards to energy consumption is given by Kim and Barles (2012), who mention political encouragement as one of the factors contributing to increased coal consumption, as a response to the wood crisis in 19th century Paris. Nation-wide and city-specific policy and planning interventions are drivers for decreasing energy consumption. Planning and policy interventions advocating substitution and diversification of energy sources are linked to declining consumption of petroleum products in Paris (Kim and Barles, 2012) and coal in Hong Kong (Warren-Rhodes and Koenig, 2001) since the 1970s. More recent interventions include the introduction of a congestion fee in Stockholm in 2007 (Kalmykova et al., 2016) and the implementation of the latest energy efficiency codes in Los Angeles (Pincetl et al., 2014). Both are related to reduced energy usage in those cities, for transportation and buildings respectively.

4.2.1.4. Cultural drivers. We speak of cultural drivers in case of changing consumption patterns under influence of changing cultural norms within society. Environmental history studies and long term flow analyses provide evidence of two types of cultural drivers: changes in standard of living and in environmental awareness. Firstly, five publications relate higher standard of living to increased consumption of either water or energy, with specific expressions of these higher standards for each resource (Athanassiadis et al., 2017a; Barles, 2007; Kim and Barles, 2012; Stergiouli and Hadjibiros, 2012; Warren-Rhodes and Koenig, 2001). Higher expectations for health and hygiene express higher standards of living that are specific for water (Barles, 2007), whereas increased demand for thermal comfort is specific for energy (Kim and Barles, 2012; Warren-Rhodes and Koenig, 2001). Secondly, three publications link increased environmental awareness among the general public to decreasing consumption patterns of water (Swaney et al., 2012; Tello and Ostos, 2012) and energy (Warren-Rhodes and Koenig, 2001) since the end of the twentieth century. Tello and Ostos (2012), for example, point out that since 1997 both total and per capita water consumption in Barcelona decreased, despite economic development and increasing population size. They ascribe this decrease to the emergence of a “New Sustainable Water Culture” in Catalonia and growing awareness of the risks of climate change.

4.2.1.5. Technological drivers. Technological drivers include changes or advancements in resource conversion and supply technologies that influence urban resource consumption patterns. These drivers range from small-scale innovations that optimize existing technologies up to long-term, structural changes in the resource system. Small-scale innovations resulting in gains in conversion efficiency are mentioned in four studies as plausible explanations for reduced energy consumption (Gingrich et al., 2012; Kalmykova et al., 2015; Kim and Barles, 2012; Sahely et al., 2003). Kalmykova et al. (2015), for example, name increased energy-efficiency as one of the underlying causes of a 20% and 45% decrease in residential energy consumption per capita between 1996 and 2011 in Stockholm and Gothenburg, respectively. A system-wide change is also mentioned as explanation for these decreases, namely a transition in energy system for heating (Kalmykova et al., 2015). Athanassiadis et al., 2017a also associate such a change in prevalent heating technology to a slow decrease in consumption of petroleum products and an increase of natural gas use in Brussels (1970–2010). Technological inventions that can fuel such transitions have shown to be drivers of energy consumption throughout history. Examples include increasing coal consumption in the nineteenth century with development of the steam engine and increasing petroleum consumption in the twentieth century with the rise of motorization and increasing mobility (Gingrich et al., 2012; Kim and Barles, 2012).

4.2.1.6. Geographical drivers. We speak of geographical drivers when consumption patterns are influenced by the geographic location of a city. The literature provides evidence for two of such drivers: natural resource availability and climate. Evidence of the effect of changing natural resource availability on consumption is found in the historical analyses of Paris and Vienna. These studies indicate that reduced energy consumption is related to lower resource availability by the end of the 18th and beginning of the 19th century. In both cities, the depletion of nearby forests contributed to energy (i.e. firewood) scarcity (Gingrich et al., 2012; Kim and Barles, 2012). Moreover, Voskamp et al. (2017) argue that the presence of the river Danube in Vienna and Amsterdam’s delta location are key features to explain “the renewable energy performance of both cities”. The second geographic driver identified is climate. Athanassiadis et al., 2017a and Weisz and Steinberger (2010) stress that climate has an impact on energy use due to its influence on heating and cooling demand. Nevertheless, Weisz and Steinberger (2010) indicate that comparative studies found a substantial range in energy use when expressed in Wh/m^2 living space/heating-degree-day, confirming that non-climate factors have substantial effects on energy consumption.

4.2.2. Facilitators and constraints

4.2.2.1. Spatial characteristics. Spatial characteristics describe the characteristics of the built and non-built surfaces within the urban landscape and reflect the form and functions of these spaces. These characteristics range from very generic city level indicators such as population density, to specific building characteristics such as building size. The spatial factor analysed most frequently is population density. According to the review by Weisz and Steinberger (2010), the relationship between transport energy requirements and population density is frequently studied, with literature suggesting lower energy usage with higher densities. This would mean that a higher population density acts as a constraint for transport-related energy consumption: by restraining the activity ‘transportation’, higher densities have lower consumption levels. However, Weisz and Steinberger (2010) also stress that the causal factors of this correlation are debated and that other factors also play an important role, for example the quality of public transportation. Three studies mention either lower total residential energy (Hall, 2011; Porse et al., 2016) or electricity (Ariza-Montobbio et al., 2014) consumption with higher population densities. Athanassiadis et al., 2017b also found that (residential) electricity and natural gas use decreased with increasing population density with their comparative analysis of ten cities. However, their results also indicate that the relationships vary significantly in intensity and that at the micro scale “a high degree of heterogeneity seems to exists across the cities”. Athanassiadis et al., 2017a found in their long-term analysis of Brussels that changing population density correlated neither with variability in energy consumption nor with water consumption. Marteleira et al. (2014) found for Lisbon that areas with higher density have a higher water consumption per capita. Yet, these findings are difficult to interpret because they correspond to total potable water volumes rather than domestic use only.

Two other spatial characteristics were found at city level: spatial distribution of functions and presence of a port. Barles (2009) concludes that both the spatial distribution of functions and population density strongly impact the UM of Paris. She stresses that different parts of the city each have their specific function and that these different functions facilitate particular activities, thus creating intra-city differences in consumption. Fossil fuel consumption was found to be the lowest in the dense city centre of Paris where public facilities and housing are the dominant urban functions. The presence of a port gives Amsterdam, Gothenburg, Hong Kong and Singapore a distinct metabolic profile, by enabling resource-intensive, port-related activities. The UM of port cities in general is characterized by large volumes of trading flows, implying a relatively high import and export per capita and a high share of crossing flows (Kalmykova et al., 2015; Schulz, 2007; Voskamp et al., 2017; Warren-Rhodes and Koenig, 2001). Warren-Rhodes and Koenig (2001) also indicate that transport sector energy use grew with increased trading volume in Hong Kong.

We also identified five spatial characteristics on a scale level more detailed than the city level. The literature indicates effects of vegetation on water and energy consumption at neighbourhood and plot level, whereas the facilitating/constraining role of building characteristics is primarily related to energy consumption at building level. In a comparison of three neighbourhoods in Syracuse, Hall (2011) found that the amount of productive tree canopy affects the energy demand for heating and cooling; a negative correlation was found between energy demand and tree canopy coverage. At plot scale, the garden typology can facilitate water consumption (Pincetl and Newell, 2017; Domene et al., 2005). Domene et al. (2005) found a significant positive correlation between the proportion of grass occupying the garden and the garden water consumption. As for the building level, three studies report higher electricity consumption per household as well as per person with larger building size (Ariza-Montobbio et al., 2014; Hall, 2011; Pincetl et al., 2014). Porse et al. (2016) found for Los Angeles County that median annual total energy as well as electricity consumption per square-foot varies by building type, which reflects both the use and construction design of a building (e.g. a single-family detached building). Institutional and commercial buildings are among the largest consuming types per square foot in L.A. (Porse et al., 2016), which is in line with the findings by Pincetl et al. (2016). Núñez et al. (2010) indicate that also water consumption varies with the function of a building. Finally, building age and energy consumption are related across all building use types in L.A. (Pincetl et al., 2014; Porse et al., 2016).

4.2.2.2. Infrastructural characteristics. Infrastructural characteristics refer to the characteristics of the physical networks and their system components that are providing goods and services to a city, for instance systems for transport, resource supply and telecommunications. Infrastructural facilitators/constrains thus include specifications of the city networks as well as of specific system components. At the network level, factors such as the size and the condition of the supply network play a role. Five studies mention increasing total water consumption with increasing size of the supply network (Barles, 2007; Gorostiza et al., 2015; Stergiouli and Hadjibiros, 2012; Swaney et al., 2012; Tello and Ostos, 2012). With regards to energy, the historical analyses of Paris and Vienna point out that the size of the supply network played a crucial role in the energy transition from fuel wood to coal (Gingrich et al., 2012; Kim and Barles, 2012). At first, wood supply could not keep up with the demand because forests were depleted (natural resource availability, 4.2.1.6) and transport routes were constraining supply from more remote places. Then, the opening of long-distance railway lines facilitated coal consumption by giving access to coal supply regions. In addition, the switch to railway transport also meant an improvement in the condition of the supply network because it also enabled constant supply – as opposed to rivers, where weather conditions influenced navigability (Gingrich et al., 2012; Kim and Barles, 2012). With regards to the condition of water infrastructure, Swaney et al. (2012) mention reduction of leakage as one of the reasons for declining water consumption in New York City since the 1990s. They also link this decline in consumption to adjustments of system components that brought about a constraining effect, namely increased metering and changes in sanitary fittings, i.e. the installation of low-flow plumbing devices. Likewise, Núñez et al. (2010) and Tello and Ostos (2012) highlight that the presence of swimming pools, bathrooms at home, shower facilities and public baths have a facilitating effect on water consumption. Moreover, Pincetl et al. (2014) found that the presence of a pool is correlated with higher electricity consumption levels and they also mention (extensive) presence of home appliances and air-conditioning as potential explanations for increased electricity usage.

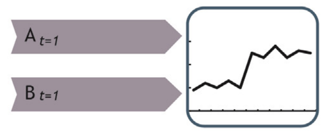
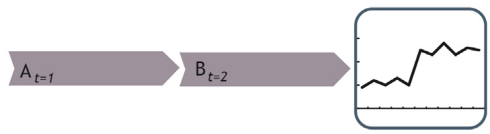
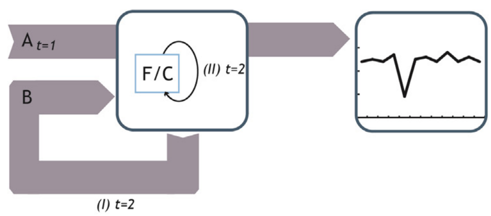
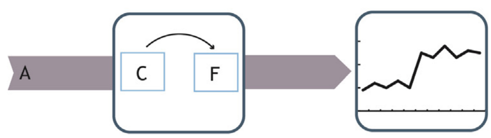
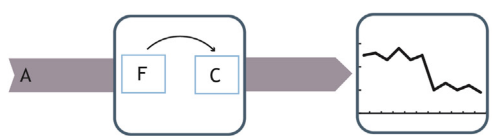
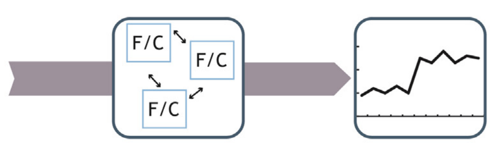
4.2.2.3. Resource characteristics. The characteristics of what is consumed can also facilitate or constrain consumption. Three such characteristics are indicated in the UM literature: the price, availability and quality of the resource. The effect of the resource price on consumption is analysed in five studies, with as common finding an inverse relationship between consumption and price (Athanassiadis et al., 2017a; Gingrich et al., 2012; Kim and Barles, 2012; Stergiouli and Hadjibiros, 2012). Sahely et al. (2003) only state that "fluctuations in the price of natural gas might have affected usage patterns". Three publications indicate that greater water availability can facilitate consumption (Gorostiza et al., 2015; Renouf et al., 2018; Tello and Ostos, 2012). Mehta et al. (2013) provide an example where limited availability constraints consumption. In Bangalore the supply network did not keep up with the growing demand from a growing population, consequently the outer districts that experienced very fast population growth are least served by the water utility. The finding that these areas have the lowest average water use in terms of litres per capita per day actually thus reflect that water availability, rather than demand, is very low here (Mehta et al., 2013). Gorostiza et al. (2015) indicate that not only greater water availability but also improved quality of the water can explain the doubling of the water consumption in Madrid in 1900–1920, which both resulted from expansion and improvement of the supply network.

4.2.2.4. Consumer characteristics. Finally, the characteristics of consumers and their context influence consumer behaviour and in doing so influence consumption patterns. In general the role of consumer characteristics receives little attention in the UM literature, but the literature does mention two factors related to personal characteristics – income level and lifestyle – one to social context - household size - and one to decision making – behaviour. The factor income level is the most commonly studied consumer characteristic. Six case studies found a relationship between higher consumption levels and higher income levels (Ariza-Montobbio et al., 2014; Athanassiadis et al., 2017b; Domene et al., 2005; Hall, 2011; Pincetl et al., 2014; Porse et al., 2016). The facilitating effect of a higher income level is also emphasized in the meta-study by Pincetl and Newell (2017) and in the review by Weisz and Steinberger (2010). The first study concludes that in the case of Los Angeles "affluence is the most important driver" of both electricity and water consumption (Pincetl and Newell, 2017). Based on their review, Weisz and Steinberger (2010) point out that it is not just the income level that is of importance but rather the high income lifestyle is the factor to blame for high energy use in urban areas. Also Hall (2011) indicates that such a lifestyle can facilitate consumption: wealthier neighbourhoods in Syracuse have a higher energy use at home per residence and per capita and use more energy for their vehicles because more people own a SUV. Ariza-Montobbio et al. (2014) point in the direction of a 'lifestyle characterized by consumerism in low-density urban sprawl', to explain the higher average electricity consumption in suburban towns. In these areas, they found higher income levels and a smaller household size. According to Weisz and Steinberger (2010), earlier studies also found a negative correlation between household size and per capita household energy use. Finally, Renouf et al. (2018) mention the relationship between behaviour and water consumption. They stress that lower water usage in Brisbane, compared to Melbourne and Perth, can in part be explained by behaviour change embedded in a preceding period of drought when water use restrictions were enforced.

4.3. Interconnectedness of factors

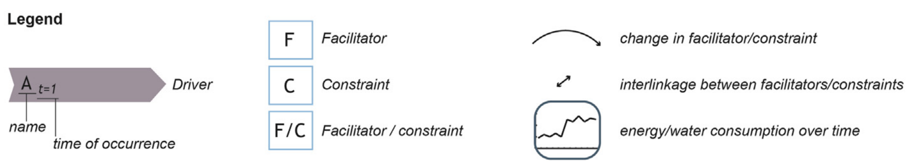
The literature reveals not just individual drivers and facilitators/constraints that affect consumption, but also discloses examples of interconnected factors that jointly influence consumption. Examples of the relationships *between drivers* demonstrate that the interconnectedness of these factors can be reduced to (a combination of) three types of relationships, namely (1) simultaneous developments, (2) effect chains and (3) response mechanisms (Table 4). These relationships differ based on at what time drivers occur relative to one another. Whereas some examples were found of the simultaneous presence of two drivers (#1, Table 4), most examples describe how drivers happen in succession (#2 and #3, Table 4). Some of these successions are a relatively straightforward effect chain of two drivers. For instance, after the end of the Greek civil war (driver A) a time of population growth (driver B) in Athens followed and subsequently water consumption increased (Stergiouli and Hadjibiros, 2012). Other interconnections are more complex, such as response mechanisms that cross various spatial scales. One such example is how the world-wide oil crisis in the 1970s (driver A) brought about political responses at national and city level, such as planning and policy interventions (driver B)

Table 4
Six different types of relationships identified between factors.

Type of relationship	Schematic representation of relationship	Examples
1. Simultaneous developments Two drivers, A and B, are present at the same time (t=1), with both a similar increasing or decreasing effect on consumption.		In times of both increasing population size (A) and economic development (B), an increase of total consumption occurs. (Gingrich et al. 2012; Tello and Ostos 2012)
2. Effect chain Driver A (t=1), triggers a change in context B that subsequently manifests as a driver itself (at t=2) and affects consumption.		A crisis (A) triggers demograohic change (B), which leads to an increase or decrease in total consumption. (Gorostiza et al. 2015; Stergiouli and Hadjibiros 2012)
3. Response mechanism Driver A (t=1) triggers a deliberate response that aims to steer away from undesirable resource consumption patterns that may result from driver A. The response (t=2) can either be: (I) interventions in context B that subsequently manifests as a driver, or (II) adjustments to urban or resource characteristics (F/C).		Political interventions (B) and adjustments to the resource price (F/C) in response to a crisis or drought (A). (Gorostiza et al. 2015; Kalmykova et al. 2016; Kim and Barles 2012; Pincetl et al. 2014; Renouf et al. 2018; Stergiouli and Hadjibiros 2012; Swaney et al. 2012)
4. Prerequisite condition Driver A is prerequiste to be able to remove/adjust characteristics that act as a constraining factor (C). Hence, after this change in context A and subsequent adjustments from constraining to facilitating factors (F), consumption increases.		Technological inventions (A) that enable the construction of higher pressure pipelines, a prerequisite for expansion of the supply system (C->F). After expansion, total water consumption increases. (Swaney et al. 2012)
5. Curtailing condition After a change in context (driver A), urban/consumer/resource characteristics that were not a constraint before (F), now become a limiting factor (C) and consumption stabilizes or decreases as a result.		If population size increases (A) but expansion of the water supply network lags behind on this, water availability and the network size become a constraint (F->C). (Mehta et al. 2013; Tello and Ostos 2012)
6. Interlinked characteristics Different facilitators and constraints (F/C) are interlinked and thus jointly influence consumption.		Differences in consumption between poorer and wealthier neighbourhoods can be related to dissimilar building age and size (F/C) and income-levels (F/C). (Pincetl & Newell 2017; Porse et al. 2016)

Note
These relationships and examples thereof are highly simplified representations of reality and should be interpreted accordingly.

Legend



(Kalmykova et al., 2016; Kim and Barles, 2012). So, drivers can occur both simultaneously and in succession, and one driver can both trigger another driver unintentionally and as intentional response.

Furthermore, three types of relationships *between drivers* and *facilitators/constraints* were identified. A prerequisite and curtailing condition (#4 and 5, Table 4) both signify how a driver can unintentionally initiate changes in urban, resource and/or consumer characteristics. In addition, a response mechanism (#3, Table 4) does not necessarily only comprise two drivers, but it can also involve deliberate changes in facilitating/constraining urban or resource characteristics. An example of this kind of response mechanism is supply network expansion (F/C) in response to

Table 5
Examples of interlinked characteristics.

	Infrastructural characteristics	Consumer characteristics
Spatial characteristics	In Los Angeles, buildings built before 1950 have the highest median annual consumption per square-foot, but buildings built 1980–2000 consume more energy than those built between the 50s and 80s (Porse et al., 2016). Pincetl et al. (2014) indicate that this is probably the result of other characteristics at building level such as building size and presence of appliances. Domene et al. (2005) point out that the suburban housing typology in the Barcelona Metropolitan Region often also comes with gardens and swimming pools and that these factors enhance outdoor water consumption.	Ariza-Montobbio et al. (2014) mention as explanation for the higher average consumption of electricity per household in suburban towns the spatial factors density, building type and size and the characteristics of the consumers living there, namely income level, lifestyle, and household size. Likewise, in their analysis of energy consumption in Los Angeles, Porse et al. (2016) stress that population density is correlated with income level. Porse et al. (2016) and Pincetl and Newell (2017) also indicate that spatial variation in energy consumption in L.A. is not only linked to the income level of the different neighbourhoods, but also to the differences in building size and age between poorer and wealthier neighbourhoods. Also Weisz and Steinberger (2010) indicate that high income is correlated with higher per capita floor space. Pincetl and Newell (2017) and Domene et al. (2005) indicate that houses in comparatively wealthy areas have a different garden typology, with a higher water demand, than lower income households.
Infrastructural characteristics	–	According to Ariza-Montobbio et al. (2014), a higher proportion single-person household leads to an increasing number of appliances, which contributes to the higher electricity consumption with smaller household size.
Resource characteristics	Kim and Barles (2012) and Gingrich et al. (2012) discuss how the shift in supply routes from river to railway reduced transport costs in 19th century Europe, making coal more affordable	Pincetl et al. (2014) found that lower-income residents who pay less for water than the next tier conserve more water than those paying more for their water.

increasing population size (driver A) (Swaney et al., 2012; Tello and Ostos, 2012; Barles, 2007; Gorostiza et al., 2015). When there is no such accurate response, and the size of the supply network does not keep up with the growing demand from a growing population (driver A), resource availability can become a constraint to consumption. Mehta et al. (2013) illustrate such a curtailing condition (#5, Table 4) in the case of water consumption Bangalore. By contrast, in case of a prerequisite condition (#4, Table 4) a driver can work as an enabler: making it possible to change constraining factors into facilitating ones. For example, technological inventions such as trains and railways, played an enabling role in the energy transition from fuel wood to coal. These inventions (driver A) were a prerequisite to overcome the constraints of the former supply network, which was based on roads and waterways; railway routes enabled access to energy supply areas that could not be reached until then (Gingrich et al., 2012; Kim and Barles, 2012).

Finally, the literature provided various examples of *interlinked urban, resource and/or consumer characteristics* (#6, Table 4). This type of relationship implies that different facilitating/constraining factors are connected and present simultaneously, making it difficult to discriminate what the effect of each individual factor is. Examples of all sorts of interlinked characteristics were found in the literature, with the exception of interlinked spatial and resource characteristics (Table 5). Most examples of interlinked facilitators/constraints comprised interconnected spatial and consumer characteristics.

5. Discussion

5.1. Robustness of the synthesis

This systematic literature review shows that the evidence-base of the UM field that analyses the factors influencing urban water and/or energy consumption is still thin. More case studies are needed to deepen our understanding of those factors. As our review revealed that this body of UM literature consists primarily of research on mature cities in the global north and in temperate climates (see Fig. 3), future empirical work with case studies in other contexts is needed. The overview of factors (Table 3) and their effects presented here should thus be interpreted with caution; this paper provides neither a complete indication of factors of influence nor a conclusive indication of their effects. Rather, this paper gives an overview of the factors and effects that the existing UM literature addresses. As such it serves as a starting point for future theoretical and empirical work. The overview allows for informed decisions on which factors to study and at the same time recognise upfront which other factors might be at play. Future case studies should improve the overview presented here by also studying potential factors of influence that hitherto have not been researched in the UM field. To identify these factors, as well as the needs of consumers, the work of the various disciplines that aim to understand the roots of consumption (Poças Ribeiro et al., 2019) may prove valuable. Likewise, it is relevant to examine the explanatory variables used in water and energy demand models, for example those presented for water in the review by House-Peters and Chang (2011). Useful input could also be provided by the body of research investigating how urban form affects urban energy consumption, especially for future case studies aiming to further understand the facilitating and constraining role of spatial characteristics (Seto et al., 2014; Wiedenhofer et al., 2013). Future research can thus not only strengthen the evidence for the factors presented here, but it can also provide insight in additional factors of influence and build a more comprehensive overview of factors.

5.2. Unification in terminology and methodology

Aligning future research is essential to build such a comprehensive overview. Unification in terms of terminology and methodology will facilitate comparison of findings from different case studies. The observed lack of consistency among empirical studies is a known challenge within the UM field (Beloin-Saint-Pierre et al., 2017). In general, the reviewed work lacks clear – and widely accepted and used – definitions and consistent terminology. Moreover, the work varies in type of supporting evidence provided. In part, this is due to the heterogeneous sample; the primary studies included in the review are diverse in research design and spatiotemporal resolution of analysis (see Fig. 4). Yet, we would argue that this heterogeneity should *not* be a reason to disregard certain research designs. After all, the review shows that different types of research provide complementary evidence on drivers and facilitators/constraints of consumption. Nevertheless, efforts are needed to unify how factors of influence are measured. A promising development in this regard is that multi-year flow analyses, which have been criticized for not using indicators to support their findings (Pincetl et al., 2012), are developing into trend analyses that use indicators to explain temporal differences. Another, next step would be to develop a common indicator set to unify the measurement of factors of influence, in terms of indicators and their units of measurement – building upon existing work by e.g. Kennedy et al., (2014) and Minx et al., (2011). Such an indicator set should, for example, clarify whether building size refers to the size of the building footprint or to the combined gross or net floor area on all storeys. Likewise, it should indicate whether to express the factor ‘climate’ with the ‘average temperature of the warmest and coldest month in degrees Celcius’ (Minx et al., 2011) or using heating degree days (HDD) and cooling degree days (CDD), as proposed by (Kennedy et al. (2014)). Together with the overview of factors and their effects, such an indicator set could be the basis for a unified approach to identifying correlations that facilitates comparability across case studies and research designs.

5.3. Data quality assessment

Our review not only reveals the need for more and aligned case studies, but it also highlights that more attention should be given to the quality and transparency of the data set used in these studies. During the quality assessment step in the review process, 19% of the publications were excluded because they were unclear about the resolution of data used and another 14% were excluded because water and energy consumption figures relied on downscaled data. Also other recent reviews of the UM literature highlight these data quality issues. According to Beloin-Saint-Pierre et al. (2017) about 9% of their primary studies “did not offer enough info to identify category of data used” and they state that as much as 65% of overall UM studies relies on downscaled data. Li and Kwan (2018) stress that “coherence and quality assurance call for more serious attention”. That said, overcoming the data gaps that exist when it comes to high-resolution case studies is a common struggle within the field that cannot be solved overnight (Porse et al., 2016; Voskamp et al., 2018). The first step to advance the field in this regard should thus be to increase transparency of the type of data used. Patricio et al. (2015) and Hoekman and von Blottnitz (2017) are valuable precedents in this regard, formulating assessment frameworks to assess the resolution, accuracy and reliability of the data underlying their case studies.

5.4. The potential of UM research to advance our understanding of cities

It still remains problematic to determine the precise causes of particular resource use patterns (Hoekman and von Blottnitz, 2017). One of the challenges is that analysing the relationship between consumption and a single factor implies identifying *correlations*, rather than identifying *cause-effect relationships.* Moreover, our findings raise the question at what level of analysis, and to what extent, consumption patterns can be attributed to individual factors present. Although our review revealed generally a prevalent effect direction for a given factor (i.e. increasing or decreasing consumption), it foremost showed no universal “factor-consumption relationships”. Our synthesis shows “factor-consumption relationships” that are subject to exceptions - cases where factors show a negative instead of commonly found positive correlation with consumption, or vice versa - as well as relationships that vary greatly in intensity or those that are inconsistent over different scale levels (see e.g. Athanassiadis et al., 2017a,b). These exceptions support the notion that consumption patterns cannot be attributed to individual factors present, and that the influence of the interconnections between factors (see Table 4) on the direction and magnitude of effects should be considered. Hence, to get more insight into the causes of consumption, further research is needed aimed at understanding the interconnectedness between factors and how these interconnections affect “factor-consumption relationships”. In this regard, we think it is especially relevant to connect with urban ecological research that aims to understand the interactions, relationships, and feedbacks of system components (McPhearson et al., 2016b). We deem this not only essential in the pursuit to better understand the effect of the interconnectedness of factors, but also agree with Bai (2016) that UM research needs to connect consciously with the theory and conceptual approaches of urban ecological research to realize its full potential in advancing our understanding of cities.

Although UM research relies upon several of the principles for conceptualising urban areas as complex social-ecological-technological systems [i] (McPhearson et al., 2016b), hitherto there is a general absence of clear and explicit conceptual approaches as starting point for these studies. Studying cities as social-ecological-technical systems offers a conceptual basis to synthesize insights from different disciplines (Bai et al., 2016) and UM research can have a valuable contribution to this common understanding of cities, complementary to urban ecological research and complex adaptive systems science (McPhearson et al., 2016b). Bai (2016) indicates that this contribution lies, among others, in improving our understanding of (I) the influence of spatial heterogeneity within cities and (II) the processes and mechanisms behind temporal differences and variation among different cities. Indeed, our findings demonstrate this potential of UM research. We found that spatial patterns house other, interlinked factors that jointly facilitate or constrain consumers in their resource consuming activities (see Table 5). Likewise, the drivers and their interactions with facilitators/constraints that we identified (see Table 4), reveal some of the processes and mechanisms behind temporal and intercity variation.

6. Conclusions

This systematic review demonstrates that a growing number of UM publications aims to provide insight in the factors that underlie spatiotemporal variability in urban water and energy consumption patterns. The diversification of this body of literature in terms of study design contributes to a more complete understanding of the factors of influence, because each design has a unique spatiotemporal resolution of analysis and thereby provides insight in specific sorts of factors. Overall, our review revealed twenty-one *facilitators/constraints* and fourteen *drivers* that affect urban water and/or energy consumption. We conclude that case-specific consumption patterns cannot be attributed solely to the effect of individual factors present, because these factors are interconnected in time and space. These interconnections can potentially influence the direction and magnitude of effects and thereby contribute to case-specific variability in consumption patterns. It is key to connect

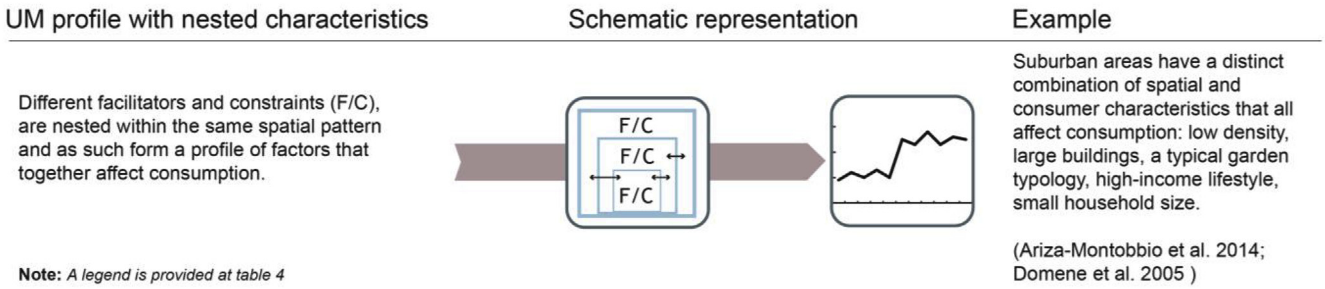


Fig. 5. An Urban Metabolism Profile consists of nested facilitators/constrains, with a combined influence on consumption.

with related disciplines to deepen our understanding of these interconnections among urban system components and their effects on UM. A common systems approach to studying urban systems can inform and advance UM research, whilst also providing the opportunity for UM research to make a valuable contribution to understanding the systemic characteristics of cities. Our findings confirm that UM research has the potential to provide insight into the influence of spatial heterogeneity on urban water and energy consumption patterns, as well as to reveal the mechanisms and interlinked processes that underlie the spatiotemporal variability in consumption. More case studies can strengthen the evidence for the factors presented here, and contribute to building a more comprehensive overview of factors by providing insight in additional factors of influence. It is essential to align these studies in terms of a common terminology, transparent quality assessment and a unified approach to measuring and expressing factors of influence.

7. Outlook

We acknowledge that a thorough understanding of the interconnectedness of urban system components and its effects on UM is a long-term effort that requires tailoring UM research designs in the near future. We suggest that research on UM profiles on the short term can inform our understanding of the characteristics and behaviour of cities as social-ecological-technological systems in the long-term. Specifically, we suggest identifying UM profiles based on spatial patterns that represent a specific combination of interlinked and nested facilitators/constraints that have a combined influence on consumption patterns (see Fig. 5). Various primary studies indicate this nested character of facilitators/constraints in spatial patterns, including examples from the suburban neighbourhoods in Barcelona metropolitan region (Ariza-Montobbio et al., 2014; Domene et al., 2005) and the different neighbourhoods in the metropolitan area of Los Angeles (Pincetl and Newell, 2017; Porse et al., 2016). Likewise, Thomson and Newman (2018), recently demonstrated that different parts of a city - the automobile, transit and walking urban fabric - differ in terms of their UM. They suggest that the UM of these areas is determined by their distinct urban form and affiliated characteristics that are typical for the time of development, including density, land use, spatial layout and transportation system. In addition to such research on intra-city variation, developing a typology of cities based on (dis) similar consumption patterns can be valuable. It can provide insight into characteristics that are of distinctive importance for the UM profile at city level. So far, UM profiles at city level have been identified based on level of economic development and economic specialisation (Ariza-Montobbio et al., 2014; Currie and Musango, 2017; Rosado et al., 2016). Other suggested distinctive characteristics include city size and urbanization dynamics depending on a city's level of maturity (Seto et al., 2014; Weisz and Steinberger, 2010; Kennedy et al., 2007). Gaining more insight into the relative importance and combined effect of factors is an essential first step to unravel the interlinkages between factors within an UM profile and to understand the cause-effect relationships that underlie specific consumption patterns.

Finally, establishing UM profiles can be a vital step in tailoring UM research towards informing sustainable resource management. After all, different UM profiles may require different interventions to steer towards more sustainable consumption patterns. Therefore, it is not only relevant to investigate how prevailing system characteristics and societal organization are linked to the *current* UM of a city, representing so-called “social-ecological regimes” (Barles, 2015; Haberl et al., 2004). Rather, it is valuable to formulate scenarios of a *desirable* UM and the corresponding context and system characteristics, as well as the plans that aim to steer towards this scenario. Detailing such plans would entail describing what kind of changes in context, i.e. drivers, can be anticipated and identifying which ones are (un)desirable. This allows for identifying the interventions that can help steer these changes towards the desirable scenario, either by targeting those drivers directly or indirectly, through altering facilitating or constraining factors. These interventions are intrinsically linked to different stakeholders: local governments, for example, can formulate policies; utilities can make decisions that affect infrastructure and resource characteristics; and planning and design professionals can suggest altering spatial characteristics. In this regard, it might be relevant to discriminate factors of influence into endogenous ones that are within the sphere of influence of a stakeholder and those that are not, the exogenous ones. This may give resource managers an idea with whom to collaborate to target factors that are outside their own sphere of influence and to account for factors that should be considered a boundary condition, such as lifestyle and income of a consumer. Ideally, when the interlinkages and embeddedness of the factors in a UM profile are acknowledged, this will give an idea which stakeholder is able to contribute in what way to sustainable resource management in a specific context.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.120310.

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