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Space-time information analysis for resource-conscious urban planning and design: A stakeholder based identification of urban metabolism data gaps

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ABSTRACT

The research presented here examined at which spatial and temporal resolution urban metabolism should be analysed to generate results that are useful for implementation of urban planning and design interventions aiming at optimization of resource flows. Moreover, it was researched whether a lack of data currently hampers analysing resource flows at this desired level of detail. To facilitate a stakeholder based research approach, the SIRUP tool – *"Space-time Information analysis for Resource-conscious Urban Planning"* – was developed. The tool was applied in a case study of Amsterdam, focused on the investigation of energy and water flows. Results show that most urban planning and design interventions envisioned in Amsterdam require information on a higher spatiotemporal resolution than the resolution of current urban metabolism analyses, i.e., more detailed than the city level and at time steps smaller than a year. Energy-related interventions generally require information on a higher resolution than water-related interventions. Moreover, for the majority of interventions information is needed on a higher resolution than currently available. For energy, the temporal resolution of existing data proved inadequate, for water, data with both a higher spatial and temporal resolution is required. Modelling and monitoring techniques are advancing for both water and energy and these advancements are likely to contribute to closing these data gaps in the future. These advancements can also prove useful in developing new sorts of urban metabolism analyses that can provide a systemic understanding of urban resource flows and that are tailored to urban planning and design.

1. Introduction

The notion of urban metabolism (UM) has inspired new ideas about how cities can be made sustainable and it has fostered quantitative approaches to the analysis of urban resource flows (Agudelo-Vera et al., 2012; Castán Broto et al., 2012; Zhang, 2013). 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). UM can be traced back to Marx in 1883, who used the term metabolism to describe the exchange of materials and energy between society and its natural environment (Pincetl et al., 2012; Zhang, 2013). In 1965 Wolman re-launched the term as he presented the city as an ecosystem, and later others also used the term UM in representing a city as an organism (Barles, 2010 Castán Broto et al., 2012; Pincetl et al., 2012; Zhang, 2013). Since Wolman's early study of urban metabolic processes, two distinct quantitative UM approaches have developed that aim to describe and analyse the material and energy flows within cities. One describes the UM in terms of solar energy equivalents ('emergy'). Related school of scholars emphasizes the earth's dependence on the sun as an energy source and the qualitative difference of mass or energy flows. The second and most widely used approach, is associated with the fields of industrial ecology and engineering (Barles, 2010; Castán Broto et al., 2012; Pincetl et al., 2012). Related research largely consist of empirical studies that account for the energy and

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material/mass flows of a city, using methods such as material flow analysis (MFA), mass balancing, life cycle analysis (LCA) and ecological footprint analysis (Castán Broto et al., 2012; Kennedy et al., 2011; Pincetl et al., 2012; Zhang, 2013).

Multiple scholars have argued that the latter type of UM analyses, the flow quantifications associated with the mainstream UM approach, are useful for urban planning and design (Castán Broto et al., 2012; Chrysoulakis et al., 2013; Kennedy et al., 2011; Moffatt and Kohler, 2008; Pincetl et al., 2012). However, these authors also argue that major efforts are still needed to make UM analyses useful for informing urban planning and design aiming at optimization of urban resource flows (Kennedy et al., 2011). Indeed, only three examples of application of UM for designing more sustainable urban infrastructures are referred to in literature (Codoban and Kennedy, 2008; Oswald and Baccini, 2003; Quinn, 2008), of which just one is a peer-reviewed article.[1] The only recent scientific contributions on this topic all discuss the planning support system developed in the BRIDGE project (Blecic et al., 2014; Chrysoulakis et al., 2013; Mitraka et al., 2014). In professional literature, some other recent examples can be found. In the Netherlands, research on the resource flows of Rotterdam was conducted and used as a basis for urban design strategies, in the context of the International Architectural Biennale 2014 *Urban by Nature* (Tillie et al., 2014). In the *Circular Buiksloterham* project in Amsterdam an 'Urban Metabolism Scan' was performed and used as foundation for a vision for the Buiksloterham area, including site-specific technical interventions and a design concept (Gladek et al., 2015). So, although the theoretical potential of UM analysis for urban planning and design is increasingly addressed in the scientific literature, scientific reports that illustrate how this potential can be realised with practical implementation remain limited thus far.

Possibly, UM analyses are still of limited use for urban planning and design because they are performed on a scale level that does not match urban planning and design practice (Moffatt and Kohler, 2008; Pincetl et al., 2012; Spiller and Agudelo-Vera, 2011). The UM is usually analysed for a period of a year on city or regional scale (Kennedy et al., 2011; Niza et al., 2009); analyses on a more detailed level are said to be hampered by lack of data (Codoban and Kennedy, 2008; Pincetl et al., 2012; Shahrokni et al., 2015). Such large-scale analyses, however, do not reveal which metabolic processes and functions are operating at various spatial and temporal scales. Yet, planners and designers need such information to decide upon the appropriate interventions to realize a resource-conscious strategy. In other words, they need this information to inform their planning and design decision-making regarding interventions aimed at urban climate adaptation, climate mitigation and/or resource efficiency. To be useful for urban planners and designers, UM analyses should thus provide detailed and spatial and temporal explicit data on the scale at which these practitioners work (Chrysoulakis et al., 2013; Golubiewski, 2012; Moffatt and Kohler, 2008; Pincetl et al., 2012; Vandevyvere and Stremke, 2012).

Therefore, the study presented here aims to answer the following questions: (a) "at which spatial and temporal resolution should resource flows be analysed to generate results that are useful for implementation of urban planning and design interventions?" and (b) "is UM analysis at this desired level of detail currently hampered by a lack of data?". To answer these questions the *"Space-time Information analysis for Resource-conscious Urban Planning"* (SIRUP) tool was developed and applied in a case study of the city of Amsterdam, the Netherlands. The SIRUP tool enables an analysis on two levels: I) assessing on which level of detail in space and time stakeholders need information on resource flows to inform urban planning and design decision-making aimed at developing resource-conscious strategies, and II) evaluating whether existing data can provide the information needed or that there is a data gap. The qualitative tool facilitates information and knowledge sharing and discussion between stakeholders. Stakeholder involvement in UM research is essential to leverage availability of and access to urban resource data and it allows identifying the information needs of urban planning and design practitioners (Voskamp et al., 2016; Zhang et al., 2015).

2. Methods and materials[2]

2.1. Development of the SIRUP tool

The *"Space-time Information analysis for Resource-conscious Urban Planning"* (SIRUP) tool is based on the work of Vervoort et al. (2014), who developed the tool *Scale Perspectives* to elicit societal perspectives and generate dialogue on governance issues. Their tool consists of a frame with pre-defined spatial and temporal scales in which stakeholders can outline the relevant scales for a particular governance issue. For the SIRUP tool, this frame is adapted for the purpose of identifying on which spatiotemporal resolution stakeholders need information on resource flows and for assessing whether existing data can provide this information on the resolution needed (Supplementary material, Fig. S1). The SIRUP tool is applied in four steps (Fig. 1). These steps aim to (I) generate an inventory of UM interventions, (II) determine the information needed for implementing each of these interventions, (III) describe the spatiotemporal resolution of existing data relevant for the intervention and (IV) identify whether the resolution of identified data can satisfy the stakeholders' intervention information needs.

2.2. Application of the SIRUP tool

The SIRUP tool was applied in a case study of Amsterdam. As part of this case study, stakeholders were involved that are engaged with urban planning and design decision-making aimed at developing resource-conscious strategies for the city of Amsterdam. The stakeholders comprised researchers, environmental managers from utilities, landscape architects and urban planning & design practitioners. Eleven of these stakeholders were interviewed, using semi-structured interviews, and thirteen stakeholders participated in a workshop.

Step I and II of the SIRUP tool were used to identify on which spatiotemporal resolution stakeholders need information on resource flows. In step I, the stakeholders were asked to describe a resource-conscious intervention that they envision to be implemented in Amsterdam. Participants were also asked to specify in the SIRUP frame (Supplementary material, Fig. S1) at which spatial scale level the intervention would take places and which time frame they envisioned for implementation. In step II, participants were asked to specify the information needed for implementing the intervention mentioned and to indicate the required spatial and temporal resolution of this information in the SIRUP frame (Fig. 1). The interviewer or workshop facilitator had to ensure that participants described the information on resource flows that is necessary to enable the intervention. Pen-and-paper format was used because this allows for greater flexibility than a digital setting (Vervoort et al., 2014). After the workshop, all contributions were digitalized and labelled to enable the selection of interventions that are within the scope of the research. The interventions were labelled according

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[1] Although Codoban and Kennedy (2008) were the first to refer to Oswald and Baccini (2003) in this light, Kennedy et al. (2011) were the first to mention all three examples.

[2] A more elaborate description of the method is provided as Supplementary material (S1. Elaborate description of methodology).

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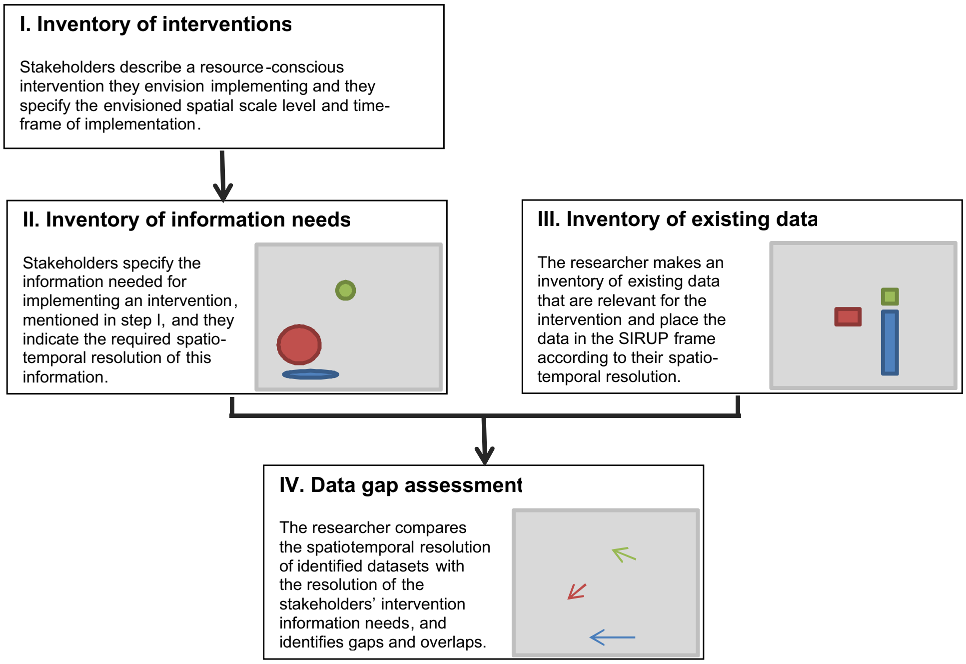

I. Inventory of interventions

Stakeholders describe a resource-conscious intervention they envision implementing and they specify the envisioned spatial scale level and time-frame of implementation.

II. Inventory of information needs

Stakeholders specify the information needed for implementing an intervention, mentioned in step I, and they indicate the required spatio-temporal resolution of this information.

III. Inventory of existing data

The researcher makes an inventory of existing data that are relevant for the intervention and place the data in the SIRUP frame according to their spatio-temporal resolution.

IV. Data gap assessment

The researcher compares the spatiotemporal resolution of identified datasets with the resolution of the stakeholders' intervention information needs, and identifies gaps and overlaps.

Fig. 1. The four steps of the SIRUP tool.

Note: The figure includes as subfigures a schematic representation of the potential outcome of the different steps. The green, red and blue circles/ellipses, rectangles and arrows represent respectively three different information needs, existing data sets and data gaps for a single intervention on the SIRUP frame (in grey). See also Supplementary material S1: Elaborate description of methodology.

to the type of intervention and the resource flow(s) for which information is needed. We limited the research to spatial and technical interventions aimed at urban climate adaptation, climate mitigation and/or resource efficiency, focussing on energy and water flows because these are strongly related to such interventions (Mitraka et al., 2014; Pincetl et al., 2012) (see also Supplementary material S1. Elaborate description of methodology).

In step III a desk study was conducted to identify which data exist on Amsterdam's energy and water flows and to compose an overview of these data, including a description of the spatiotemporal resolution of these data. In the study, data portals, databases and reports were considered that contain open or restricted data on Amsterdam's energy and water flows. Expert consultation was used to identify relevant datasets and to obtain access to restricted datasets. Metadata was described for all datasets obtained, using a format that was based on the ISO 19115 and the INSPIRE (Infrastructure for Spatial Information in the European Community) metadata standards to ensure compatibility with other datasets in the world. The mandatory elements of the metadata standard used were, amongst others, the level of detail of the data in the spatial dimension and in the time dimension, i.e. the spatial and temporal resolution of the data. Moreover, it was required to state the limitations and rules on accessing, use and publishing of the existing data to indicate whether the data is open or restricted (Supplementary material, Table S1). Based on the metadata-description on spatial and temporal resolution, the datasets were placed in the SIRUP frame (Fig. 1).

In the final step, step IV, the data inventory was used to analyse whether the identified data can satisfy the stakeholders' information needs. For each intervention it was evaluated whether the attributes of each data set were relevant for the information needed. Then, the relevant data and the information needs for the intervention were combined in one SIRUP frame and arrows were drawn from the dataset to the information needed (Fig. 1). When the spatiotemporal resolution of information needs are equal to the resolution of existing data, these exact matches were indicated by a circle (◯) in the SIRUP frame. Subsequently, the size and dimension of the arrows were analysed to assess the presence and severity of data gaps. An arrow either indicates a two-dimensional data gap, when both the spatial and temporal resolution of existing data are insufficient, or it indicates a one-dimensional data gap, when either the spatial or the temporal resolution of existing data is lower than required. A two-dimensional data gap is indicated by arrows pointing towards the lower left corner (↙). Arrows pointing downwards or to the lower right corner (↓,↘) indicate a one dimensional data gap, in the spatial dimension only. The reason for this is that the arrows indicate that the temporal resolution is equal to or higher than needed. Because aggregation from higher temporal resolution to lower resolution is possible without an information loss, the required temporal resolution can be derived from this information. For example, hourly totals can be derived from data on minute level by summing all available minute data points. Arrows pointing to the left or higher left corner (⟵,↖) represent a gap in the temporal dimension only, because the spatial resolution of the data is sufficient or higher than needed. There is no data gap when existing data has either the right resolution in one dimension and a higher resolution in the other or a higher resolution in both dimension, implying that data can be aggregated to get to the required resolution. These matches are indicated by arrows pointing up (↑), to the right (→), or diagonally in the upper right direction (↗).

3. Results

3.1. Inventory of interventions

In this case study a total of 52 different interventions were suggested by the stakeholders during the interviews and workshop. We selected fourteen of these interventions for further analysis, namely the spatial and technical interventions for which information on energy and/or water flows is required. The selected interventions have a total of 26 information needs that relate to energy and/or water flows. These information needs were cate-

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Table 1
The 14 interventions and 26 related information needs that were considered in this research.

	Information needs													
	Piped water			Non piped water				Energy demand				Energy supply		
Interventions and intervention ID (#)	Drinking water quantity	Waste water quantity	Waste water quantity	Fluvial flooding risk	Groundwater quantity	Groundwater quality	Intensity and repeat time of extreme rains	Surface water level and flow rate	Household cooling demand	Electricity demand of public lighting	Total urban electricity demand	Cooling supply by drinking water network	Electricity supply in a regional smart grid	Potential electricity supply by PVpanels
1 Converting cellulose in waste into power	–	–	–	–	–	–	–	–	–	–	I	–	–	–
2 Dike reinforcement	–	–	–	–	–	–	–	I	–	–	–	–	–	–
3 More concentrated sewage flows	–	I	I	–	–	–	–	–	–	–	–	–	–	–
4 Park on a brownfield site	–	–	–	–	II	I	–	–	–	–	–	–	–	–
5 Parking garage as battery	–	–	–	–	–	–	–	–	–	–	I	–	–	–
6 Phytoremediation of green areas	–	–	–	–	II	II	–	–	–	–	–	–	–	–
7 PVs on roofs for public lighting	–	–	–	–	–	–	–	–	–	I	–	–	–	I
8 Rainwater buffering and infiltration	–	–	–	–	–	–	I	–	–	–	–	–	–	–
9 Recovery of protein from sewage	–	I	I	–	–	–	–	–	–	–	–	–	–	–
10 Regional smart grid	–	–	–	–	–	–	–	–	–	–	I	–	II	–
11 Small-scale parks	–	–	–	I	–	–	–	–	–	–	–	–	–	–
12 Usage of cold from drinking water for cooling	I	–	–	–	–	–	–	–	I	–	–	I	–	–
13 Water-robust vital infrastructure	–	–	–	–	–	–	–	II	–	–	–	–	–	–
14 Water square	–	–	–	–	–	–	I	–	–	–	–	–	–	–

Note: '–' means that no information need is expressed in the corresponding category for the indicated intervention.
"I" means that one information need is expressed in the corresponding category for the indicated intervention.
'II' means that two information needs are expressed in the corresponding category for the indicated intervention.

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gorized into four different clusters to facilitate interpretation: I) piped water, including waste water and drinking water; II) non-piped water, including groundwater, surface water, storm water and rainwater; III) energy demand; and IV) energy supply (Table 1).

3.2. Piped water

Results show that out of the five information needs related to piped water, two can be met by existing open data and one by restricted data (Fig. 2). Fig. 2a shows that the information needs that were expressed for piped water are scattered over the SIRUP frame. However, no information needs appear in the lower left corner of the frame, up to 12 h and district, nor at the highest scale levels, that is metropolitan region and five years and higher. The SIRUP frame of existing data, on the other hand, shows a different pattern (Fig. 2b). In terms of temporal resolution, these data fall in the range 'minutes' to 'one year'. In terms of spatial resolution, open data ranges from the scale of a small neighbourhood to the metropolitan region. Additionally, one restricted access database provides drinking water quantity data on building level. No piped-water data has been identified that has both high temporal and spatial resolution. When the resolution of information needs and existing data are compared, it appears that two information needs can be met: I) the quantity and II) the quality of waste water that enters Amsterdam's waste water treatment plants at seasonal up to yearly level (indicate as ◯, Fig. 2c). For the remainder of the data gaps, it shows that the size and dimension of the gaps depend on which existing data source is considered. The drinking water data gaps, for instance, are either two dimensional (↙), using dataset 3, or with a spatial dimension only (↓,↘), when using the open data from source 4 or 6. Yet, with access to restricted datasets, there is a data gap with a temporal dimension only (⟵). Nevertheless, when using the restricted data, the size of the gap in the temporal dimension remains the same as when dataset 3 is used, from 'one year' to 'month'. On the other hand, restricted data can close the data gap regarding waste water quantity at municipal and minute level entirely. Regarding waste water quality, there is a two dimensional data gap when using open data (↙) and a data gap in the spatial dimension only when using restricted data (↘). The size of the gap in the spatial dimension remains equal when restricted data can be used.

3.3. Non-piped water

In the case of non-piped water, the spatiotemporal resolution of existing open data meets the resolution of six out of the twelve information needs (Fig. 3). Regarding the resolution of these twelve information needs, a cluster of six shows on the right side of the field at the temporal scales 'quarter of a year' till 'five years' (Fig. 3a). Of the remaining six information needs, four appear in the lower left corner of the SIRUP frame, delineated by week and district. Two of these information needs are rainwater related, the other two relate to groundwater quality and quantity. For these four information needs a data gap exists, because existing rainfall and groundwater data have a lower resolution than required (Fig. 3bc). In the case of groundwater quantity, this is an exception because the resolution of the existing data – small neighbourhood to small district at seasonal level – is sufficient for the other three groundwater quantity related information needs. By contrast, the resolution of groundwater quality data, which is the metropolitan region and one to four year resolution, is insufficient for the two related information needs. Likewise, the resolution of rainfall data – in between municipality and metropolitan region for a day to half a year – is inadequate for all rainwater related information needs. The resolution of existing surface water data is sufficient to meet the three related information needs (↗,→). Overall, six data gaps for non-

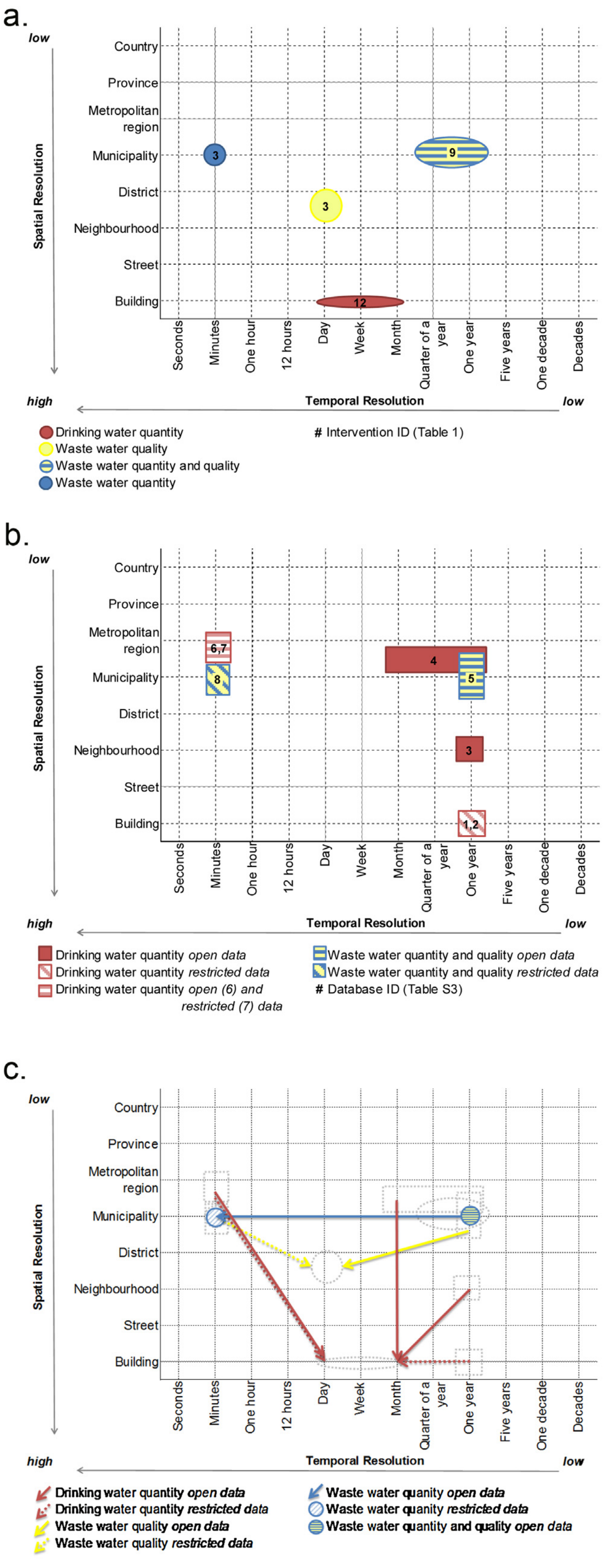

Fig. 2. Results for piped water.
a. Information needs; b. existing data; c. data gaps (results of SIRUP step II, III, IV).

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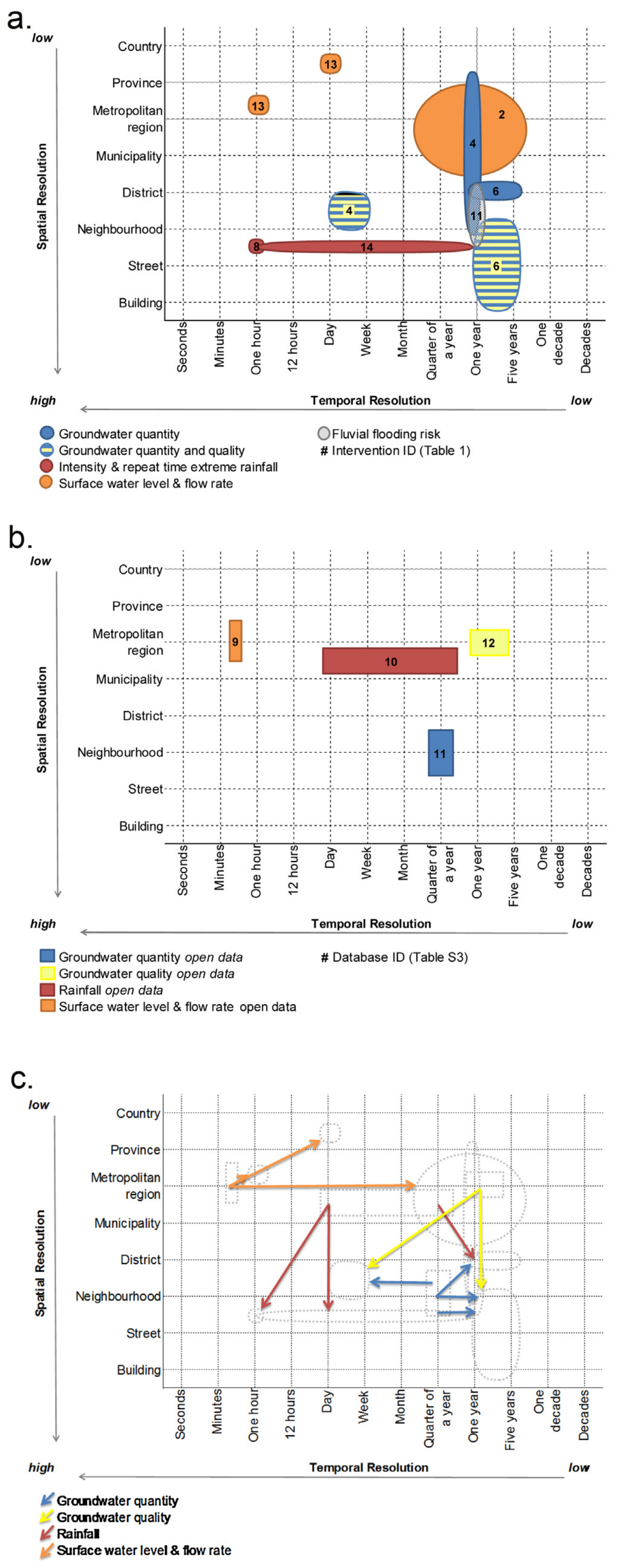

Fig. 3. Results for non-piped water.
a. Information needs; b. existing data; c. data gaps (results of SIRUP step II, III, IV).

piped water remain, including two data gaps in both dimensions (↙), one data gap with a temporal dimension only (↖) and three gaps with a spatial dimension only (↓,↘) (Fig. 3c).

3.4. Energy demand

Out of the five information needs on energy demand detected, one can be met by existing restricted data (Fig. 4). The information need that can be met, electricity demand of a neighbourhood at yearly basis (↗), is the only one that is not part of the cluster in the lower left corner of the SIRUP frame, delineated by week and district (Fig. 4a). Existing data sources on Amsterdam's energy demand, on the contrary, primarily provide data on yearly totals, within a spatial range of building to country level (Fig. 4b). The exception to this is a restricted dataset that provides data on the electricity demand of a streetlight per day. Accordingly, for all four information needs in the high-resolution cluster there is a data gap (Fig. 4c). Although these data gaps are similar because they have a temporal dimension only (⟵,↖), they differ in the size of the gap. The data gap is smallest for household cooling demand, from one year to month resolution, whereas the data gap regarding total urban electricity demand is more substantial, from one year to week up to from one year to one hour.

3.5. Energy supply

Results for energy supply show that out of the four defined information needs, one can be met by existing open data (Fig. 5). All four information needs appear on the lower half of the SIRUP field, that is a spatial resolution of district level or higher (Fig. 5a). In terms of temporal resolution the information needs cover a larger range, namely from 'seconds' to 'one year'. When the temporal resolution of existing energy supply data is considered, it appears that data is primarily available for yearly totals (Fig. 5b). The exceptions to this are a restricted database that provides electricity supply data on a monthly temporal resolution and open data on drinking water cooling supply with a half yearly resolution. In terms of the spatial resolution of existing data, findings show that open data with a resolution as high as the building level exists. As a result, energy supply related data gaps have a temporal dimension only (⟵,↖) (Fig. 5c). When only open data is considered, the gap for household cooling supply is the smallest, from one year to month resolution. The data gaps regarding total urban electricity demand range from one year to one hour or minutes. These gaps reduce in terms of the number of temporal scale levels to be bridged when there is access to the restricted database of the electricity supply of the waste-to-power plant. The information need that can be met, potential yearly electricity supply by PV panels on neighbourhood level (↑), relates to the same intervention for which the energy demand related information need can be met, namely "PVs on roofs for public lighting".

4. Discussion

4.1. Patterns in information needs and existing data

To inform resource-conscious urban planning and design, information on water and energy is required on a higher spatiotemporal resolution than the resolution of current UM analyses. For 12 out of 14 interventions, stakeholders require information on a higher level of detail than the city/region scale and the annual time interval at which UM analyses are currently performed (Kennedy et al., 2011; Niza et al., 2009). In detail, three of the 26 expressed information needs are on the city-annual resolution. Ten information needs have either only a temporal resolution that is higher than annual or only a spatial resolution that is higher than city level, including six information needs on the neighbourhood-annual level. Another

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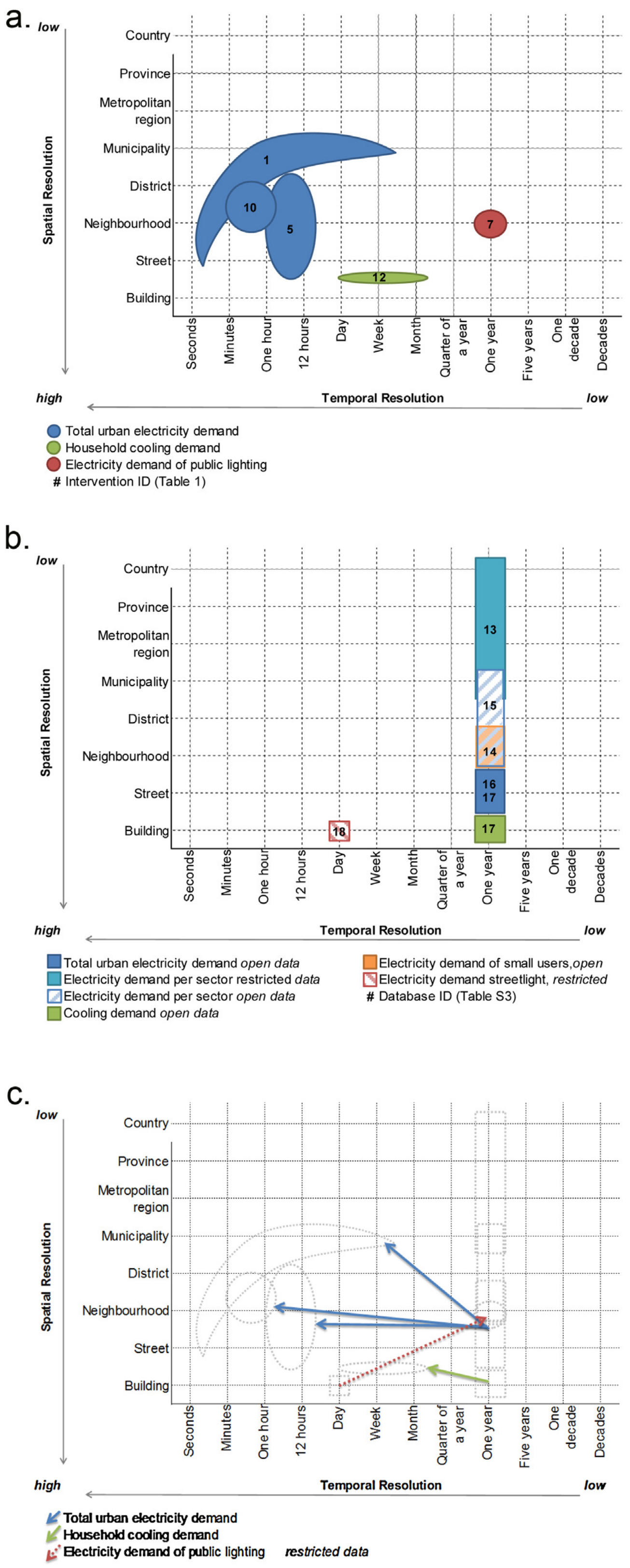

Fig. 4. Results for energy demand.
a. Information needs; b. existing data; c. data gaps (results of SIRUP step II, III, IV).

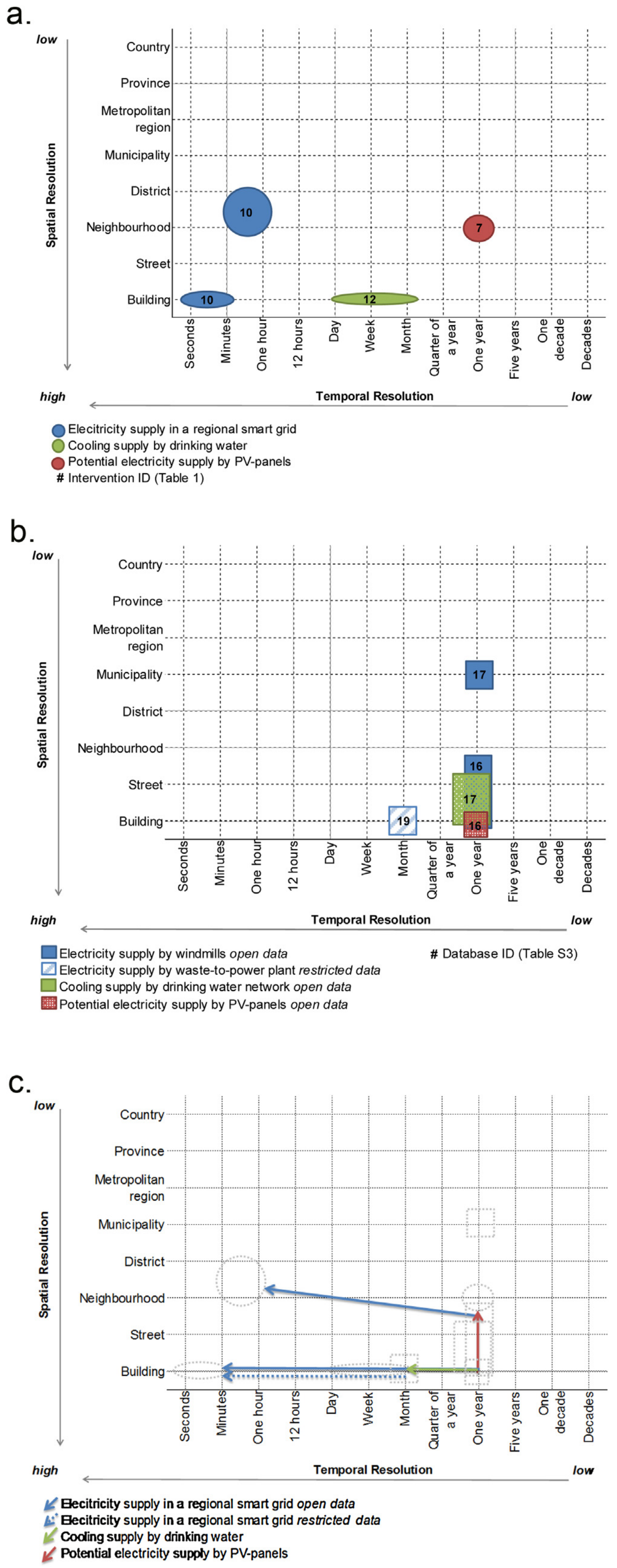

Fig. 5. Results for energy supply.
a. Information needs; b. existing data; c. data gaps (results of SIRUP step II, III, IV).

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13 information needs are on a high resolution in both the temporal and spatial dimension. The temporal resolution of these information needs is within the range seconds to week and the spatial resolution is between building and district level. The required spatiotemporal resolution appears to be linked to the resource flow targeted by an intervention. The resolution of water related information needs is scattered across the SIRUP frame, including a large range of both low and high spatiotemporal levels, whereas energy related information needs are on a high spatiotemporal resolution.

That water related information needs cover a large range of scale levels could be indicative for current developments towards total water cycle management, also known as sustainable or integrated urban water management (Van De Meene and Brown, 2009). Such an integrated management approach requires an understanding of the dynamics of urban water flows and the processes that affect these flows at multiple scales in time and space (Leusbrock et al., 2015; Pahl-Wostl, 2007). These different scales are required because of the complexity of the urban water cycle, which includes sewerage, drinking water and drainage as well as surface water runoff, open water bodies and rainwater. All of these flows have different dynamics in space and time and therefore the level of spatiotemporal detail at which information is needed, varies with the water flows targeted by an intervention. This can be illustrated by comparing the interventions “Water square” and “Dike reinforcement”. High spatiotemporal resolution rainwater data up to small neighbourhood – hourly level, is needed for the storm water management intervention “Water square”. The information need for “Dike reinforcement”, on the other hand, covers the range months to five years, and large district up to provincial level. The relatively high spatiotemporal resolution of rainwater related information needs is known to be prerequisite to assess and predict urban runoff behaviour (Fletcher et al., 2013). Likewise, for urban flood management it is essential to understand the dynamics of surface water flows at different spatiotemporal scales, including the scale of the catchment level and a long-term perspective (Zevenbergen et al., 2008).

In contrast, energy-related interventions require information on a high spatiotemporal resolution. Unlike water, decentralisation of energy services is becoming more frequent. This shows, for example, in the increasing penetration of renewable energy in the urban energy system – a consequence of current efforts to decarbonize the urban energy infrastructure (Chu and Majumdar, 2012; Manfren et al., 2011). The two-way flow of energy that comes with this decentralization and the periodicity in both energy demand and in generation of renewable energy, call for a design and management of energy infrastructure that avoids negative impacts on the network, such as fluctuations in voltage or power output (Franco and Salza, 2011; Manfren et al., 2011; Passey et al., 2011). Accordingly, to enable an optimal management of energy generation, distribution and storage, highly detailed data is needed about when and where energy is generated as well as when and where it is required (Manfren et al., 2011). This is evident for the intervention “Regional smart grid” that aims to optimize energy management on the metropolitan scale. To implement this intervention, energy demand and supply data is needed on a spatial resolution of the building up to the district level and a temporal resolution of seconds to one hour.

The inventory of existing data reveals another difference between water and energy flows, namely, in Amsterdam, high-temporal resolution data is available for water but not for energy. This gap is partly due to diverging data protection policies of water and energy utilities. Our energy data providers indicated that a strict data sharing policy is applied. One of the stakeholders indicated that this is due to their high stakes in the energy market—data have high commercial value in a competitive open energy market. As water utilities operate in a natural monopoly, their data have less commercial value. Further investigation is needed in order to facilitate a more in-depth explanation of these findings. With regard to the inventory of existing data in Amsterdam it should be noted that more sources might exist, especially databases with restricted data. Moreover, the scope of the present research was limited to an analysis of existing data on its spatiotemporal *resolution*. Nevertheless, the usefulness of data for urban planning and design may also be affected by the accuracy of the data and the spatiotemporal *extent* of the data, i.e., the geographical area and time period that the data cover. When aiming to compare different datasets on their information value, the SIRUP tool can also be employed to plot datasets according to their spatiotemporal extent.

4.2. Implications of data gaps

The findings show that the majority of resource-conscious interventions envisioned in Amsterdam require information on a more detailed spatial and temporal resolution than existing data can provide. Data gaps are absent for four out of the 14 interventions, including three water-related interventions: “Dike reinforcement”, “Recovery of protein from sewage”, and “Water-robust vital infrastructure”. The intervention “PVs on roofs for public lighting” is the only energy-related intervention without a data gap. One should keep in mind that the presence and/or size of data gaps of an intervention can depend on the objective of the stakeholder. The information need of the designer for the intervention “PVs on roofs for public lighting”, for example, was related to a hypothetical demand-supply matching. Namely, supplying a yearly amount of energy by PV panels in a neighbourhood that is equal to the amount used by the streetlights in that area on a yearly basis. When the objective would have been to implement PVs to make the neighbourhood self-sufficient in terms of its electricity for public lighting, a more detailed insight in the temporal differences in electricity supply and demand would be needed to design a reliable energy system. In that case, there would have been a data gap. Overall, the findings seem to imply that water-related interventions face fewer data barriers for implementation compared with energy-related interventions, such as “Parking garage as battery” and “Regional smart grid”. For energy-related interventions, the combination of high-resolution information needs and a lack of (open) data may impair implementation.

It must be emphasised that there are possibilities to close identified water and energy-related data gaps. In both fields technological advancements in sensor technology and modelling are likely to generate more high-resolution data in the future. For households monitoring, instalment of water smart-meters could yield water consumption data on the building level on a real-time or near real-time basis. These high resolution water demand data can inform both the planning of drinking water and waste water infrastructure (Stewart et al., 2010), such as the intervention “More concentrated sewage flows”. Smart meters could also provide high(er)-resolution energy demand data. The privacy issues that come with the sharing and use of high spatial-temporal resolution smart meter data can be minimized when appropriate data selection and ‘privacy friendly’ processing techniques are applied (McKenna et al., 2012). For non-piped water too, new high-resolution monitoring systems are being developed. The potential of X-band radar and the microwaves that serve mobile networks as new sources for measuring precipitation on a high resolution is currently being researched (Van de Beek et al., 2009; Fletcher et al., 2013). Furthermore, modelling techniques are advancing fast for both water and energy to provide high time resolution and high spatial resolution data (Fletcher et al., 2013 Widén et al., 2009). To assess the cooling supply of drinking water for the intervention “Usage of cold from drinking water for cooling”, for example, a model that calculates the temperature change of drinking water in the supply system could be

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used (Moerman et al., 2014). Although models are a simplification of reality and are therefore not fully accurate, the information value of these data may be accurate enough to inform the implementation of interventions. Further investigations are needed to understand which data accuracy is necessary for different resource-conscious interventions and UM analyses, and which data sources can provide data at this level of accuracy. Besides data accuracy, the potential impact of an intervention on the UM as well as the cost-effectiveness of an intervention are two other relevant aspects to consider when aiming to evaluate the feasibility and urgency of closing the different data gaps. These aspects were beyond the scope of this paper.

4.3. Disclosing UM knowledge for urban planning and design

Finally, results indicate that a fine scale approach to UM analyses alone will not suffice to disclose UM knowledge for urban planning and design practice. There is not ONE scale level of analysis that will serve all information needs. Rather than pursuing a linear, fine-scale approach to UM analysis, we suggest that a multi-scale, systemic approach to UM analysis is needed to provide the required information on resource flows from fine to coarse scale levels. The need for a systemic understanding of urban resource flows is supported by stakeholders expressing for half of the interventions that, next to insights on resource flows, information about the urban infrastructure is needed too. One of the stakeholders explicitly indicated that insight in the urban infrastructure is essential to evaluate the effects of an intervention on the functioning of the entire system. Moreover, this systemic approach should also account for social and ecological processes that influence the actual resource flows of cities. After all, a better understanding of the multi-scale processes of human-environment interactions that affect these flows is essential for sustainable resource management (Pahl-Wostl, 2007). Stakeholder input revealed that insight in biophysical processes underlying the urban system, such as solar irradiation, rain and the infiltration capacity of the soil, is needed for implementing resource-conscious interventions. Indeed, it has been suggested that these processes should be accounted for to improve the usefulness of UM analyses for urban planning and design that contributes to the sustainable management of resource flows (Pincetl et al., 2012). UM analyses should describe the complexity of urban systems more accurately, by linking the physical, quantitative knowledge of resource flows to its interaction with (current and historic) environmental, social and economic conditions (Castán Broto et al., 2012; Golubiewski, 2012; Moffatt and Kohler, 2008; Pincetl et al., 2012). So, in order to disclose UM knowledge for resource-conscious urban planning and design, it is thus of key importance to develop a systemic understanding of urban resource flows. This systemic understanding should provide insight in the social and ecological processes that affect resource flows and in the interlinkages between processes and resource flows at different spatial and temporal scale levels.

5. Conclusion

In conclusion, our results suggest that there is not one particular scale level of UM analysis that will generate meaningful results for urban planning and design aiming at optimizing resource flows. The relevant scale of analysis appears to depend on the nature of the intervention and the resource flow targeted. Findings do show that the current resolution of UM investigation, on city level and per year, is of insufficient detail to provide the information that is needed to inform resource-conscious urban planning and design decision-making. Moreover, the spatiotemporal resolution of existing data is a limiting factor for performing UM analyses that provide useful information for implementation of resource-conscious interventions. The SIRUP tool, proposed in this study, proved to be a practical tool for identifying these data gaps. The tool may also proof helpful to understand UM information needs and data gaps in other cities.

Rather than performing conventional UM analyses on a finer, more detailed scale level, other types of UM analyses are required to disclose UM knowledge for urban planning and design. Further research is needed to investigate what type of analyses can provide a systemic understanding of resource flows and are tailored to inform urban planning and design aimed at optimizing resource flows. In such research, the accessibility of UM analyses for urban planners and designers should have a central position.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2016.08.026.

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