The urban harvest approach as framework and planning tool for improved water and resource cycles
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ABSTRACT
Water and resource availability in sufficient quantity and quality for anthropogenic needs represents one of the main challenges in the coming decades. To prepare for upcoming challenges such as increased urbanization and climate change related consequences, innovative and improved resource management concepts are indispensable. In recent years we have developed and applied the urban harvest approach (UHA). The UHA aims to model and quantify the urban water cycle on different temporal and spatial scales. This approach allowed us to quantify the impact of the implementation of water saving measures and new water treatment concepts in cities. In this paper we will introduce the UHA and its application for urban water cycles. Furthermore, we will show first results for an extension to energy cycles and highlight future research items (e.g. nutrients, water–energy nexus).

Key words | resource cycles, water management, water–energy nexus, decision-support

INTRODUCTION
Efficient and effective use of resources is one of the major global challenges for the future, especially in regard to resource depletion, anthropogenic pollution of ecosystems, increasing population numbers and urbanization. Reliable and sustainable supply of water in sufficient quantity and satisfactory quality to people, industry and agriculture has to be mentioned as a key concern. Worldwide, densely urbanized regions and their hinterlands are characterized by high water demand for drinking water, agriculture, industry and food production as a result of our socio-economic development. This high water demand is predicted to increase in future even further if no countermeasures are taken (Darrel Jenerette & Larsen 2006). Already now, water scarcity in many regions of the world is at hand and limiting and hampering daily life. Analogies can be made with other resources such as nutrients, e.g. phosphorus (Cordell et al. 2011), organic matter, energy and food, where future demand and projected scarcity represent a major problem as well.

To prepare our resource supply and urban services delivering these resources for these upcoming challenges, innovative and improved concepts are indispensable. Effective and sustainable management of urban water cycles and integration of alternative water sources are vital for the reduction of water stress. Competing claims call for an increase of local self-sufficiency. These concepts have to (a) enable a reduction in water consumption through demand minimization and (b) facilitate an increase in water self-sufficiency of urban systems (Daigger 2009) and consequently reduce water stress for humans and nature by identifying and using alternative water sources – salt water, precipitation and wastewater – for high-quality potable, and lower quality non-potable, water uses. Next to water, the related resource streams of nutrients, organic matter and energy also have to be addressed simultaneously in these concepts to achieve an overall, integrated solution to resource scarcity.

Recent developments and research to quantify urban water and resource cycles and to assess the (positive or negative) influence of human interventions on these resource cycles (e.g. increased urbanization, new sanitation concepts) are scarce or limited in scope (Pahl-Wostl 2007; Blokker et al. 2008). The dynamics of the processes and the fact that multiple scales in time and space are relevant result in a call for integrated and more detailed studies (Pahl-Wostl 2007; Blokker et al. 2008). Currently available
tools often focus on one resource due to the complexity of reality (e.g. mutual influence and dependency of energy and water cycles for warm water) and are based on yearly averages and best practice while temporal and spatial resolution are coarse. Contrary to this, innovative water and resource concepts and technologies often require a more detailed spatial and temporal scale for evaluation to truly show their benefits and shortcomings in comparison to the current large and centralized state-of-the-art approaches. Thus, a sound understanding of the dynamics of water flows in detailed spatial resolution is crucial here. Recent projects like Prepared (Prepared: An EU FP7 project 2014) and SWITCH (SWITCH: Sustainable water management improves tomorrow’s cities health 2014) have been focusing on tackling this issue. Moreover, these concepts have to be extendable/extended to other resources such as energy and nutrients as these are interlinked.

In recent years we have developed the urban harvest approach (UHA) (Agudelo-Vera et al. 2011; Agudelo-Vera 2012). The UHA allows quantification of urban resource cycles on different spatial (down to household level) and temporal (down to minutes) scales. Next it provides a structured framework with steps aimed at closing the resource cycles. Lastly, UHA provides an option to quantify the impact of the demand minimization measures and resource recovery and reuse concepts proposed for the selected urban area. During the development of UHA the main focus was on the water cycle, and here it has proven a powerful tool to develop new concepts for cities and neighbourhoods that minimize water demand and achieve (partial) self-sufficiency (Agudelo-Vera et al. 2012). We are now extending the UHA towards the energy cycles. In this paper, we will give a short overview of the UHA and highlight main results found for urban water cycles. Furthermore, we will highlight our current research results on the extension of UHA for energy cycles and discuss further extension towards nutrient cycles.

MATERIALS AND METHODS: URBAN HARVEST APPROACH

The UHA was originally developed for water cycles, yet can be applied with adaptations to other resource cycles such as energy, nutrients (N, P, K) or organic matter (C). A joint evaluation of several resource cycles is the current focus of our research. Water and resource will be used in the following synonymously if not mentioned otherwise.

The UHA is based on four steps: (i) baseline assessment of the investigated case based on characteristic parameters of an urban setting (e.g. urban typology, demand patterns), (ii) minimizing resource demand by implementing resource saving measures, (iii) maximizing resource re-use by cascading, recycling and recovery of used resource streams, and (iv) exploitation of multi-sourcing through capture and use of alternative resource sources (see Figure 1(a)).
Baseline assessment

In the baseline assessment, all inputs, throughputs and outputs within the system boundaries are quantified. In addition, the qualities of the flows are also registered based on the demand. All streams are calculated in a high temporal resolution (from minutely upwards) in order to account for diurnal and seasonal patterns. The exact resolution will depend on the characteristics of the resource flows, which can vary per minute due to the dynamic behaviour of the users. This is made possible by the use of highly detailed demand data. The water demand of households is calculated by SIMDEUM, a statistical software package used in the Dutch water sector to predict water-consumption on a small timescale (down to 1 minute) and on building scale based on end-use patterns (Blokker et al. 2010; Agudelo-Vera 2012). This is in contrast to other metabolism studies, where, for example, yearly averages are frequently applied. Current research focuses on developing similar tools for energy and nutrient cycles. The inclusion of these dynamics offers a large advantage in the evaluation of technologies and comparison of concepts, yet are inevitably linked with an increased complexity of the overall analysis (Pahl-Wostl 2011).

Demand minimization

In the second step, technical interventions are implemented in order to reduce the overall resource demand. Here, the idea is to evaluate saving measures from the smallest scale possible upwards to the scale of the overall case. The result of this step is a ranking of technologies based on the expected savings.

Output minimization

The third step of UHA aims at minimizing outputs. This can be achieved by three different strategies:

- Cascading of resources: direct reuse for a lower quality purpose
- Recycling of resources: reuse after treatment
- Recovery of resources: harvesting of other components/resources.

While cascading and recycling refer to one resource stream, without and with quality upgrading respectively, recovery includes the removal of other valuable products from the main resource stream (e.g. recovery of nutrients from black water) (Agudelo-Vera et al. 2012).

Multi-sourcing

Multi-sourcing refers to the creation of resource supply based on local resource potential. Local resource supply has the advantage of requiring short transport infrastructure and the possibility to achieve self-sufficiency on local scale. Examples here are production of water from humidity (Bergmair et al. 2014), the harvesting of rain water (Nanninga et al. 2012) or the production of electricity via photovoltaic (PV) panels.

Urban metabolic profile

In order to evaluate and quantify the strategies of UHA and to compare different concepts with each other, the urban metabolic (UM) profile was developed. The UM profile includes criteria and indicators. For the water cycle these are on demand minimization, waste output, self-sufficiency, and exportation of water. An overview of the main indicators is given here:

- Demand minimization index (DMI)
  \[ DMI = \frac{\text{Baseline demand} - \text{Minimized demand}}{\text{Baseline demand}} \]
- Waste output index (WOI)
  \[ WOI = - \frac{\text{Exported waste}}{\text{Minimized demand}} \]
- Self-sufficiency index (SSI)
  \[ SSI = \frac{\text{Harvested resources (Rh)} - \text{exported resources}}{\text{Minimized demand}} \]
- Resource export index (RXI)
  \[ RXI = \frac{\text{Exported resources}}{\text{Minimized demand}} \]

A graphical representation of the urban metabolic profile can be found in Figure 1(b).

Based on this evaluation and use of criteria/visualization (e.g. difference between initial demand and after demand minimization, compare Figure 1(b)), the influence of human interventions (e.g. efforts for water demand minimization or reuse of water streams) or of external factors (e.g. increased consumption and population numbers, temperature and climate changes) to reduce resource stress can be quantified. UHA was developed to evaluate possible options and scenarios for improved urban resource management. The results of UHA are to be used by urban planners,
technologists and governmental organizations as decision-support information.

**Extension of UHA to energy cycles**

In order to extend the UHA towards energy, an evaluation of the energy demand of three residential buildings in Wageningen, The Netherlands, was performed. These three buildings represent typical Dutch dwellings (a detached house, a row house and a gallery house). As the energy cycle shows different properties in comparison to the water cycle, we have adapted and extended our criteria and indicators for the water cycle:

- **Demand minimization index (DMI)**
  \[
  \text{DMI} = \frac{\text{Baseline demand} - \text{Minimized demand}}{\text{Baseline demand}}
  \]

- **Energy recovery index (ERI)**
  \[
  \text{ERI} = \frac{\text{Recovered and reused energy}}{\text{Minimized demand}}
  \]

- **Self-sufficiency index (SSI) for thermal, electric, and total energy**
  \[
  \begin{align*}
  \text{SSI}_\text{thermal} &= \frac{\text{Thermal energy produced}}{\text{Minimized thermal energy demand}} \\
  \text{SSI}_\text{electric} &= \frac{\text{Electric energy produced}}{\text{Minimized electric energy demand}} \\
  \text{SSI}_\text{total} &= \frac{\text{Total energy produced}}{\text{Minimized demand}}
  \end{align*}
  \]

- **Resource export index (RXI)**
  \[
  \text{RXI} = \frac{\text{Exported energy}}{\text{Minimized demand}}
  \]

The ERI quantifies the extent of recovered, cascaded and reused energy in comparison to the minimized demand. For a domestic case, this index is primarily interesting for thermal (heating, cooling) energy recovery measures, for instance heat recovery from showers and taps. The SSI was extended to three indicators: one for thermal energy, one for electric energy and one for the total energy. The DMI and the RXI are comparable to those of the water cycle.

**RESULTS AND DISCUSSION**

**UHA for water cycles**

The UHA has been developed and tested for the urban water cycle (Agudelo-Vera 2012; Agudelo-Vera et al. 2013). In order to show the impact of water saving measures and reuse and recycle options on smaller scales, two residential blocks based on the boundary conditions of Wageningen with identical gross surface areas were analysed with the UHA: (a) a low-density block consisting of freestanding houses and (b) a high-density block of flat-like residential apartments (Agudelo-Vera 2012). The chosen timeframe was 1 year. To compare the effect of different interventions on the water cycle, four scenarios were developed. All scenarios included a demand minimization step consisting of water saving technologies for shower, toilet and laundry water. Scenario 1 furthermore included the recycling of light grey water from shower and sinks. Scenario 2 included rainwater harvesting from roofs. For these two scenarios, the harvested water was used for lower quality purposes such as toilet flushing or irrigation. Scenario 3 combined Scenario 1 and Scenario 2, while Scenario 4 extended Scenario 3 with green roofs as an additional storage step and for run-off reduction. Results of the study showed that the demand minimization resulted in average water-savings of 23–25%, depending on the household size. Scenario 4 showed the largest improvement in terms of self-sufficiency in comparison to the baseline assessment. Furthermore, Scenario 2 showed the smallest improvement in terms of harvested resources and exported waste streams. Figure 2 shows the urban metabolic profile, as described before, for the baseline and the four scenarios. Note that the presented values are aggregated for the course of a year while the individual time steps are 5 minutes. Furthermore note that storage and buffer calculations (e.g. for rain water or treated grey water) are included in the model, which necessitates the use of smaller time steps to quantify the impact of these measures. An extended description of this assessment can be found elsewhere (Agudelo-Vera et al. 2013).

To show the impact of different demand minimization steps and reuse and recycle options on a city scale, the urban water cycle was described for the complete city of Wageningen as well. Technologies like the ones mentioned for Scenario 4 for the block scale were applied in addition to systems enabling the collection of surface runoff water. A comparison between the baseline water cycle and the improved scenario is shown in Figure 3. As can be seen in Figure 3, application of the UHA enables a water demand reduction of 14% if the proposed measures are implemented at city level. Furthermore, the total volume of wastewater leaving the investigated system is decreased by more than 60% (Table 1) and would be available in a concentrated state, which facilitates treatment and resource recovery processes. Additionally, water of high quality could be exported, e.g. for groundwater recharge, and parts of the
Water flows are recycled within the system under the assumed boundary conditions.

Results of the UHA show the integration of different technical options on different spatial scales can result in significant improvements in the urban water cycle. Here, we have presented the results of technical interventions on building/block scale and on city scale.

Complete optimization of the water balance (SSI = 1 and WOI = 0) is technologically feasible, where for instance potable water is produced by treating wastewater with advanced membrane filtration or wastewater is indirectly reused for irrigation and lower quality purposes. The efficiency and the benefits of such technological concepts can be derived from the UHA and used as decision-support tools. However, implementation of these measures requires additional resources such as energy for treatment and pumping. This would require the integration of energy demand as

### Table 1  
Overview of the criteria of UHA for a city-wide application of water saving and recycling/reuse measures

<table>
<thead>
<tr>
<th></th>
<th>After decentralized and centralized saving measures</th>
</tr>
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<tbody>
<tr>
<td>DMI</td>
<td>14%</td>
</tr>
<tr>
<td>SSI</td>
<td>34%</td>
</tr>
<tr>
<td>WOI</td>
<td>69%</td>
</tr>
<tr>
<td>RXI</td>
<td>37%</td>
</tr>
</tbody>
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Figure 2  
Urban metabolic profiles for the two blocks, for the baseline and the four scenarios (indicated by numbers and stars) on yearly basis. Adapted from Agudelo-Vera (2012).

Figure 3  
Yearly water balance of a case city (Wageningen) evaluated by urban harvest approach (a) under conventional conditions and (b) with centralized and decentralized saving measures; wastewater in (a) is diluted while in (b) it is concentrated.
well as investment and operational costs among other criteria in the UHA.

**UHA for energy cycles**

To show the applicability of the extended UHA also for energy cycles, five different scenarios were evaluated and compared:

- Scenario I: demand minimization
- Scenario II: demand minimization, shower heat recovery
- Scenario III: demand minimization, grey water heat recovery (shower and sinks) and production of biogas from source-separated wastewater streams (black wastewater and kitchen waste)
- Scenario IV: demand minimization, grey water heat recovery and production of biogas from source-separated wastewater streams, electricity supply via PV panels
- Scenario V: demand minimization, grey water heat recovery and production of biogas from source-separated wastewater streams, electricity supply via PV panels, electricity storage with batteries.

Each scenario was applied on three existing residential buildings (a gallery house, a row house, a detached house) typically found in the Netherlands. Data on these buildings were derived from cadastral information. A population of 92 was assumed. As input for each scenario, local climate data from Wageningen (Meteorology & Air Quality Group Wageningen UR 2013), water consumption patterns derived via SIMDEUM (Blokker et al. 2009, 2010) and standard energy consumption patterns for the Netherlands (Ecofys 2002) were used. From this information, baseline demand patterns for the buildings were derived in a temporal resolution of 5 minutes over the course of 1 year. In Scenario I, demand minimization measures were performed (e.g. improved insulation of the building envelope, efficiency improvements in appliances and lighting, lower energy demand for water heating due to lower hot water consumption and more efficient appliances). Scenario II includes additionally heat recovery from shower water (Schuitema et al. 2005; Agentschap NL 2011; Tomlinson et al. 2012). Scenario III includes heat recovery from shower and sinks and production of biogas via anaerobic digestion (Kujawa-Roeleveld & Zeeman 2006) from source-separated black water and kitchen waste (Zeeman et al. 2008). The amount of biogas produced was assumed as 0.83 L per person per hour (De Graaff et al. 2010). Scenario IV includes electricity production via PV panels with an assumed efficiency of 20% and internal losses of 5%. The total roof area was assumed as 1,700 m² (1,100 m² with a tilt of 0 degrees, 600 m² with a tilt of 39 degrees) with all roofs orientated to the south. Scenario V additionally includes electricity storage via a lithium battery with an assumed capacity of 1,000 MJ and an overall efficiency of 90% (Ibrahim et al. 2008). All excess electricity from PV panels is assumed to be stored until the storage is full. If demand exceeds supply, stored electricity is used first before external energy is imported. More information and underlying assumptions can be found elsewhere (Lieberg 2014).

Figure 4 shows the SSI for all four seasons over the course of a day for an average day of each season for Scenario III (left) and Scenario V (right). Clear differences can be seen in self-sufficiency between the seasons with summer being the highest and winter the lowest. For Scenario III, the main reasons lie in the lower overall energy demand, especially heat, during summer. For Scenario V, the large impact of PV panels and storage in summer can be observed. Next to the comparison between the seasons, also the times
of the day can be identified where external energy supply before and after application of technical measures (e.g. PV and storage) is needed. For Scenario V, these are the night and early morning due to diurnal patterns of solar insolation. Based on this information, additional options could be investigated to increase the self-sufficiency during these timespans (e.g. wind energy or heat pumps).

A comparison of the results of the scenario study can be found in Figure 5 in form of a radar chart. With the help of this visualization form and the application of the extended UHA, the different scenarios and the related technological concepts can be easily compared and evaluated. For instance, the impact of additional storage in Scenario V on SSI$_{electric}$ can be clearly seen in comparison to the lower SSI$_{electric}$ of Scenario IV.

**Future research**

The UHA has been developed and tested for the water cycle. In this paper we introduce the first results from a study where the UHA is applied to energy cycles. However, this work is not yet completed. Further ideas for extension are the evaluation of concepts for heat recovery from wastewater (Meggers & Leibundgut 2011) and an extension to the internal energy demand of water supply and treatment technologies (Frijs et al. 2013), which can produce energy or recover nutrients from (waste)water streams.

Future research will also focus on extending the UHA to nutrient (N, P) and organic matter (C) cycles as wastewater contains resources such as water, nutrients, organic matter and energy. This can happen for one resource flow (energy or water) or a joint evaluation of resource flows (e.g. nutrients, carbon and energy). The latter is needed to give a clearer picture of the benefits and costs of a concept, as resource cycles are interrelated (Kuntke et al. 2012) and can influence each other. An extension of the used indicator sets is necessary to increase the applicability of the UHA (as demonstrated for energy), such as the introduction of a WOI for nutrients or the extension of the SSI to include the produced energy or the amount of energy needed for the recovery and recycling of other resources.

So far we have used demand and supply data on the smallest time scale (5 minutes) available to us. While this represents a large improvement in comparison to other studies as it allows, for example, the evaluation of the impact of storage on self-sufficiency, larger time steps might still allow the same accuracy of the model while reducing computational load. An evaluation of the most preferable time step for this type of model is currently part of our research.

![Figure 5](https://iwaponline.com/wst/article-pdf/72/6/998/486635/wst072060998.pdf)
As shown above, such an extended UHA can be applied to develop efficient resource management cycles, for structuring efforts that envisage increased sustainability resource management and as a decision-support tool. The UHA can also be used for the evaluation of existing concepts and technologies, including those that are focussing on more than one resource (e.g. ‘new sanitation’ (Zeeman 2012)).

CONCLUSIONS

A dire need exists for tools and methods which can be used for the development and comparison of improved resource management concepts and which include the dynamic behaviour of resource demand and supply. In order to describe urban water cycles and the impact of human interventions, we have developed the urban harvest approach. The UHA has been applied successfully for the quantification of water saving measures and recycle and reuse options as well as energy cycles in residential buildings. It was shown with the help of the UHA that these measures can reduce the drinking water demand on city level by 13% and the volume of wastewater by more than 60%, and that a self-sufficiency of 36% in terms of energy demand for residential buildings in Wageningen can be achieved. Furthermore, the UHA can be applied to compare technological concepts by improved visualization and extended indicators. Thus, it represents an important tool that urban planners and technologists can use to develop and compare new concepts for improved water cycles. Further extensions of the UHA are still necessary to be able to give an evaluation of complete urban resource cycles in terms of energy, nutrients and carbon. Nevertheless, current results show that the UHA is a promising tool that can be used for a complete evaluation.

REFERENCES


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