Dynamic water resource management for achieving self-sufficiency of cities of tomorrow

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Chapter 1

Introduction

1 Introduction

Over the last centuries, with urbanization booming worldwide since the 1800s, the majority of cities has become highly dependent on their hinterlands for resource supply and waste disposal (Bai, 2007; Girardet, 2003). This has grown to a level that in the near future, global crises can be expected as a result of resource constraints and severe degradation of agricultural lands and natural habitats (Rockström et al., 2009). Chapter 2 of this thesis shows, based on literature review, that our current urban un-sustainability is rooted in massive resource consumption and waste production beyond natural limits. New approaches towards urban resources management in the frame of sustainable development are urgently needed.

Sustainable development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). One of the various interpretations is that resource planning and management should guarantee reliable resource provision, while maintaining the state of the resource for future generations and taking into account potential trade-offs and different scales in space and time (Pahl-Wostl, 2007). Urban spatial characteristics, such as urban functions, densities and building typology influence urban resource management, i.e. via resource consumption and waste production. Since long-term spatial characteristics are largely shaped by urban planners, urban planning is a formal and critical link between resource management and sustainable development. Innovative urban planning can contribute to improve local resources management towards cities with a smaller resource footprint. For this, planners need formal information and tools to understand cities and regions as environmental systems that are part of regional and global resource networks (Campbell, 1996, Kennedy et al., 2011).

1.1 *Problem definition*

Recent urban metabolism studies have provided a comprehensive picture of urban resource flows in a given urban area at a certain point in time (Kennedy et al., 2011). However, usually the temporal and spatial scales are coarse, i.e. cities are treated as homogenous systems and often resource flow is estimated based on yearly averages. Coarse scales are appropriate for traditional centralized urban infrastructures, like large scale energy and water supply networks. However, emerging decentralized options based on resource efficiency saving and local reuse of ‘wastes’ (or secondary resources) require a more detailed understanding of urban systems in time and space. In reality, urban systems are composed of sub-units, e.g. houses, neighborhoods or industrial parks. These sub-units have a related metabolism, in terms of quantity, quality and tempo-spatial distribution of resources use. To make urban metabolism more sustainable, there is a clear need to develop tools to evaluate and re-design our urban systems, while making a link between (sustainable) resources management and long term urban spatial planning.

It is clear that urban environmental challenges vary among cities. For instance some cities face water scarcity meanwhile others face high risk of flooding. Additionally, when looking at cities and their internal diversity – e.g. different density, land coverage, building types – it can be expected that these environmental challenges also vary within the city and have a relation with resources flows. Because urban systems are not static entities, special attention should be given to the dynamics of the urban resource flows. The urban system itself changes continuously, for instance, seasonal variations may affect the land cover, and growth might affect densities and increase the urban heat island effect. Additionally, availability of resources depends on geographical location, but also on seasonal changes and even on daily/night variations (e.g. sun radiation that influences evapotranspiration). Despite the large availability of technologies and options to improve resource management in cities, we lack tools to select the most appropriate technology and the most suitable scale of management given the characteristics of the resources, the resource demands and the local context.

1.2 Objective

Our hypothesis is that urban systems and their direct peri-urban surroundings can – to a large extent – become self-sufficient in resources and can reduce their waste production by improving local resource management at the smallest scale possible. We argue that coupling of scales is needed to identify key multi-scale interactions and to identify the optimal scale(s) of management of different urban flows, as water, energy and materials.

The objective of this research was to test our hypothesis on one urban resource – water – to determine the optimal scale(s) of water resource management. To test our hypothesis we developed an approach, the so-called Urban Harvest Approach (UHA). In our approach, a city is regarded to have multiple potentials in the form of untapped primary and secondary resources that can be harvested and (re)used within the urban system. The UHA is a multi-scale approach to scan an urban area and its flows, and propose measures to improve urban resources management towards self-sustainability by applying demand minimization, output minimization (by resource cascading, recycling and recovery), and multi-sourcing. This scan provides insight in implications of urban typologies on urban flows, elaborates on a balance of primary and secondary resources available within the urban area, and calculates the potentials for harvesting those resources taking into account spatial and temporal conditions, such as storage and distribution.

The urban harvest approach is a systematic approach, which starts from the lowest scale possible (building) and scales up to block, neighborhood and city level and takes stock of the dynamics and non-linearities of urban resource flows. The approach aims, after a baseline assessment, at developing a portfolio of scenarios with measures for improving urban metabolism including their optimal scales of application. This information facilitates design and management of urban infrastructure and supports urban planning by investigating how urban characteristics can be used to improve resource use within cities.

1.3 Focus of this study

This study focused on urban water metabolism in the Netherlands. In urban areas, water supply and wastewater management is a major concern and represents both a risk and an opportunity to improve current practices. Nowadays, cities are highly dependent on external resources, while overlooking local possibilities of self-producing resources. For instance, rain water is seen as a nuisance and as such is removed from cities instead of valuing its potential as a local resource to optimize the urban water cycle.

In the last decade, the efficiency of isolated measures on urban water systems has been addressed by different researchers (Brodie, 2008, Liaw and Tsai, 2004, Peter-Varbanets et al., 2009). Publications reviewing technological approaches for grey water treatment and reuse are also available (Li et al., 2009), as well as determinants of residential water consumption (Arbués et al., 2003, Jorgensen et al., 2009). However, optimizing water quality and yields require information about the varying use and availability of water and simultaneous evaluation of the strategies. For this reason, it is important to gain insight into the dynamics of the urban water balance.

For the Netherlands, extensive knowledge is available on the natural water balance (Schuurmans and Droogers, 2010) and residential water consumption (Blokker et al., 2010, Foekema and van Thiel, 2011), but the interactions and synergies between natural and man-made cycles (piped water, residential consumption and sewer system) are unexplored. The Netherlands is one of the countries with largest urbanization and additionally with a relative high percentage of land use change (Feranec et al., 2010). With increasing problems, such as ground water salinization and higher recurrence of extreme events leading to local flooding (Bonte and Zwolsman, 2010), cities should become more able to adequately store and use water resources in a sustainable way.

In this thesis we simulated and evaluated the effect of the different water management measures following the UHA: minimizing input, minimizing output and multi-sourcing. Moreover, “metabolic profiles” are defined to describe the metabolism of the urban area.

These metabolic profiles are not only calculated based on the consumption, but also on the production of secondary resources and unwanted emissions.

1.4 Scope of this thesis

Chapter 2 presents a historical review of the urban resources management and urban planning and proposes ways for their integration in sustainable development. Exploring new options to cope with growing pressures, especially for resource supply, we propose that cities may be considered as resources reservoirs and producers of secondary resources. Based on the extensive literature overview of chapter 2, we defined two basic research questions to be addressed in this thesis:

i) can cities structurally be organized as producers of secondary resources thus significantly reducing demands of primary resources? This is addressed in chapters 3 and 4;
ii) can reorganized urban water structures contribute to sustainable urban resource metabolism and can this be quantified by distinguishing different tempo-spatial scales using a dynamic modeling approach? This is addressed in chapters 5-8.

In **Chapter 3**, we proof our concept by quantifying the potentials to harvest water and energy at two different scales for the Netherlands. The results indicate the large potential of cities as providers of their own resources. In **Chapter 4**, we introduce the Urban Harvest Approach as a tool for sustainable urban resource planning.

After testing and developing the UHA method on average water data (yearly basis) and in steady state. Our further research concentrated on the dynamic modeling approach. The aim was to more adequately assess the actual resource potential at different tempo-spatial scales.

In **Chapters 5-7**, we evaluate the potential of improving urban residential water cycles at building, block and city scale, respectively, for the Netherlands. Here we also address measures that are more effective on centralized level, whereas for many secondary resource harvesting and reuse scenarios, decentralized approaches may be more optimal. In **Chapter 8**, we provide a synthesis of the results obtained for the water cycle in the Netherlands and provide an outlook for urban resource management in the city of tomorrow. Fig. 1 shows a schematic representation of the content of this thesis.

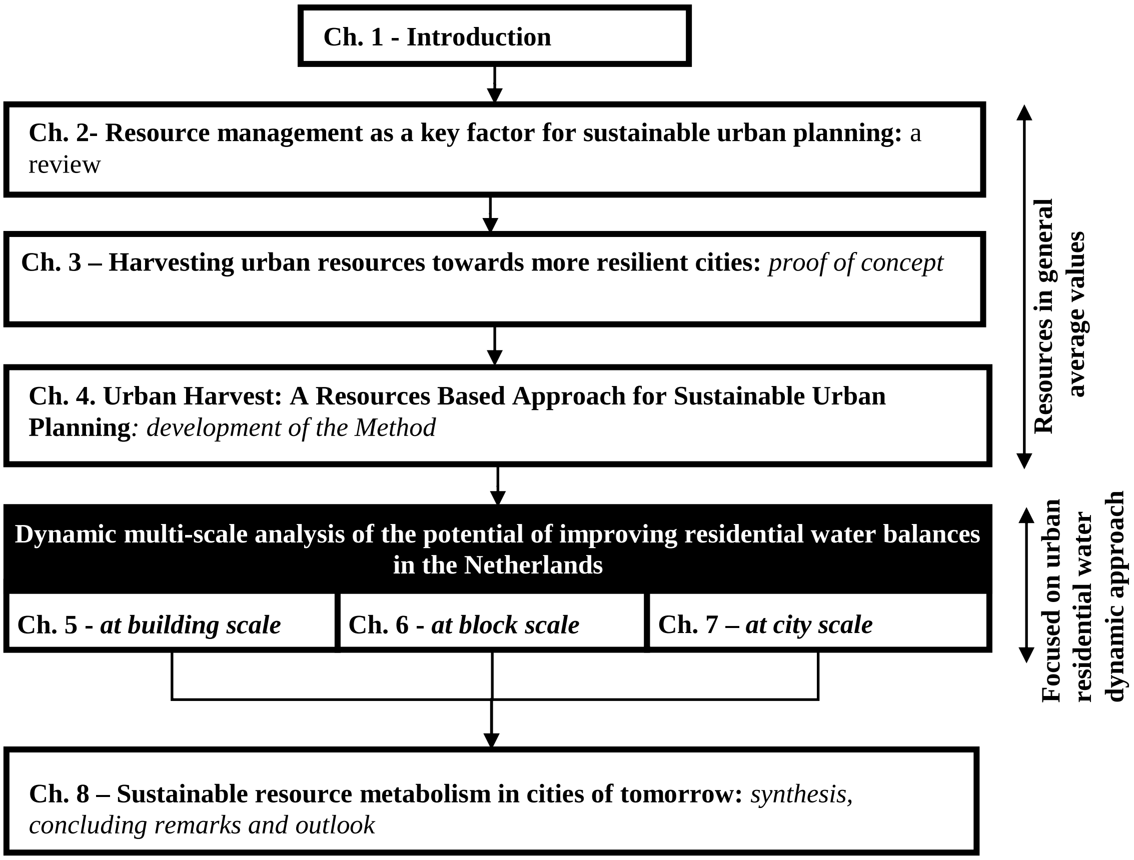

Figure 1 Schematic representation of the content of this thesis

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Chapter 2

Resource management as a key factor for sustainable urban planning: a review

Abstract

Due to fast urbanization and increasing living standards, the environmental sustainability of our global society becomes more and more questionable. In this historical review we investigate the role of resources management (RM) and urban planning (UP) and propose ways for integration in sustainable development (SD). RM follows the principle of circular causation, and we reflect on to what extent RM has been an element for urban planning. Since the existence of the first settlements, a close relationship between RM, urbanization and technological development has been present. RM followed the demand for urban resources like water, energy, and food. In history, RM has been fostered by innovation and technology developments and has driven population growth and urbanization. Recent massive resource demand, especially in relation to energy and material flows, has altered natural ecosystems and has resulted in environmental degradation. UP has developed separately in response to different questions. UP followed the demand for improved living conditions, often associated to safety, good manufacturing and trading conditions and appropriate sanitation and waste management. In history UP has been a developing research area, especially since the industrial era and the related strong urbanization at the end of the 18th century. UP responded to new emerging problems in urban areas and became increasingly complex. Nowadays, UP has to address many objectives that are often conflicting, including, the urban sustainability. Our current urban un-sustainability is rooted in massive resource consumption and waste production beyond natural limits, and the absence of flows from waste to resources. Therefore, sustainable urban development requires integration of RM into UP. We propose new ways to this integration.

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2. Resource management as a key factor for sustainable urban planning

2.1 Introduction

For the first time in history more than half of the world population, which is 3.5 billion people, are living in urban areas. This urban fraction will increase to almost 60% by 2030 and 70% by 2050 (ESA-UN, 2007). This large-scale urbanization requires large amounts of resources[1] – energy and materials – to build, feed and fuel cities (Girardet, 2003).

Cities are complex dynamic systems in a continuous state of change. They evolve in complex ways due to their size, social structures, economic systems, geopolitical settings, and the evolution of technology (Kennedy et al., 2007). Moreover, they require vast amounts of resources to function, displaying diverse patterns, agglomeration and intense competition for space with other land uses (Batty, 2008).

In the past, the depletion of the nearest and most accessible resources may have become a constraint on the growth of cities (Tainter, 2000). However, technological and infrastructural innovations have driven the increments on urban inputs and outputs (Kennedy *et al.*, 2007; Krausmann *et al.*, 2008, 2009; Monstadt, 2009). On a global scale and especially over the past two centuries, resources pressures have increased due to industrialism, rapid growth of the world population, urbanization (Tarr, 2002) and technological development. For instance, because of the development of advanced transport systems, resources can be imported from far away, which has led to a world-wide and complex resources network. Currently, cities are highly dependent on other cities and hinterlands to supply resources and dispose waste (Bai, 2007). Hence, the environmental impacts are spread, thus enlarging the ecological (global) footprint of cities (McNeill, 2000; Monstadt, 2009; Rees, 1999).

Cities have direct and indirect global impacts on the atmosphere, hydrosphere, geosphere and biosphere by extracting large quantities of natural resources, in some cases leading to depletion, and disposing of urban waste (Mills, 2007). Global resource extraction has been grown steadily, from 40 billion metric tons (Gt) in 1980 to 59 Gt in 2006 (SERI, 2010). And global primary energy use has increased from 256 Exa-Joules (EJ) in 1973 to 514 EJ in 2008, 81% of that from non-renewable fossils fuels (IEA, 2010). Since the industrial revolution, we have paid less and less attention to the carrying capacity of the global

[1] In this paper resources refer to energy and materials. Therefore, “resources” and “energy and materials” are used interchangeably. Materials and energy are two different aspects of the same process. Regarding materials, earth is a closed system, meanwhile for energy it is an open system due to solar energy input. To understand the metabolism of a society it is necessary to consider both because many interdependencies exist between them e.g. energy can be used to increase the availability of materials and materials can be used to reduce energy flows. Additionally, production of energy for example nuclear power can generate hazardous radioactive material (Haberl, 2001; Lior, 2010).

ecosystem. Diamond (2005) and Ponting (2007) described how the consequences of irreversible damage to the environment can cause the collapse of ecosystems and societies. A famous case is Easter Island, where a human society was based in the period 900 - 1700 AD[2]. Massive environmental degradation due to indiscriminate deforestation of the island resulted in lack of essential materials not only for cooking, heating and building dwellings, but also to build canoes and nets for fishing. In addition to this, the quality of the soil also deteriorated due to erosion. All these factors brought the Easter Island civilization to a collapse. The current global human impact is unprecedented. In the past decade became widely accepted that continued growth with current utilization rates is unsustainable (Arrow *et al.*, 2004). As humankind, we have to realize that the earth, like Easter Island, does not has unlimited resources to support human society and its demands (Ponting, 2007).

In a world of cities, it is becoming more and more clear that sustainable urban development is a crucial challenge (Girardet, 2003) and is maybe the most significant current and future environmental issue (McDonald and Patterson, 2007). To tackle this challenge, it is imperative to understand how urban metabolic systems function (Decker *et al.*, 2000; Girardet, 2003). We can affirm that towards sustainable cities, it is crucial to manage available resources strategically. Isolated technical solutions are insufficient to deal with the complex problems we face today (Pahl-Wostl, 2007). As such, Resource Management (RM), as stated in the title, is a key factor for Sustainable Development (SD).

Recently, SD is increasingly being used to guide Urban Planning (UP). However, its implementation is not immediately apparent, because there has been no general agreement on how the concept should be translated into practice (Berke and Conroy, 2000; Jepson, 2001). UP and SD seem to be parallel activities with the common goal of sustainable cities. Both UP and SD refer to future. However, as stated by Hjorth and Bagheri (2006, p. 78) “Managing the future is a ‘wicked’ problem, meaning that it has no definitive formulation and no conclusively ‘best’ solutions and, furthermore, that the problem is constantly shifting”. Nevertheless, RM is an essential aspect that should be part of both, UP and SD.

The link between UP and SD is currently not strong. There is a significant number of articles approaching UP and sustainability in a broader sense and not becoming concrete and specific (Jepson, 2001). By investigating urban history, we aim to understand which factors have shaped RM and UP. It is important to highlight that UP and RM are different

[2] There is considerably uncertainty about the date that Easter Island was occupied (Diamond, 2005).

among regions; this paper refers mainly to UP and RM in the developed world: Europe and North America. This paper explored the relationship between urbanization, UP and RM reflecting on to what extent RM has been an element for UP. It gives an overview of past UP and RM practices, while taking into account the changes that cities have experienced over time. In the discussion, the paper also elaborates on the importance of urban RM as a key consideration for UP towards SD and how this could be achieved.

2.2 Defining RM, UP and SD

Let us start by defining RM, UP and SD in some more detail. As yet, there is no formal definition of RM, although definitions for “natural resources management” and “integrated resources management” are available. Within the scope of this paper, RM refers to the conscious handling of natural resources – energy and materials – and the utilization of infrastructure and technology to meet human needs; including extraction, transformation, consumption or use and disposal of resources. Hence, RM includes natural resources and man-made products.

Planning, in general, aims to achieve an objective, and it proceeds by assembling actions into some orderly sequence (Hall, 2002). However, UP has multiple definitions. “UP refers to a planning with a spatial or geographical component, in which the general objective is to provide for a spatial structure of activities which in some way is better than the pattern that would exist without planning” (Hall, 2002, p. 3). Davidson (1996, p. 457) states that “UP is (or should be) a tool of urban management that helps to answer the questions what?, where?, when?, by whom?, and how?, urban development should take place”. Moreover, “UP has been continuously in a state of flux, reacting against what are seen as problems in the previous system” (Davidson, 1996, p. 452). Thus, although “UP is most often concerned with managing land development at the urban and regional scales, the field has broadened enormously since its origins, and now can be said to encompass the act of planning for desired future conditions at all scales of endeavor, within public and private sectors” (Wheeler, 2004, p. 11). In this paper UP is defined as the sequence of activities aimed to manage spatial development at urban and regional scales considering sociological, economic, political, technological and environmental aspects.

Likewise, SD has many definitions. Sustainability is a concept with many claims and definitions, but it is very difficult to translate into concrete terms (Gunder, 2006; Sahely *et al.*, 2005). A major obstacle to the achievement of SD is lack of agreement of the conceptual basis. There is an inherent ambiguity of the terms: and the question that arises is what can be sustained and developed at the same time? Moreover, for different parties, the direct object of sustainability has different meanings (Seiffert and Loch, 2005). Parkin (2000) refers to more than two hundred definitions of sustainable development. The most accepted definition comes from the World Commission on Environment and Development (WCED) “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987, p. 8). Within this paper we interpret SD as RM that guarantee reliable resource provision for current and future generations, taking into account all potential trade-offs and different scales in space and time (Pahl-Wostl, 2007). And we recognize that SD is not a fixed state of harmony, but a process of change (Reid, 1995).

The relationships between RM, UP and SD is shown in Fig. 1. Although, there is not unanimity of definitions of UP and SD, both activities are concerned with improving the future. Over history UP and RM have evolved over time and adapted to restrictions given by the changing state of cities. Increasing RM has caused increments of urban impact in the hinterland. We identify RM as a key factor within UP towards SD. The following paragraphs will identify the main factors within RM and UP along city development over history.

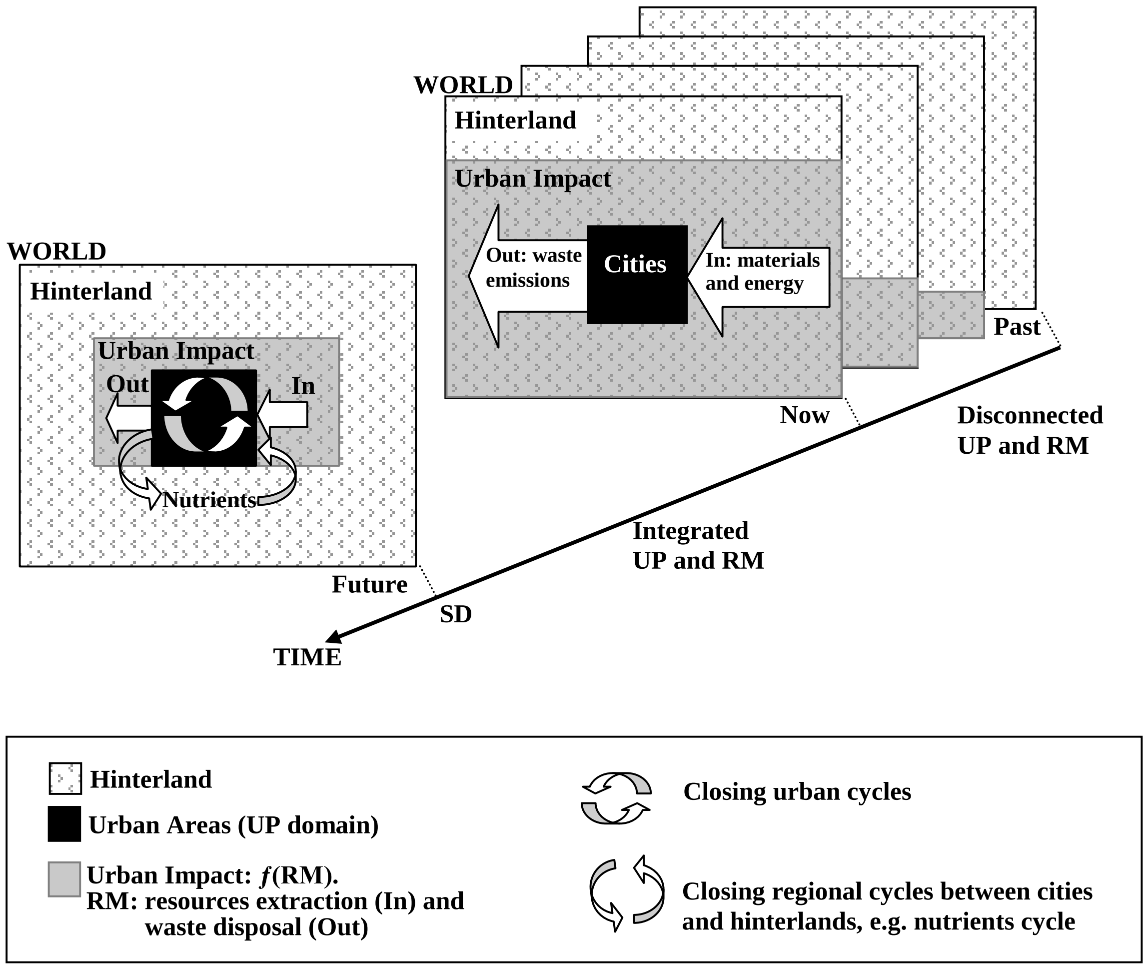

Figure 1 Relationship between UP, RM and SD, and transition from a linear extraction-disposal based RM (now) towards closed cycles based RM (future).

2.3 RM and UP over city history

2.3.1 The beginning of RM and emergence of settlements (8000 BC - 3000 BC)

The relationship between humans and their environment and natural resources has been in continuous change over the years. At the beginning, nomadic communities were basically hunters and gatherers. They collected resources in different places, migrating when resources became scarce. The energetic metabolism of hunters and gatherers has been described as an 'uncontrolled solar energy system' (Krausmann *et al.*, 2008).

The first milestone in organized, large scale RM started with the invention of agriculture, about 10000 years ago (Grübler, 1998; McNeill, 2000; Ponting, 2007). Ponting (2007) refers to agriculture as the most important transition in human history. Many societies changed from hunters and gatherers to an agrarian mode of subsistence. Adoption of agriculture had two major consequences – settled communities and a steadily rising population. Domestication[3] of plants and animals was a key factor on human domination on earth. Domestication and trade of agricultural products enabled division of labor, specialization, and faster technological change, which in turn led to further domestication (Grübler, 1998; McNeill, 2000). Domestication also affected social dynamics because since then, land resources and food were generally seen as a property (Ponting, 2007).

Agriculture also increased human pressure on the environment. Agrarian societies are fueled by solar energy and rely on the energy conversion provided by plant biomass (Krausmann et al., 2008). Compared with hunter and gatherer societies, the metabolism per capita of agrarian societies increased in terms of energy four to six fold and in terms of materials four fold (Fischer-Kowalski and Haberl, 1997). With agricultural development - plowing, fertilizing, flooding and irrigating - and feeding of animals, humankind caused ecological irreversible effects, because domestication improved productivity but involved tradeoffs, causing disturbances of natural cycles (Ehrlich, 2009; Kareiva *et al.*, 2007, Mays *et al.*, 2007).

2.3.2 The rise of the cities and empires (3000 BC – 18th century)

Agricultural production surpluses were a fundamental condition for the emergence of cities. Cities can be seen as a human strategy for survival. Cities concentrate population and resources, provide opportunities, e.g. jobs and services, but also concentrate problems, e.g. pollution (Bugliarello, 2006). With growing population, further RM developments were required, settled societies have to transport resources from their vicinities to survive. Consequently, complex social and infrastructural systems developed to deliver resources

[3] "Domestication involves the selection of traits that fundamentally alter wild species to become more useful to us" (Kareiva *et al.*, 2007 p. 1866).

and services to more densely populated areas (Lee, 2006). As a result, early civilizations[4] appeared about 3000 BC in Mesopotamia and Egypt, and few hundred years later in the Indus Valley, a millennium later in China and another two millennia later in the Americas. In Mesopotamia, Uruk became the first city[5] in the world (Ponting, 2007).

The rise of the first empires, the steady but slow increase in the population and the development of trade led to the development of "pre-industrial" cities. They were characterized by a surrounded wall, not only for defense but also for political and economic control; they also developed water management techniques to guarantee survival (Ponting, 2007). Although, there were no formal UP principles at this time, many ancient cities were planned, meaning that, their existence and their location were laid down consciously (Hall, 2002). Smith (2009) described a combination of planned central zones and unplanned residential neighborhoods as the most widespread principle of spatial organization in the ancient world. In addition, urban hydraulic systems, such as wells, baths and rainwater harvesting, were developed during the Bronze Age in the Indus valley and Mesopotamia (ca.2800 – 2100 BC), later it extended to Greece and finally to the Romans who inherited and improved these technologies (Mays *et al.*, 2007).

During the following centuries, between 1000 BC and 1000 AD, various states and empires rose and fell. For example, in southern Mesopotamia, irrigating the desert soils brought prosperity and fostered population growth. However, after a few years of over irrigating, saline groundwater rose and ruined the soil; yields declined and after some attempts the dynasty finally collapsed (Tainter, 2000). The Indus valley civilization collapsed due to soil salinization but also due to deforestation. Deforestation has been, as well, a common problem in China, Japan, Greece, Italy, among others in different points of history (Ponting, 2007). They are examples of societies and its destructive impact on the environment, leading to their own collapse (Ponting, 2007). They demonstrate the relevance of RM to guarantee sustainability. Population growth and resources availability are an old concern, Greeks were aware that a city should balance its population with its resources, and Plato recommended zero population growth for his utopian republic (Harrison, 1993).

[4] Civilizations are societies that became cohesive states and created organizations, institutions and culture (Ponting, 2007).

[5] Childe (1950) described the following conditions to identify cities from earlier settlements: extensive areas densely populated; with specialized division of labor; and social stratification with centralized power, therefore, leaders - priests, civil and military leaders and officials - will control surpluses by taxes and regular foreign trade. To symbolize the concentration of the social surplus monumental buildings were built. And development of writing, early scientific disciplines: arithmetic, geometry and astronomy. And finally the state organization based now on residence rather than kinship.

The creation of the Roman Empire increased the pressure on the environment due to a large food demand (Ponting, 2007). Romans developed complex and large water supply systems (Mays *et al.*, 2007) and also consumed enormous quantities of water supplies. They also developed a large paved road network system. And the city of Rome even developed problems of traffic congestion (Hall, 2002). Unfortunately, after the decay of the Roman Empire their knowledge was lost. Therefore, water supply systems, water sanitation and public health declined in Europe, low hygienic conditions were common and minimum improvements were present regarding city livability. In Europe, this period is known as the dark ages (Mays *et al.*, 2007). And it was not until the eighteenth century, that formal UP emerged (Hall, 2002).

2.3.3 The industrial and urban revolution (18th and 19th century) – strong urbanization and the need for planning

“Historical evidence suggests that industrialization is a transition process allowing populations to overcome scarcity and the sustainability problems of the agrarian socio-metabolic regime” (Krausmann *et al.*, 2008, p. 642). Industrialization caused changes in RM because the constraints from the controlled solar energy system became abolished. With fossil fuels and their associated technologies, energy became an abundant resource, productivity increased, transportation was fostered, and larger populations could be sustained, triggering an extraordinary growth of urban agglomerations.

Even though at the end of the 18th century, not more than three per cent of the world’s population lived in cities (Ponting, 2007), concern for increasing scarcity of resources was already raised. In his ‘Essay on the Principle of Population’, Malthus (1798) pointed out the unbalance between exponential human population growth and the linear food production growth. Some decades later, Jevons (1865) described the circular causation of RM, stating that economically justified energy-efficiency improvements will increase rather than reduce energy consumption. Additionally in 1885 to create awareness of the massive flows of resources in cities, Geddes used the concept of urban metabolism and established an urban energy and material budget in physical input–output terms (Geddes, 1885). Unfortunately, Geddes’ approach was not sound at that time (McDonald and Patterson, 2007).

Initially, the technological development – inventions in textiles and iron making - caused by the Industrial Revolution seemed to disperse industries out of the towns and into the open countryside. However, when coal became a principal raw material of industry, industry was concentrated where coal supplies were available (Wheeler, 2004). Consequently, industrial towns were developed across Europe to provide the energy source for the industrialization (Ponting, 2007). However, due to the fast development, growing and overcrowding of these towns did not include UP principles.

Early in the 19th century, in European cities, human excrements were collected in cesspools, emptied periodically and reused in agricultural fields (Barles, 2007). However, during the industrial revolution and the rapid growth of cities, environmental problems related to human excreta overwhelmed city governments. This rapid growth resulted in increments on density because public transport systems were nonexistent. Therefore, houses were located within walking distance to the work place (Hall, 2002). In addition to the removal of human excrements, the procurement of adequate drinking water was one of the most important concerns. Due to city growth and overcrowding, the limited water supplies became more and more contaminated with sewage and waste. The simplest RM approach – dumping wastes in the nearest watercourse and drinking from it too – worked only where people were few and water plentiful (McNeill, 2000). Additionally, greater mobility induced by trade facilitated the spread of epidemics like Cholera across the world (Hall, 2002).

Before the industrial revolution, RM and economic systems were primarily local and regional. With the industrial revolution, technological advances in transportation and communication established a global economy. In this economy, the main actors were Great Britain, Germany and the United states. Consequently, they were the most affected by urbanization. As a response to the problems caused by urbanization, formal UP schools were developed in these countries (Goff *et al.*, 1994).

Hence, UP emerged as a very direct response and as a critique of unhealthy and polluted living conditions caused by the urbanization and industrialization (Fainstein, 2005; Watson, 2009). For example, in Britain, after the cholera epidemics of 1831 and 1854, British politicians established requirements for the construction of new housing from the 1870s onwards. The regulations stated that “streets should have a uniform minimum width to guarantee a modicum of air and light; each house originally should have a separate external lavatory, with access to a back alley running parallel to the street” (Hall, 2002, p. 17). The same regulations also posed restrictions to the maximal urban density (Hall, 2002).

The Industrial Revolution dramatically changed RM (McNeill, 2000). The expansion of industrial production required large amounts of natural resources. At the same time, new technologies facilitated the discovery of new resource deposits and improved accessibility and recoverability of the existing resources (Grübler, 1998). In the early 19th century, the massive use of coal made large quantities of manufactured steel available, which in turn fostered mining, industrial production, building construction, transport and warfare. These developments also gave an unprecedented access to the earth's stores of resources (Girardet, 2003).

The exploitation of the earth’s vast, seemingly unlimited, stocks of fossil fuels led to a great transition in our societies which became highly dependent on energy use. Before, all the forms of energy used by human societies were renewable – human and animal power, water, wind and wood (McNeill, 2000; Ponting, 2007). Our current urban metabolic problems stem from the industrial revolution which brought about a shift in the use of materials from the organic to the inorganic and the change from a solar fuelled economy to a fossil fuel based economy (White, 2002). Additionally, industrial societies use three to five times as much energy and materials as did agrarian ones (Krausmann et al., 2008).

In cities, further RM was fostered by infrastructure. Infrastructure was designed to extract, transform, transport, supply and dispose resource. Consequently, an interactive relationship between cities and environment was established, with cities having massive effects on the natural environment and the natural environment influencing urban configurations (Tarr, 2002). This development of urban infrastructure had two major implications. First, infrastructure was and is a driving force for development. Second, infrastructure development may in time lead to path dependency[6].

UP and in particular networking the city was not only a technical task. The implementation of these networks also generated a social and cultural process of adaptation. Infrastructure development led to fundamental changes in behavioral patterns of urban residents regarding RM, in both, their use of resources and disposal of waste. It favored the growth of resources use and caused a complete dematerialization of resources use, from which the only sensitive issue remaining is the price (Schott, 2004). This also implies that, towards an urban SD, a transition of existing infrastructures should take place (Monstadt, 2009).

2.3.4 The 20th and 21st century: rapid urban changes

During the 20th century, the human population quadrupled to almost six billion. Resources consumption increased further and for every increase in production there was a corresponding increase in the excretion of entropic waste and eco-degradation. By the end of the twentieth century, half the world’s land mass had been directly modified for human purposes and people were using half the accessible fresh water (McNeill, 2000). Fast

[6] Path dependency means that choices for certain key technologies and systems can limit the future room of maneuver for municipal policies and urban development. Changes in the system will imply great expenses, inhibiting changes of direction in how cities manage their resources (Schott, 2004), i.e. become a restriction for further development and innovation because infrastructure is extremely slow to change (Tarr, 1984).

urbanization and consequent land use change had altered ecosystems, destroyed wildlife habitats, changed regional climates and released large amounts of carbon into the atmosphere (Grübler, 1998).

As the world industrializes and urbanizes, the global flows of energy and materials were and are still increasing, (Decker *et al.*, 2000), and a growing mismatch between human demand patterns and the capacity of the planet to supply resources and absorb wastes has emerged. In addition, during the 20th century, human action put more harmful gases into the atmosphere. One major source of pollution was and is the mining, melting, refining, and use of heavy metals. When these pollutants become present in soils, they easily enter the food chain. In addition to heavy metals, industrialization also generated many other types of toxic wastes. Man-made chemicals became into existence after the mid-19th century but they only acquired environmental significance after the mid-20th (McNeill, 2000). Moreover, improvements in food production and preservation combined with decreasing of transport costs of the railway and steamship era allowed an unprecedented expansion of agricultural trade (Grübler, 1998). Between 1950 and 1985, the world population doubled and the global food production almost tripled (Goff *et al.*, 1994).

During the 20th century, crude oil and natural gas became the dominant energy sources. Cities became highly dependent on electricity, not only because of the spread of electric motors for different uses but also because electricity provided light and heat. In the late 20th century and early 21st century, several carriers, including nuclear energy, and modern renewable sources have risen in importance and are expected to play an important role in the energy mix of the future (Marcotullio and Lee, 2003; McNeill, 2000).

1901 - 1960: Fertilizers, automobiles and the search for the ideal city

Early agricultural techniques included a basic RM strategy by recycling of organic wastes and minerals in the form of manure and planting nitrogen-fixing legumes to preserve soil fertility (Grübler, 1998). Around 1900, the invention of chemical fertilizers allowed for tremendous increments in the agriculture production and fostered population growth. The impact of chemical fertilizers strongly influenced the choice of crops in and after the 1950s. Those crops that responded well to fertilizers spread far and wide, replacing those that did not. By chemical fertilizer use, food production became dependent on fossil fuels that are needed for fertilizer production. Moreover, fertilizers became water pollutants. Some estimates indicate that more than 50% of chemical fertilizers applied end up in nearby waters (McNeill, 2000).

The spread of the automobile strongly influenced the structure of modern cities, leading to large investments in road infrastructure and to the development of suburbs and less dense cities. New philosophies of road design emerged in the United States and Britain in the early 20th century (Hall, 2002). However, making room for cars took a lot of space and had a negative impact on urban environment as reflected by lead emissions (McNeill, 2000).

Some of the pioneers of UP pursued to design the “ideal city”. To mention some, in the Anglo-American tradition, one of the most influential thinkers was Ebenezer Howard. His “Garden city” concept was proposed in 1898 and reappeared in 1902 in “Garden Cities of To-morrow” (Howard, 1902). The garden city concept took the regional polycentrist view and included self-contained, self-sufficient communities surrounded by greenbelts. Howard’s vision influenced several generations of urban designers in Europe and the United States, including contemporary new urbanism movements (Berke, 2008; Miller, 2002). A new milestone in UP was made by Patrick Geddes, whose book “Cities in Evolution” appeared in 1915. He described how technology development and RM in cities influenced changes of cities (Geddes, 1915). His main contribution was to include human geography as basis of planning and giving planning a logical structure. His method became part of the standard sequence of planning: first, the preparation of a survey of the region, its characteristics and trends; secondly, an analysis of the survey and thirdly, the development of the actual plan (Hall, 2002). Geddes’ approach illustrates that diversity of the local context was already acknowledged in UP in the early 20th century.

Also architects like Frank Lloyd Wright in the United States, Raymond Unwin in England, and Le Corbusier in France moved far beyond design of individual structures to design entire communities and societies (LeGates, 2003). In the early 1930s, Le Corbusier’s “Radiant City” took a centrist urban perspective. Le Corbusier developed the idea of a city with high local concentrations of people in tall buildings, which would preserve open ground space. Uniformity was to be the basis of improving public health and livability. Frank Lloyd Wright’s “Broadacre City” took a decentrist suburban view. His idea of decentralization was motivated by technological developments like the automobile and electricity. In his opinion with these technologies, there was no need of being concentrated in urban areas (Berke, 2008).

1960 - 1990 UP diversification and RM concern

Up to the 1960s, UP was a local government task focused on exercising control over private land use and building design practices, and guiding spatial design of capital improvements such as streets, water pipes and sewers (Berke, 2002). During the 1960s, it was argued that UP should focus on broad principles rather than on details. Moreover, it should stress the process to reach the goal, rather than present the desired end state in detail (Hall, 2002). Between the 1960s and 1970s, cities in the USA and Europe faced poverty, racism, and high pollution levels. These problems questioned the efficacy of the classic view on UP (Berke, 2002). Moreover, critiques also argued that UP theories did not really affect the practice of urban architects and engineers (Hamlin, 2007).

In that same period, RM became high on the public agenda due to problems related to environmental degradation and resources scarcity. In 1962, when Rachel Carson published her book “Silent Spring”, environmental degradation called the attention of the public and of politicians (McNeill, 2000). In 1965 Wolman revised the concept of urban metabolism, proposed by Geddes in 1885. In his study ‘A Typical American City’ (Wolman, 1965), Wolman called for attention towards the large resources consumption of cities. In 1969, McHarg published the book “Design with Nature”, in which, he argued that cities should be planned as an integral part of natural systems. He proposed to use ecology to understand interactions between people and their environment and to use these as guiding principles for UP (McHarg, 1969). In 1968, Hardin published a warning statement on resources management in his “Tragedy of the commons” and concluded that “Freedom in a commons brings ruin to all” (Hardin, 1968, p. 1244). Also modern Malthusians ideologies re-appeared, as in for instance, “The population bomb” (Ehrlich, 1968) and the report “Limits to Growth” (Meadows *et al.*, 1972). Both sources basically concluded that continuation of the growth trends of the 1970s would lead to a collapse of human society because of scarcity of essential resources and food. According to the Club of Rome, this collapse could be avoided by establishing a condition of ecological and economic stability that should be sustainable far into the future (Meadows *et al.*, 1972).

From the 1970s, in UP new urban forms were promoted as a response to environmental concerns. Within these approaches urban planners and designers also strived for a greater sense of place and identity. One example is the “compact city concept” that aims for a more efficient design by building high densities and mixed uses, especially considering energy for transportation. Also containment policies to limit urban growth encouraged densification and protection of surrounding natural resources (Watson, 2009). In the 1980s, communities set out on different development paths as a reaction on unified planning approaches. As described by Allmendinger, (2002) the development of UP theories has been in a hyperactive state since the early 1980s. These theories showed developments in a number of fields, including neo-liberal and public choice perspectives, postmodern planning, neo-pragmatism, political economy approaches and collaborative planning. New urbanists have revived the pre-1960s’ idea that UP is about big, visionary ideas (Berke, 2002). But, it is not until 1987, that the WCED and its report “Our common future” placed the issue of SD at the core of urban policy and UP.

1990 – Now: Managing cities and resources, methodologies and assessments

At the end of the 20th century, "empirical evidence suggests that resource consumption already exceeds the productive capacity of critical biophysical systems on every continent and waste production already breaches the assimilative capacity of many ecosystems at every scale" (Rees, 1999, p. 208). As stated by Vitousek *et al.* (1997, p. 498) "We are changing Earth more rapidly that we can understand it". The scale of pollution increasingly surpassed the thresholds at which waters could assimilate wastes. Dilution as water pollution control did not work anymore (McNeill, 2000) and growth of flows of urban resources caused great problems regarding solid waste.

Initially, RM has been focused on mainly controlling environment deteriorating emissions to water, soil and air, the so called end-of-pipe solutions. Later, pollution prevention and design for the environment with strategies, such as dematerialization, material substitution and recycling have been implemented to minimize environmental impacts (Mihelci et al., 2003). A noteworthy result of this is the general decline in metal emissions after 1980, a consequence of environmental awareness and regulation, and of new technologies with better efficiencies in metal removal and reduced waste productions (McNeill, 2000).

Some of the current global issues related to RM are the availability of resources such as: oil, fresh water, phosphorus, metals; and the disruption of natural cycles, for instance the nitrogen and carbon-cycle (Gordon et al., 2006; Rockström et al., 2009). Moreover, energy and materials are intertwined, for instance fossil energy and agricultural yields, as modern agriculture relies heavily on energy-intensive products such as fertilizers, pesticides and machines (Chambers, 2008).

Recently, the relevance of RM within SD has been recognized. And different approaches have been developed to study urban complexity and its impacts. Some examples of those approaches are Environmental Impact Assessment (EIA), Life Cycle Assessment (LCA) and Ecological Footprint (EF). EIA is an environmental tool used to assess the potential environmental impact of an activity. It assesses the level of impacts and provides recommendations to minimize them (Dincer and Rosen, 2005). LCA is a tool for quantitative assessment of materials, energy flows and environmental impacts of products, services and technologies (Krozer and Vis, 1998). LCA examines products ''from cradle-to-grave''. EF is based on the fact that many material and energy flows can be converted into land-area equivalents. Thus, the EF of a specified population is the area of land required to produce the resources consumed, and to assimilate the wastes generated (Rees, 1999). However, all these approaches have drawbacks, such as the use of aggregation methods and the need for extensive data sets. Therefore, currently, combined and hybrid methods are being developed, e.g. ECO-LCA (Zhang et al., 2010).

From the late 1990s, the notion of SD required that environmental issues were addressed at the same time as economic and social issues, and UP was viewed as having a central role to play in achieving this (Watson, 2009). LeGates and Stout (2003) gave words to the UP complexity by naming some of the issues that planning theory and practice must confront in the twenty-first century. The issues he mentioned are: design, economic feasibility, decision-making theory, conflict resolution, advocacy, race, class and gender equity, and sustainability. Moreover, new agendas in UP are continuously emerging. In 2009, the journal "progress in planning" published two special issues about emerging agendas in UP, showing that UP is an evolving field that should adapt to the current cities' needs. Furthermore, environmental sustainability and climate change concerns have been a fundamental source of new ideas and approaches in UP over the last years (Watson, 2009).

2.4 Discussion: Outlook

Table 1 summarizes the findings of this paper and includes an overview of the development of cities over time, of RM, of innovations in technologies and UP and the debates on urban spatial planning. The paper showed that RM, innovation and technology diffusion are at the core of the historical changes. The agricultural revolution, an innovation in RM, in approximately 8000 BC favored the emergence of cities. The newly established cities required storage, transportation and distribution of food, water and goods, thus increasing the energy demand. Discovery of new energy carriers foster technological innovation that in turn, enhanced population growth, urbanization (Tarr, 1984) and domestication of entire landscapes and ecosystems (Kareiva et al., 2007), by redistributing organisms, energy and materials flows (Alberti *et al.*, 2003).

The historical overview in this paper shows that since the existence of the first settlements, a close relationship between RM, urbanization, technological development and some form of UP has always been present. The first cities usually had some form of road planning in order to facilitate transport. During and after the industrial revolution – an era of many new inventions, such as the steam engine, electricity, chemical fertilizer and the automobile – urban growth accelerated exponentially and resulted in poor living conditions. As a response, various UP schools started to develop in the 1850s. The paper showed that urban RM and UP have developed separately in response to different questions: the demand for urban resources versus the demand for improved living conditions in cities. UP has been a flexible research area since, changing according to new emerging problems in urban areas. It developed further with the increasing complexity of urban areas. Nowadays, the demands posed on UP are overwhelming with many objectives that are sometimes conflicting, including sustainability which has been added in recent years.

Table 1 Historical overview of world population, changes on resources management (RM) and urban planning (UP) Note: Sources for population values are ESA-UN; 1999, 2005a, 2005b; Marcotullio and Lee, 2003; Modelski, G., 2003;UN-Habitat, 2008

		BC							AD					
		-20000	-8000	-3000	-2000	-1000	-500	0	1000	1200	1500	1700	1800	1850
World population (Millions)		-	-	-	-	-	-	300	310	400	500	790	1000	1200
% Urban		-	-	-	-	-	-	-	-	-	-	-	<3	-
Biggest city Population (Millions)		Non existing	First settlement	Uruk 0.04		Thebes 0.12	Babylon 0.20	Rome 0.80	-	Baghdad 1.0	Beijing 1.0		Beijing 1.1	London 2.3
Main feature		Nomads	Agriculture	Empires	Trade & defense				Dark ages				Industrialization	
RM – RM DRIVERS	Food	Hunters gatherers	Agriculture surplus		Small ploughs						Malnutrition due to growing popullation		Use of human excrement as fertilizer Worldwide diffusion of crops and animals	
RM – RM DRIVERS	Water		Irrigation, Sewer Pipes				Aqueducts							
RM – RM DRIVERS	Energy		Human and animal power							Water power Water mills		Wind, wood	Steam Coal	
RM – RM DRIVERS	Materials	Wood Stone Bones			Metals: Copper & bronze	Iron					Textiles	New products from colonies brought to Europe		Mining
RM – RM DRIVERS	Transport	Walking	Horses				Roads ("pikes") water Transportation (ships)					Canals Ports	Carriage Bicycle	Steamship Railways
RM	Approaches												Nature absobs human load Dilute	
RM	Bottlenecks						First description of traffic congestion Large water consumption						High densities, Pollution of water bodies, and epidemics	
RM	Thinkers													
UP	UP drivers	Cities developed close to water resources			Religious and political power: Palaces		Surrounded wall for defense and political and economical control					Public health	Formal UP	
UP	Models			Planned central zones and unplanned residential neighborhoods			Timber frame-houses and earthworks constructed with timber and stone						Walking cities	
UP	Bottlenecks			Cities developed close to water resources		Security							Rapid urban growth	Dense unplanned settlements
UP	Thinkers						Plato: Zero population growth						Malthus: Unbalance between geometrical population growth and linear food production growth	

Table 1 (Continuation)

				AD							
1870	1890	1900	1920	1950	1960	1970	1980	1990	2000	2010	Future
-	-	1600	2000	2535	3032	3699	4451	5295	6124	6907	
-	-	13	-	29.1	32.9	36	39.1	43	46.4	50.6	
-	-	London 6.5	-	New York 12.5	-	Tokyo 21.0	-	-	Tokyo 34	-	
			Mass production and consumption				Pollution & Environmental concern				**SD**
		Chemical fertlizer Increasing livestock	Industrialization of agriculture	Pesticides Ovefishing	Improvements on food preservation Worldwide food web Green Revolution:genetic modification of species				Phosphorus availability concern Competing claims with energy crops		Integrating UP + RM = Low impact urban design RM towards closed cycles Local context specific models
Sewer			Water pollution due to fertilizer use						Integrated Water Management		
			Oil Electricity				Gas	Nuclear	Renewable		
industrial production, building construction		Mining, smelting, refining Heavy metals		Petrochemicals, plastic, steel, aluminum		Electronic, recyclable and degradable					
Paved roads			Car Roads	Subway Bus			Air transport				
	From organic to inorganic	Export products	Dump & export waste				Pollution control, environmental technology, disassembly and recycling		Dematerialization Material substitution, Cleaner production	Resource recovery	
		Water and soil pollution	Ecosystems alteration Toxic waste		Pollution due to man made chemicals		Environmental degradation and resources scarcity		Earth carrying capacity exceeded	Climate change Resource Scarcity Un-sustainable consumption	
	Geddes input-output analysis				Wolman: metabolism of a typical American city	Limits to growth		Our common future	EIA, LCA, Ecological footprint Cradle to Cradle		
					Regional economic development, indefinite expansion, decentralization Containtment		Environmental planning, sustainability Compact city			Planning for long term sustainability	
Streets minimum width and maximum densities	Land use regulation: Zoning Transportation planning		Planning for cars	Master plan		Public participation	New urbanism Environmental justice	Smart growth			
			Space for cars		Critiques about UP theories not affecting the practice		Hyperactive state of UP theories		Difficulties to translate sustainability into practice		
Jevons' Paradox	Howard's: Garden City		Geddes' planning methodology Frank Lloyd Wright's Broacre city and Le Corbusier's Radiant city		McHarg: Design with nature						

After the industrial revolution, RM increased and shifted to inorganic materials and to a fossil fuel based economy. It is very clear that our current urban un-sustainability is rooted in a massive resource consumption and waste production beyond natural supply and recycling limits. To guarantee urban sustainability, cities must be planned to foster strategic RM. Knowing that the spatial organization of a city and its infrastructure influence RM (Alberti et al., 2003), UP for SD needs to go beyond traditional planning and strategy making (Bagheri and Hjorth, 2007). As presented in section 2, RM is a key component of SD. From that perspective, it is also clear that if SD and UP are to be integrated, RM is an important element, if not the key element, to take along.

A remarkable aspect is that, UP pioneers in the 19th century were already thinking about the ideal shape of the city from the perspective of managing resources and providing high quality of life to inhabitants. Paradoxically, more than a century later, formal links are still missing between RM and UP. There is clearly a need to develop a holistic approach to evaluate our cities, integrating sustainable RM and UP.

Concluding, there is a need for a comprehensive framework that integrates RM and UP. Towards urban sustainability, RM becomes a formal and critical link between UP and SD. As stated by Rees (1999, p. 216), "Urban planning in the 21st Century should evolve towards an ecologically-oriented macro-architecture, fully integrating the design and location of energy-and material-efficient buildings and urban infrastructure with overall spatial planning further to minimize material throughput". As a consequence of this, in the first place, planners need tools to understand cities and regions as environmental systems that are part of regional and global networks (Campbell, 1996). Such tools should be used by different stakeholders during UP processes and translated into effective decision making. As stated by (Graedel and Klee, 2002, p. 528), "If we are indeed serious about sustainability…we can move forward only by converting that fuzzy concept to dependable, measurable metrics". It is our opinion that only by using RM as a formal link to integrate UP and SD, we will achieve sustainable urban planning. Sustainable UP should aim for low impact cities by integrating RM and UP.

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Chapter 3

Harvesting urban resources towards more resilient cities: proof of concept

Abstract

With accelerating global changes, cities have to cope with growing pressures, especially for resource supply. Cities may be considered as resources reservoirs and producers of secondary resources. This paper introduces the concept of urban harvesting as a management tool to change inefficient linear urban resource usage and waste production into sustainable urban metabolism. The Urban Harvest concept includes urban metabolism and closing urban cycles by harvesting urban resources. The purpose of this study was to quantify the potentials to harvest water and energy at different scales. We investigated potentials for the Netherlands. Results show that at national scale, potentials can cover up to 100% of electricity demand, 55% of heat demand and 52% of tap water demand. At neighborhood level, similar percentages were found for energy. Only 43% of water demand was achieved, due to fact that treatment measures were not considered. These results indicate the large potential of cities as providers of their own resources. Therefore urban resources management is a key element of future city design towards more resilient cities.

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3 Harvesting urban resources towards more resilient cities

3.1 *Introduction*

Currently, cities are highly dependent on other cities and hinterlands to supply materials and energy, and to dispose waste (Bai, 2007; Cola et al., 2005). This dependency can be measured by calculating the ecological footprint of cities. Several ecological footprint studies have shown that cities greatly exceed, or overshoot, their bio-capacities by typically 15–150 times (Doughty and Hammond, 2004). Cities are not sustainable because they do not use resources efficiently. In general, cities have a linear usage of resources and waste production, without feedbacks of resources in terms of quantity and quality (Leduc et al., 2009). The root of the current urban un-sustainability is the massive resource consumption and waste production beyond natural supply and recycling limits. Therefore, cities worldwide are facing the challenge to find and implement alternative strategies (Cola et al., 2005) towards more sustainable management of urban resources.

“Cities are concentrated centers of production, consumption, and waste disposal that drive land change and a host of global environmental problems” (Grimm et al., 2008 p 759). Cities are both responsible for, and respond to, changes in biogeochemical cycles (Grimm et al., 2008). The current pace of global change is unprecedented. Considering the current level and rate of urbanization and growing ecological footprints, the impact of inadequate urban resource management has become a global issue. Some of these global issues are the availability of the resources such as: oil, fresh water, phosphorus, metals; and the disruption of natural cycles, for instance nitrogen and carbon-cycle (Boyle et al., 2010, Gordon et al., 2006; Rockström et al., 2009). Therefore, the urban system, as the world’s primary sink of resources, turning these into waste, plays a key role to find solutions for these global pollution and depletion problems (Xu et al., 2010). By harvesting urban resources, global impacts are reduced and the resilience of cities can be improved as well. “Resilience is a measure of robustness and buffering capacity of the system to changing conditions” (Berkes and Folke, 1998, p. 12).

For a typical city in an average industrialized country, consumptions per capita per year are 150-400 GJ for energy, and 15-25 tons for materials (Krausmann et al., 2008). Large portions of the flows of wastewater, solid waste, demolished construction materials, etc., are exported out of the urban system, while others remain in the system as urban ‘stocks’ as internal resource reservoirs (Brunner 2007). Looking at the urban networks some of the city outflows and stocks, often called waste, still have a remaining quality or a set of potentials that can be harvested and used within the city itself. There are several possibilities within cities to harvest resources (Agudelo et al., 2009; Leduc and Rovers, 2008). In contrast to linear, resource-to-waste systems, cities can also be considered as resources reservoirs and producers of secondary resources. This chapter introduces the concept of “urban harvesting” as a management tool towards more resilient cities. The potential for harvesting urban water and energy in the Netherlands is explored at two different scales: country and neighborhood scale.

3.2 *Urban metabolism*

The concept of metabolism has been adopted from biology. It refers to “physiological processes within living things that provide the energy and nutrients required by an organism as the conditions of life itself” (Tarr, 2002 p. 511). This concept has been adapted for cities as “urban metabolism”. Urban metabolism treats cities as organisms and provides an extensive framework for analyzing a city’s input–output relationships with its surrounding biophysical environment (McDonald and Patterson, 2007). Urban metabolism is a means of quantifying the overall flux – input-transformations and outputs – of resources. Urban metabolism can be studied at different scales, including global, country, city and household levels. In the last decades, several “urban metabolism” studies have provided valuable information about the resources flows through and in cities (Kennedy et al., 2007). Moreover, urban metabolism is also being used as basis for sustainable urban design and for policy analysis (Kennedy et al., 2011).

3.2.1 Quality losses in the system

As described by Leduc et al. (2009), we can explain the current urban energy and water system as shown in Fig. 1. At the supply side (Fig. 1, left side), different sources provide water or energy at different qualities. The urban water or energy network must be fed with a certain quality, generally the highest quality demand, e.g. tap water or electricity at given voltage. To reach the required network quality, a conversion step to upgrade the original quality is necessary, e.g. energy transformers or water purification. Each conversion step consumes energy and materials, influencing the efficiency of the system. At the demand side (Fig. 1, right side), different activities require different resource qualities. But, because the network can provide only a single quality, some of the activities will get a higher quality than needed, the “quality surplus” (*Qs*). Also, when a given activity is performed, some remaining quality is left, the “un-used remaining quality” (*Qr*). To minimize losses, *Qs* and *Qr*, quality of supply and demand should be matched according the “fit for purpose” principle.

3.2.2 Linear Metabolism

Currently, urban metabolism is mostly linear. For their resources, cities depend on hinterlands and other cities to import water, energy and goods, and to export wastes (Bai, 2007; Cola et al., 2005). Cities use these resources inefficiently and after use, valuable remains contained in waste streams, are thrown away (Girardet, 1992), e.g. emissions of nutrients to water or energy dissipated as unused heat (see Fig. 2a). Linear metabolism can be associated with two main problems. On the one hand, the high rate of resources consumption puts stress on resources availability by depletion; on the other hand, massive disposal of waste causes pollution. The urban metabolism is built up of different components: water, energy and materials. In general, all of these components are in a linear sequence, completely depending on import of high quality resources to function, without harvesting and feedbacks in the chain. This we identify as linear metabolism. This external dependency and inefficiency makes cities more and more vulnerable (Cola et al., 2005).

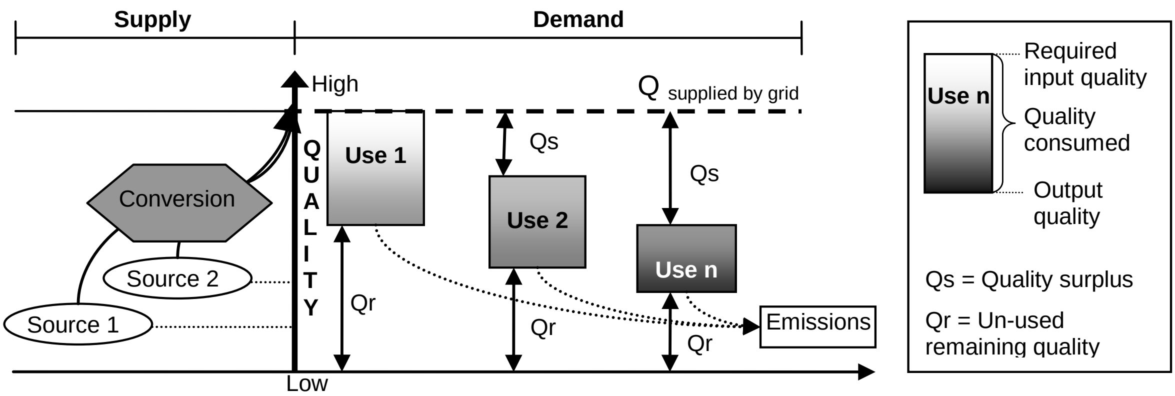

Figure 1 Illustration of quality losses within the urban energy and water system (After Leduc et al, 2009)

In contrast, circular metabolism, that resembles the metabolism of natural ecosystems, has a low consumption rate, and includes recycling and reuse of the different urban flows. Circular metabolism has less impact on hinterlands and other cities and enhances the resilience of cities (see Fig. 2b).

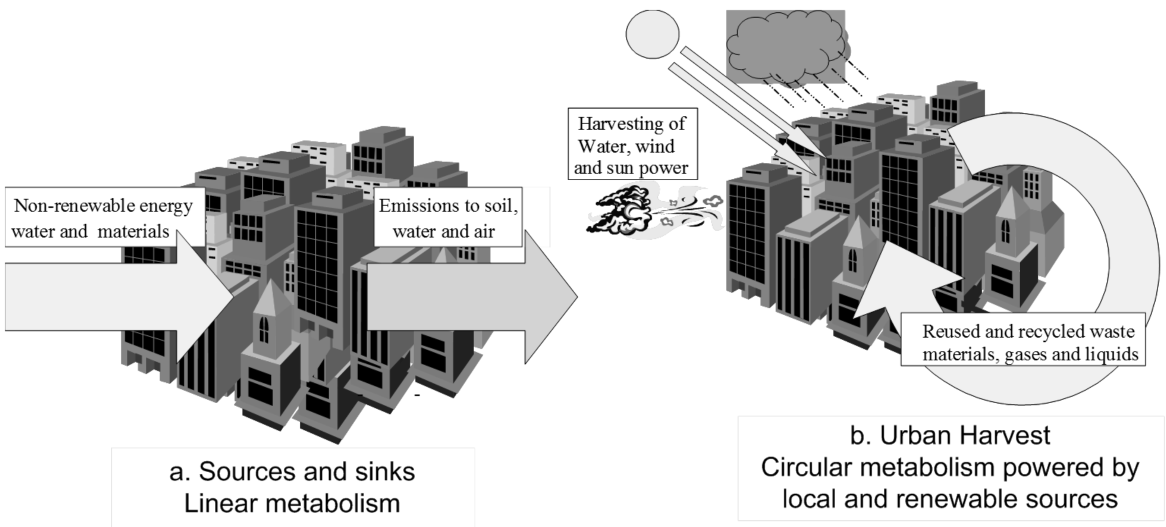

Figure 2 Linear vs. circular urban metabolism

3.2.3 Urban Harvest concept and Urban Harvesting Strategies

The current challenge towards more resilient cities consists in closing open links between sources and demand. However, most of the cities ignore their potential resources. Traditional resources management focuses mainly on natural resources. Reijnders (2000) categorized natural resources as flux, renewable, and virtually non-renewable. With increasing urbanization, secondary resources are important flows to consider. Secondary resources are outputs from human activities that can be used as an input to other human activities. Examples of secondary resources are grey water or residual heat. Therefore, cities can be seen as producers of secondary resources.

Based on the concept of urban metabolism, the Urban Harvest concept has been developed to investigate all possible options for harvesting flux, renewable and secondary resources to be used within the city itself (Rovers, 2007). The urban harvest concept aims for closing the open links towards a circular metabolism (Fig 2b). Towards closing cycles, the first step is to make an inventory of the demand; secondly, to explore options to minimize demand; thirdly, to make an inventory of alternative sources; and fourthly, to couple supply and demand by harvesting local and renewable resources. To harvest local resources, four main harvesting strategies are defined (Agudelo et al., 2009):

1. multi-sourcing;
2. cascading;
3. quality upgrading and recycling;
4. quality upgrading and closing loops.

Multi-sourcing refers to harvesting primary and secondary resources that are locally available and renewable, e.g. harvesting of rain water or solar energy. Cascading refers to harvesting remaining qualities of flows, by re-using remaining qualities for lower quality demanding purposes (Sirkin and Houten, 1994; van den Dobbelsteen et al., 2007). Cascading aims to reduce waste inputs and outputs. Cascading further aims to better match qualities of demand with supply, by using low quality flows for low quality demand activities, e.g. using wastewater from the shower to flush the toilets or harvesting remaining heat in shower water. Quality upgrading and recycling refers to on-site treatment for further re-use, e.g. grey water reclamation or using a heat pump to increase the temperature. Quality upgrading and closing loops refers to on-site treatment of a system which does not have inputs or outputs. However, quality upgrading implies resources and energy inputs, and those should be powered by local non-fossil energy and sustainable materials.

3.2.4 Urban Harvest as a tool for planning resilient cities

Cities and their surroundings are systems in constant change. “Urban resilience generally refers to the ability of a city or urban system to withstand a wide array of shocks and stresses" (Leichenko, 2011 p 164). We propose resource management as a key factor for sustainable urban planning to close open links between sources and demand. The urban harvest concept aims to reduce single source dependence by optimizing the demand and by harvesting local resources. Using the urban harvest concept, multiple resource linkages among functions will result in a flexible network which allows overcoming shock or failure of one of the sources. By producing its own resources, an urban area diminishes external dependency being less vulnerable to external changes and being able to cope with changing conditions.

Harvesting of urban resources requires an inventory of flows in terms of quantity and quality. Furthermore, to harvest available resources within a city, it is also important to know at what time and at which location the resources are available. The four parameters – quantity, quality, location and temporal characteristics – link the field of resources management with urban planning practices. To design more sustainable and self-sufficient cities, city planners have to take into account those parameters. If a city wants to use the remaining energy and water qualities, certain infrastructure and planning changes are necessary (Leduc et al., 2009). For instance, to use the remaining heat of an industrial process, another function has to have a demand for the remaining quality and quantity at the moment it comes available and this has to be located close by. Therefore, infrastructure, like piping, needs to be installed to transport the heat from supply to demand locations. In case the supply and demand are periodically out of phase, the remaining quality should be stored, e.g., in underground water reservoirs such as aquifers. By creating storage, cities can reduce the importance of temporal characteristics.

Using remaining qualities efficiently, and keeping track of the described parameters, can help cities in their transformation towards more resilient cities. We propose an urban harvesting based method, in which supply and demand coupling options and storage are explored. Water, energy and materials are intertwined flows in cities, thus special attention should be given to those inter-relations. The urban harvest concept can be used for the different urban flows, like water, energy and materials. Fig. 3 shows different possibilities to couple energy, water and material cycles, taking into account the qualities required and linking urban, industrial and agricultural functions. In addition, measures to limit spillage, such as measures to reduce household water usage, and insulation of buildings for reducing thermal energy demands, are an important part in any sustainability effort.

This chapter only considers two flows - water and energy - at two spatial scales - nation and neighborhood - and one temporal scale – average year, to show the applicability of the method. But a complete analysis should include material flows as well as other spatial scales, e.g. city or regional scale, and other temporal scales, e.g. monthly or weekly.

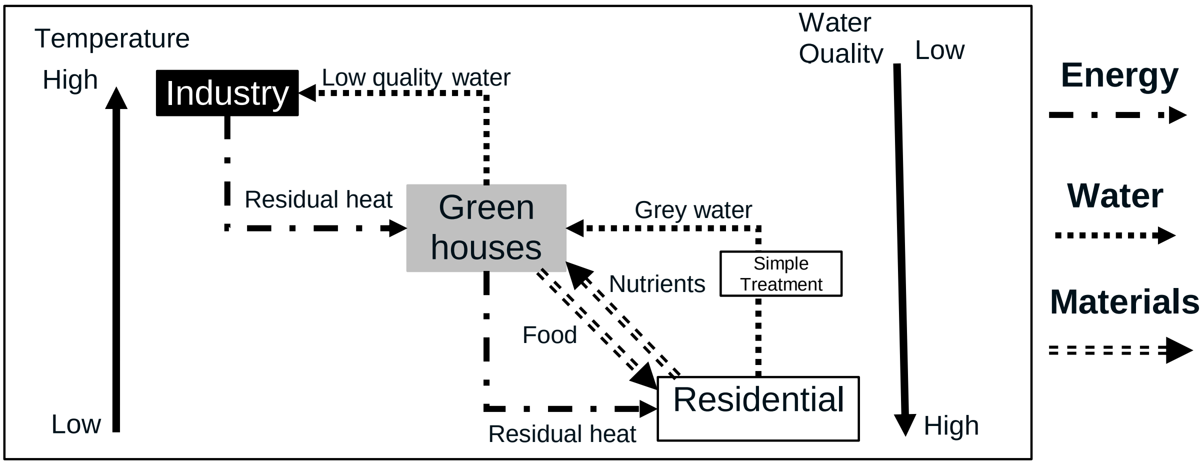

Figure 3 Example of possibilities to couple energy, water and materials. Supply and demand are based on resources quality

3.3 Methodology

Resource consumption patterns in cities are closely linked with land uses, more specifically with urban functions. Various functions can be defined such as: residential, business, etc. In general, all urban functions need water, energy and materials. Description of urban functions can provide an overview of the resource consumption intensity in the area in relation to land-use. To give an aerial overview of land-use distribution and urban functions and to relate that to the harvesting potential, we used the urban tissue (UT) as the functional unit. Leduc and Rovers (2008) defined the UT as a conceptual approach to visualize resource demand and resources supply potential of an urban area, in an easy to grasp visualization. The UT is a standard unit, 1 hectare that allows identification of the different flows within the urban region, like energy, water, food, etc.

The Urban Average Tissue (UrbAT) is the visualization of all the urban functions fitting in an average hectare. The UrbAT provides insight in the distribution of functions in an urban area, percentage-wise and building-wise: e.g., number and type of houses on the tissue. First, the total urban surface of the given area is determined. Then, the area of the different urban functions is calculated. After that, all function surfaces are recalculated to m² per hectare (Leduc and Rovers, 2008; Rovers 2007). The UrbAT is a way to express the typologies of the built environment and can be used as a general benchmark to compare the urban harvest potentials with other cities with different typologies (Rovers, 2007).

The description and calculations for the urban water and energy tissues are based on the UrbAT. The urban energy average tissue, Energy-UrbAT, and the urban water average tissue, Water-UrbAT, were developed as a tool for an accounting and planning methodology. Energy-UrbAT gives an overview of how much energy, of certain qualities, can be captured and converted within the urban area when applying several technologies, and it is described in detail in Leduc and Rovers (2008). Water-UrbAT systematically investigates the potentials for multi-sourcing, re-using and cascading water within the system and aims for a more efficient water resources use, and it is described in detail in Agudelo et al. (2009).

An urban area has a maximum amount of a resource that is available or can be made available, collected or captured, within the boundaries of the urban tissue, the Potential Urban Harvest (PUH). When capturing and converting this potential, even though the best available technologies are applied, there are limited efficiencies and losses. Therefore only a percentage of the maximum potential can be harvested. Furthermore, the characteristics and typologies of the urban area will provide additional limitations as well as temporal patterns of demand and supply. Thus, the real potential that can be harvested, taking into consideration technology, urban typology, and temporal characteristics, is called the Urban Maximum Technical Harvest, (UMTH). UMTH is calculated as follows:
$UMTH = PUH \times Ø_{tech} \times Ø_{urban} \times Ø_{temp}$.
In which $Ø_{tech,}$ $Ø_{urban}$ and $Ø_{temp}$ are reduction factors related to technical efficiency restrictions, urban typology restrictions and temporal restrictions, respectively. The method to develop the specific tissues for urban water and energy consists of the steps (based on Agudelo et al., 2009) as described in Table 1.

Table 1. Method to develop the specific tissues

Step	Action
Demand inventory	Hierarchical quality identification: quantification of water and energy use within the urban tissue
Demand Minimization	Identify measures that contribute to lower the demand, focusing on technology implementation
Supply inventory	Hierarchical quality identification and quantification of available water and energy sources. Identification of hidden flows as new water and energy sources and calculation of the PUH
Optimize coupling of Supply– Demand	Calculation of the UMTH by scenarios development, considering restrictions by technology and urban typology. Ensure that the quality of the water and energy is as high as required for the use but not higher, by implementing multi-sourcing, cascading and recycling

3.4 Results

This chapter focuses on estimating the potentials to harvest water and energy at two spatial scales: country and neighborhood. Minimization was not addressed. Firstly, results of the Dutch average case are presented. Secondly, results for a specific neighborhood within the Netherlands, a small district in the city of Wageningen are presented.

3.4.1 Dutch urban average tissue (UrbAT-NL)

The distribution of functions in an average urban area in the Netherlands is represented in the Dutch Urban Average Tissue[7] (UrbAT-NL). Fig. 4 shows the UrbAT-NL.

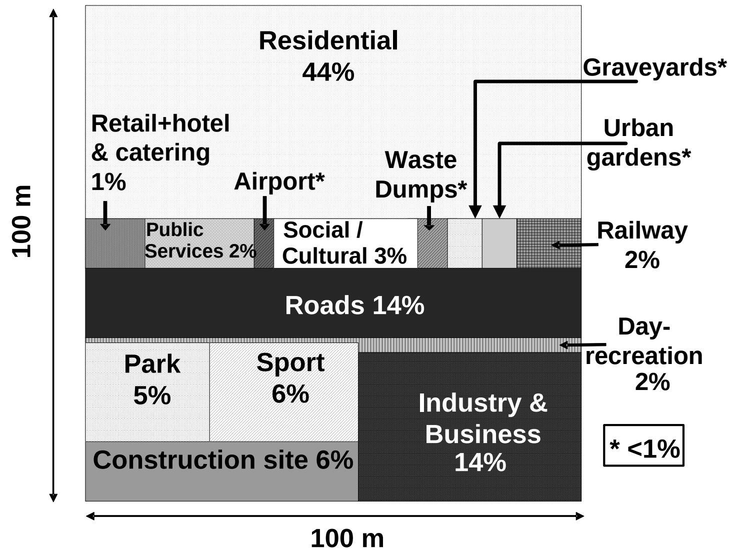

Figure 4 Dutch average urban tissue

Dutch energy average tissue - Energy-UrbAT

The energy demand of the UrbAT-NL was calculated for different urban functions shown in Fig. 4: households (EnergieNed, 2002; SenterNovem, 2007), industries (CBS, 2010a; ECN, 2010), and offices, business buildings, care sector facilities, educational facilities, hotels and catering industry facilities, and shops (Klinckenberg, 2004). To calculate the potentials of the tissue to generate energy, two different qualities of urban energy demand were considered: electricity and heat. Those qualities were studied considering several technologies: e.g. Photo-Voltaic (PV) cells; Peltier-elements in the roads; and wind turbines. Cascading of waste heat is also a potential source, but due to lack of data, we did not further study this option. Table 2 shows the results for the studied potentials for the UrbAT-NL, for electricity and heat. We calculated the results for two scenarios.

Scenario 1: PV-cells on roofs and facades, half of road surface available for Peltier-elements, to generate electricity, and other half for RES® (Road Energy Systems), to generate heat; and 5 small wind turbines. These measures result in 98% savings due to renewable electricity generation and 28% savings due to renewable heat generation. Scenario 2: PV-cells on roofs and facades, full road surface available for RES®; and 5 small wind turbines. Results showed that harvesting of local resources can fully supply the existing demand and generate a 9% surplus due to renewable electricity generation and 55% savings due to renewable heat generation.

[7] Total Dutch surface: 4,150,000 ha; Dutch urban surface: 507,020 ha (Leduc et al., 2008).

Table 2. Potential energy supply-demand for UrbAT-NL

		Electricity MWh/ha –year		Heat GJ/ha-year	
		Scen. 1	**Scen. 2**	**Scen. 1**	**Scen. 2**
Current Demand [a]		450		1800	
Harvest	PV[b]	225[d]	295[e]		
	Road	20 [f]		500 [g]	995 [g]
	Wind turbines [c]	195	195		
Potential Savings		**98%**	**109%**	**28 %**	**55 %**

Source: (CBS, 2010a; EnergieNed, 1995, 2001, 2002; Klinckenberg, 2004; SenterNovem, 2007).
[a] PUH, of solar radiation in the Netherlands is c.a. 1 MWh/m²-year or 10000 MWh/ha-year (Sinke, 2001).
[b] Roof and façade area based on Rovers et al., 1997.
[c] Proven 15 kW-type. Yearly yield is calculated by formula: $E_{yr} = b*A*V^3$ (Leijendeckers and van Arkel, 2002); b (beurskens factor) = 3.7 (Constant), V = 5.5 m/s, A = surface rotor, diameter is 9 m.
[d] PV-cells with an efficiency of 15 %.
[e] PV-cells with an efficiency of 20 %.
[f] Combrink et al., 2004.
[g] www.roadenergysystems.nl

Dutch water average tissue - Water-UrbAT

The water demand of the tissue was calculated for different urban functions: households and industries (CBS, 2010b; Foekema et al., 2008). The baseline inventory showed that at industry level multi-sourcing is already practiced. Nevertheless, remaining quality of the effluent is still lost when diluted in the sewer and transported to the wastewater treatment plant. Only a small percentage of industrial water is reused by other companies. Furthermore, linkages among industry and residential functions do not exist.

To calculate the potentials of the tissue to generate water, four different qualities of urban water demand were considered: tap water, direct ground water, surface water and brackish water. For the case of the water cycle, several state-of-the-art technologies allow decentralized treatment of rain and grey water for reuse (Li et al., 2009; Peter-Varbanets et al., 2009). However, treatment might imply using chemicals, energy and space. To calculate the potential harvest, we studied the cases in which only simple treatment is required. Two measures were taken into consideration: multi-sourcing by using rain water, and cascading of grey water to industries and cascading 10% of industrial water. Table 3 shows the results for the studied potentials for the UrbAT-NL, for water. Results showed that by harvesting rain water 32% of the tap water demand can be fulfilled. Furthermore, by combining cascading and recycling tap water demand could be minimized up to 52%.

3.4.2 Neighborhood scale - urban average tissue

Analyzing the results for the Water-UrbAT and Energy-UrbAT, we can identify several potentials to improve resources management within urban areas. However, to define feasible implementations, studies at local scale are necessary. The same methodology as for national scale is suitable for neighborhood scale, and it allows comparison among different tissues. A specific neighborhood within the Netherlands was selected to calculate the different tissues. This neighborhood is located in the city of Wageningen, Wageningen Noordoost, there are in total 15 duplex houses, 30 dwellings, and the average occupancy is 1.8 people per dwelling (CBS, 2008). Fig. 5 shows the area and its urban function distribution and the urban average tissue of the neighborhood. And table 4 shows the different functions with their respective areas.

Table 3. Potential water supply-demand for UrbAT-NL, in m^3/ha-y

	Current supply sources		Tap water	Direct ground water	Surface water	Salt-brackish water
Current demand			2154 [a]	555 [b]	16957 [b]	14562 [b]
		PUH				
Harvest	Rain water	8840 [c]	688 [d]	555		
Harvest	Grey water	622 [e]	436 [f]			186
Harvest	Industrial/business waste-water [g]	3207 [h]			55 [d]	3152[d]
Potential Savings			52%	100%	0.3%	23%

[a] Tap water consumption in Netherlands in 2007 was 1088 million m^3, of which 72% households (1551 m^3 ha^{-1} y^{-1}), 12% small scale business (258 m^3 ha^{-1} y^{-1}), and 16% (345 m^3 ha^{-1} y^{-1}) industries (VEWIN, 2008). Sources for tap water are groundwater (55%), surface water (39%) and dune and bank filtration (6%).
[b] Extraction for industrial purposes, from which 95% is for cooling (CBS, 2010b).
[c] Yearly average rainfall 884 mm -Average 1981 to 2009, (CBS, 2010c).
[d] Only rainwater harvesting from residential areas, assuming 30% losses, 2732 m^3/ha are available. Assuming that rain water is used for laundry machine, only 85 m^3/ha is needed. If the tap water used by industry is replaced by rain water, (603 m^3/ha) the maximum use of rain water is 688 m^3/ha.
[e] Only considering harvesting of wastewater from the shower (light grey water).
[f] 436 m^3/ha-year for toilet flush.
[g] In 2001, 457 m3/ha-y was already reused within industries (CBS, 2010b).
[h] Assuming 10% or recycling of each source of water.

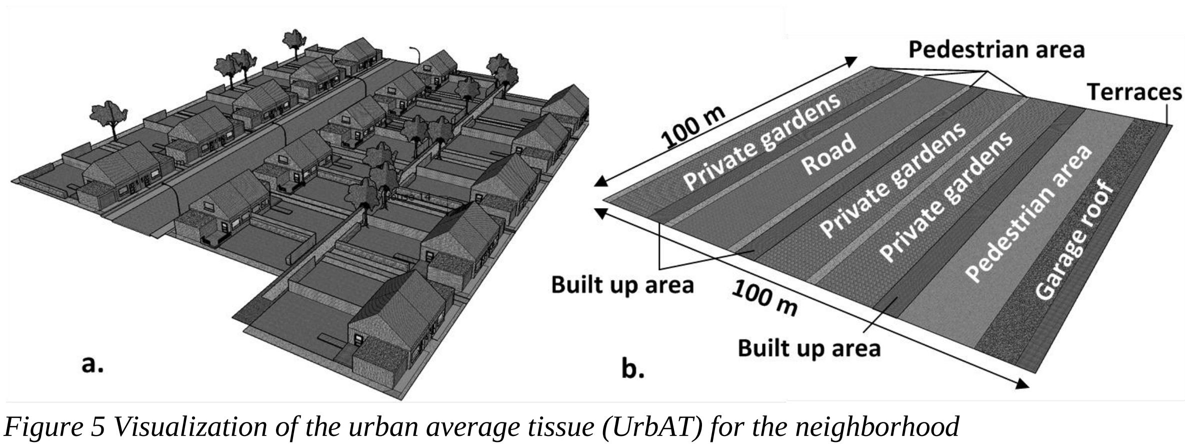

Figure 5 Visualization of the urban average tissue (UrbAT) for the neighborhood

Neighborhood energy average tissue - Energy-UrbAT

Following the described methodology, the energy demand and energy sources inventory were defined for the average tissue. To quantify the UMTH, we defined two scenarios considering electricity and heat. Scenario 1: solar boilers on roof of garages, PV-cells on half of roof surface of built up area, and on half of remaining roof surface of garages; Peltier-elements in half of road surface and RES® in other half of road surface. Scenario 2: solar boilers on roof of garages; PV-cells on half of roof surface of built up area, and on half of remaining roof surface garages and RES® in complete road surface. Table 5 summarizes the results. Results showed that this neighborhood can provide for its own electricity demand, and have a 33% surplus. The heat generation is not enough, but scenario two can provide about half of current heat demand.

Table 4. Functions and areas of Neighborhood tissue

Block description : 30 dwellings		**Average Tissue (1 ha) – 35 dwellings**
Function	**Total Area (m²)**	**Area (m²/ha)**
Built up area	1261.1	1474.4
Roof garages	585.8	684.9
Private gardens	3138.6	3669.5
Pedestrian area	1960.0	2291.4
Road	1329.3	1554.1
Terraces	278.6	325.8
Total	8553.4	10000

Table 5. Potential energy supply-demand for the neighborhood

		Electricity, MWh/ha – year		Heat, GJ/ha – year	
		Scen. 1	Scen. 2	Scen. 1	Scen. 2
Current demand [a]		126		2594	
Harvest	PV [b]	149	149		
	Road	19		520	1,040
	Solar boilers [c]			375	375
	Total	168	149	895	1,415
	Potential Saving	133 %	118 %	35 %	55 %

[a] Based on Dutch average (SenterNovem, 2007).
[b] PV-cells with an efficiency of 15 %.
[c] 5 m^2 per household.

The advantage of the urban tissue is that consumption and harvestable sources within the area can be visualized, indicating their amount and location. Fig. 6 shows the demand and supply for electricity and heat for the two scenarios studied. Notice that the potential in Fig. 6 and 7 refers to the production of energy per m² of the specific urban function. Thus, the volume represents the potential of harvesting resources from the average hectare.

Neighborhood water average tissue – Water –UrbAT

Following the described methodology, the water demand and water sources inventory were defined for the average tissue. To quantify the UMTH, we defined two scenarios considering three qualities. The first scenario uses the maximum potential of rain water that can be collected from the roofs to supply for laundry (Q_2) and toilet flushing (Q_3). For the remaining demand of toilet flushing, grey water cascading was used. The second scenario uses rain water for laundry, and cascading of grey water to supply for toilet flushing demand. Table 6 shows the results. Results showed that only 43 % of the total household consumption is minimized, even though the potentials are three times the demand. In a similar way as for energy, water demand and sources are visualized in Fig. 7.

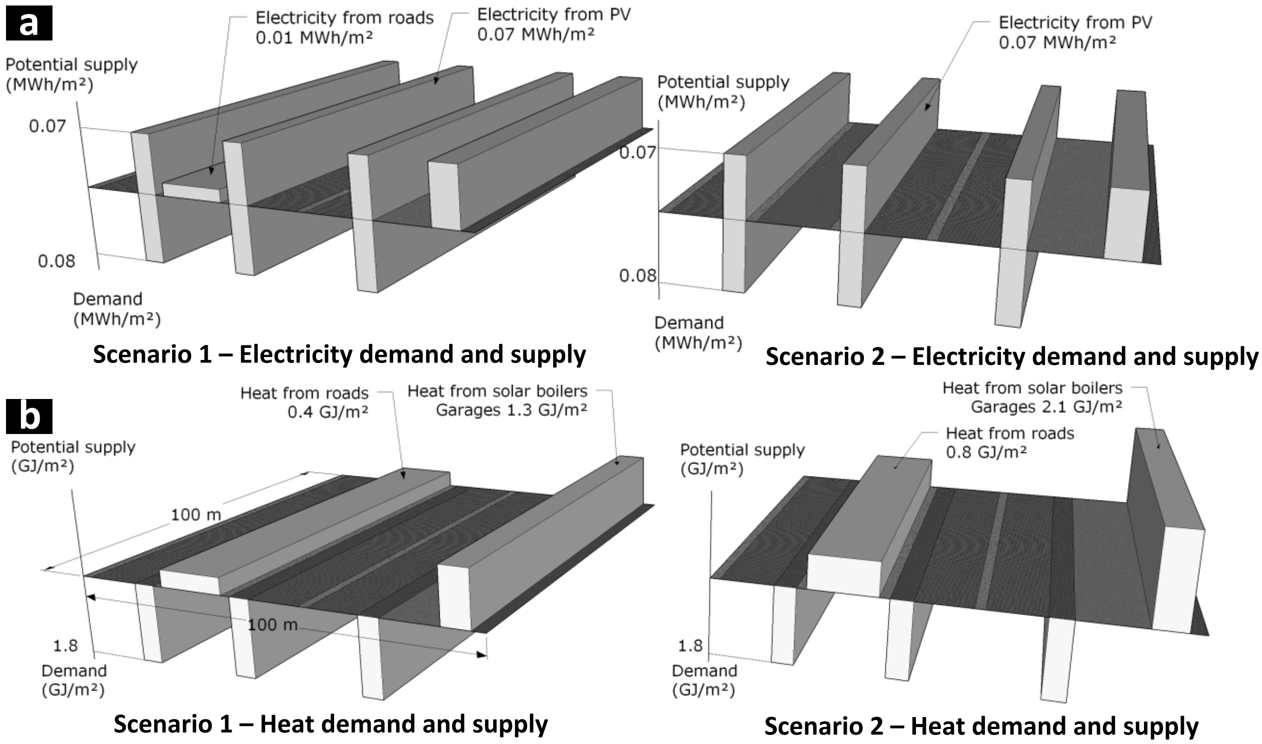

Figure 6 Visualization of the electricity and heat demand and supply for the neighborhood

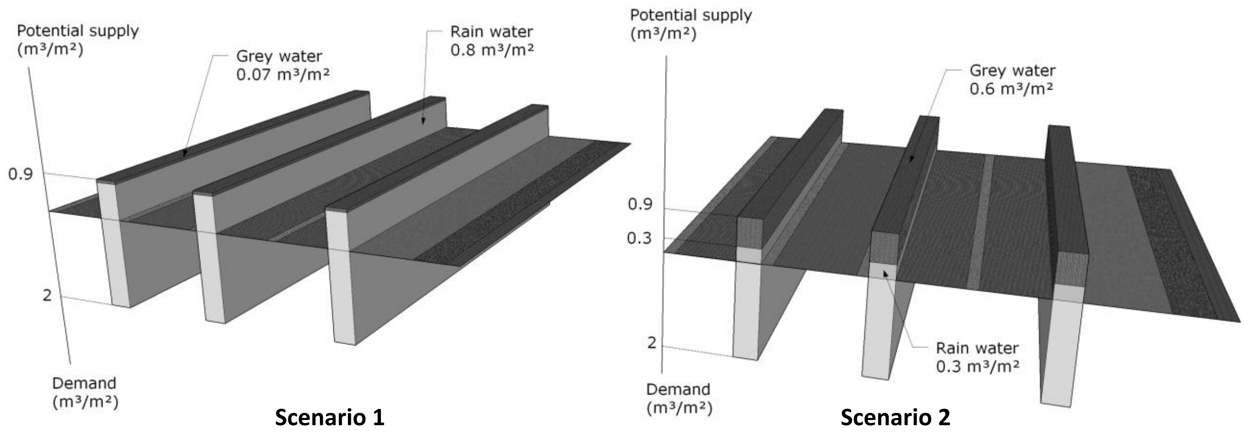

Figure 7 Visualization of the water consumption and sources in the urban area

Table 6. Potential water supply-demand for the neighborhood in m^3/ha-y

Current demand m^3/ha-y (Q_1)			2940					
			Scenario 1			Scenario 2		
			Q_1 [a]	Q_2 [b]	Q_3 [c]	Q_1 [a]	Q_2 [b]	Q_3 [c]
Demand per quality [d]			1688	396	855	1688	396	855
Harvest		PUH						
	Rain water	8840 [e]		396	754		396	
	Grey water	958 [f]			101			855
Potential Savings			43%			43%		

[a] Drinking water, personal hygiene & kitchen use.
[b] Washing clothes.
[c] Toilet flush .
[d] Foekema et al., 2008.
[e] In the complete hectare 8840m³/ha-year, if harvested only in roofs:1303 m³/ha-year.
[f] Assuming cascading water from shower.

3.5 Discussion

In urban areas, provision of resources and disposal of waste is a major concern. This represents both a risk and an opportunity to improve current practices to cope with the global challenges we currently face. Cities are complex systems with mixed activities and functions. This complexity can represent an opportunity to create linkages among different functions to use resources more efficiently. These linkages are based on harvesting local resources and reusing them locally. By harvesting local resources cities can become less dependent. This will further contribute to the ability of cities to cope with changing conditions, towards becoming more resilient.

Generally, infrastructural systems are designed individually and not in regional context, ignoring linkages among different infrastructural systems (Engel-Yan et al., 2005). By isolation of the different flows, urban complexity is simplified and single flow solutions may be optimized. And, there is no guarantee that the sum of optimal single flows is equal to urban sustainability, due to the dependency or competition of the different flows within the city (Leduc et al., 2009). Hence, a traditional sectoral approach for urban resources should be replaced by an integrated approach.

3.5.1 Limitations

The calculations in this paper focused on harvesting available local resources, but demand minimization is another important aspect to reach more resilient cities. A lower demand results in less need to harvest resources. Cities can lower the demand by changing behavior or by installing certain technologies. Minimization is the first step of the Trias Energetica (Duijvestein, 1997) and of the waste management hierarchy (Price and Joseph, 2000). At building scale, options for minimization are for example improved insulation to lower heat demand, or installing water saving appliances.

Temporal characteristics are given by changes in daily, weekly and seasonal demand and supply patterns. These temporal variations imply storage to match supply and demand.

Currently, at national scale, the electricity network acts as storage to balance the power supply, but this can become problematic with increasing renewable suppliers. Therefore, new technologies to tackle problems due to temporal disparities between supply and demand are being developed and tested, e.g. smart grids.

Spatial limitations are given by the spatial distribution of urban functions. At national scale, diversity of functions results in variety of flows allowing multiple combinations to match supply and demand. However, this might imply long distance transport from source to consumer. At neighborhood scale, spatial limitations are given by the single function; low function diversity limits the availability of flows. On the other hand, transport from source to consumer is less relevant due to the small scale.

3.5.2 Findings

By studying the urban tissue, it is possible to calculate the potential resources that can be captured, transformed and (re)used within the city and to study potential linkages between functions. We investigated the potential for multi-sourcing and cascading energy and water. Results at national scale showed that multi-sourcing by harvesting solar and wind power potentials can cover up to 100% of electricity demand and harvesting of heat from the roads by using Road Energy Systems can cover up to 55% of heat demand. By harvesting rain water from roofs tap water can be reduced up to 32%. Additionally, if at residential scale, cascading of light grey water is implemented, and at industrial level 10% of the wastewater is cascaded, tap water can be reduced up to 52%. At neighborhood scale, similar percentages were found for energy. For tap water, 43% reduction was reached, due to the fact that treatment measures were not considered. If quality upgrading and recycling, or closing cycles are implemented, larger potentials can be achieved, however, it is required to evaluate the additional demands of water, energy or materials.

These results indicate the potential for improvement compared to the current urban resources management. The results for electricity and water are promising. However integrated resources management should take into account all potential trade-offs and different scales in space and time (Pahl-Wostl, 2007). Supply of alternative sources may be available at a moment and location with low or no demand.

When comparing the results at national and neighborhood scale, we identified some restrictions due to functional diversity. For the studied neighborhood, total electricity demand can be supplied by using fewer technologies. At national scale, more functions are located on the Average Tissue and then implementation of more technologies is required, e.g. wind turbines to generate enough electricity to supply industrial demand. When focusing on water at national scale, the variety of functions allows more linkages and therefore, more possibilities to reuse waste flows. These results highlight the importance to integrate different scales to achieve maximum benefits, because each resource has a different optimal scale for management.

3.5.3 Implications

Urban resilience could be reached through an efficient (re-)utilization of local resources. Our study shows that there are multiple possibilities to improve current resource use at different scales. And a combination of strategies will result in more robust urban systems. Moreover, if separation of waste streams is implemented, additional benefits can be reached. For instance, by separating urine and fecal matter nutrients can be recovered and energy can be generated by anaerobic digestion (de Graaff 2010). Regarding multi-sourcing, new sources are being explored, for example electricity generation by microbial solar cells as part of green roofs (Strik et al., 2011) or producing drinking water by using hydrogen fuel cells (Hristovski et al., 2009). For cascading heat at national scale, heat from industries or greenhouses can be used for heating households. At neighborhood scale several options with a heat exchanger and/or heat pump exist to recover part of the heat energy present in the wastewater, either at the household scale, or from the sewer (Verstraete and Vlaeminck, 2011).

When harvesting urban resources, special attention must be given to interactions among different urban flows. When looking at the potentials, there are competing claims. Different resources can be harvested from a specific surface. For instance roofs can be used to collect solar energy to generate electricity, or can be used for rain water collection. But solutions should be always based on local context. Possibilities for beneficial infrastructural linkages are increasing in densely built urban space and provide ample synergistic opportunities (Mitchell and Campbell, 2006). For instance green roofs can reduce energy consumption and reduce the urban heat island effect (Arnfield, 2003) and reduce peak flows during storm events due to retention capacity (Bliss et al., 2009). Furthermore, urban infrastructure systems for water, energy, transport, and communication are actually dependent systems that rely on each other (Mitchell and Campbell, 2006).

Therefore, we still need a better understanding of the complexity of urban systems and of how the different urban infrastructure systems interact (Xu et al., 2010). Symbiotic relationships within urban areas among different urban functions should be explored to create win-win situations and minimize competing claims. Thus, it is crucial to investigate those relationships to optimize the overall performance of the city. Recently, increasing attention has been given to the interactions among the different urban flows – water, energy and nutrients – and land (de Graaff, 2010; Verstraete et al., 2009) This confirms the need of integrating resource management with urban planning, aiming to optimize linkages among different urban functions.

3.5.4 Outlook

The described Urban Harvest concept relates urban characteristics to water and energy harvesting potentials and land use, aiming to foster a re-thinking of our current urban water and energy systems. The concept can be extended to materials. The urban harvest concept can be used by urban planners and decision makers to understand the urban system and the internal flows within the same system, to provide smart, customized solutions for existing and new urban areas. The current challenge for resilient cities consists in closing open links between sources and demand. Towards urban sustainability, it is necessary to change the way we approach problems. “The paradigm of sustainable urban metabolism will require profound changes in the ways we conceptualize, plan, and manage cities and metropolitan regions” (Beatley, 2007, p. 43).

Resource flows occur at multiple spatial and temporal scales. Each scale is associated with boundaries, activities and flows. Inventory and visualization of the activities and flows using the urban tissue can help to identify resources “hot spots” and define policies and measures to handle those spots. Efficiency of the different measures depends on scale, local conditions, urban pattern and characteristics, and technology used. The resilience approach recognizes change as inherent part of any system. The challenge from a resilience perspective is to learn to live with change and develop the capacity to deal with it (Miller et al, 2010). Diversity of function has been shown to increase ecosystems resilience, because organisms can substitute each other, thereby compensating for disturbance and maintaining the function of the ecosystem (Gunderson and Holling, 2002). In cities, with a large diversity of functions and with changing conditions inside and outside the system, improving resources management by optimizing the demand and by harvesting local resources will make urban systems more robust to disturbances.

3.6 Conclusion

The Urban Harvest concept aims for a paradigm shift in urban sustainability. Cities, as consumers of goods and services and producers of waste, have the ability to transform into resilient cities that produce their own renewable energy and harvest their own internal resources. In this approach, waste flows are not only key indicators of systems efficiency, but may also provide insights into potential infrastructural linkages for a more efficient urban metabolism. Our study shows that there are ample options for such linkages among various urban resource systems. Towards sustainable urban metabolism, the Urban Harvest framework helps to evaluate the different urban flows at different scales and to communicate with other urban disciplines, such as urban planning and policy making. In aiming for resilient urban areas, it is evident that new approaches in urban resources management, such as Urban Harvest and city design and planning, need to be integrated.

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Chapter 4

The Urban Harvest Approach as an aid for Sustainable Urban Resource Planning: development of the method

Abstract

Now that more than half of the world's population lives in cities, improving urban resource cycles is crucial for sustainable urban development. Currently, cities are highly dependent on external supply of water, energy, nutrients and other materials, while local possibilities of self-production of such resources are generally overlooked. This chapter describes a novel method, the urban harvest approach (UHA), its rationale and the steps towards sustainable urban resource planning. UHA is based on the urban metabolism concept. Herein, a city is regarded to have multiple potentials in the form of untapped primary and secondary (already used) resources that can be utilized. UHA works on the principle that urban systems and their direct peri-urban surroundings can become self-sufficient by applying three strategies, namely: minimizing demand, minimizing outputs and multi-sourcing. An elaboration of UHA for the resource "water" at building scale is also presented in this chapter. A free standing house in the Netherlands and a similar house in Australia were studied, with a focus on indoor demand. Results showed a 40% demand reduction when water-saving technologies were implemented. In both cases, after demand minimization, local resources were sufficient to cover the demand by recycling grey water and harvesting rain water. These findings confirm that a multiple-measure implementation according to the three different strategies is needed to achieve sustainable urban water systems. UHA helps to structure large influences of urban context on water and other resource cycles as an aid to urban planners and water managers in designing sustainable urban areas.

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4 Harvesting urban resources towards more resilient cities

4.1 *Introduction*

The urban system, as the world's most significant user of resources, currently housing more than 50% of the world population, plays a key role towards sustainable development (ESA-UN 2007; McDonald and Patterson 2007; Xu et al. 2010). To guarantee global sustainability, cities must be planned to foster strategic resource management to integrate sustainable resource management and urban spatial planning (Kennedy et al. 2011; Rees 1999). Current pressures – accelerating urbanization, limiting availability of resources and changing climate – force us and provide us opportunities to re-think and redesign urban systems towards closed cycles, minimization of impacts and strategic management of resources (Agudelo et al. 2009). We face the challenge to develop a socio-technological planning and design methodology to identify appropriate solutions and to resolve trade-offs across various spatial and temporal dimensions (Guest et al. 2009).

4.1.1 Urban Metabolism

To design sustainable urban resource systems, it is imperative to understand how urban metabolic systems function (Decker *et al.* 2000; Girardet 2003). In the last decades, several urban metabolism studies[8] have provided valuable information about the resource flows through and in cities (Kennedy et al., 2011; WWF 2006). As a consequence, abundant information regarding urban inputs, outputs, and transformations of materials and energy is available (Decker et al. 2000). However, the available information is diffuse and methods for quantification are not standardized (Hashimoto and Moriguchi 2004). Therefore, conceptual frameworks and models are needed to take up information on quality and quantity of urban energy, water and materials flows. Thus, knowledge about urban resource system functioning can be structured, built, consolidated, and made available in an intelligent way for further use and decision making (Decker et al. 2000; Cole 2004).

Current urban metabolism – massive and global – is characterized by linear flows and missing linkages among urban and peri-urban production and consumption functions. Urban metabolism differs from metabolism of natural ecosystems in different aspects. In natural ecosystems, processes are generally cyclic and subsidized by sustainable inputs, such as solar energy fluxes and fluxes from organic and biogeochemical storage systems. Additionally, wastes are bio (chemically) transformable and feed other parts of the system. Therefore systems conserve mass (Kennedy et al., 2011; Kibert et al. 2000). Synergies and

[8] Within the urban metabolism, two different types of resource flows are identified: direct and indirect flows. The direct flows are the direct demand of consumers, and the indirect flows are the resources embedded in the products. For instance, water is a single resource that is directly fit for consumption. But water production implies the use of energy and chemicals used to abstract, produce and transport. All these hidden resources are so called indirect flows.

production–consumption relationships between organisms are crucial to keep a system in equilibrium. This promotes resilience across all scales and promotes efficient use of materials by developing cooperative webs of interactions between members of complex communities (Kibert et al. 2000). Therefore, towards a sustainable urban system, analogies with natural systems should be explored and exploited.

Inspired by natural ecosystems metabolism, urban systems have to be re-designed to re-use and recycle resource outputs, i.e. wastes. Ideal metabolic systems are based on closed loops. In reality, however, according to thermodynamic laws, each metabolic conversion has inherent losses, and it requires energy to mitigate these losses. Hence, full sustainability can never be achieved for products, without using an extra-global source of energy. Fortunately, we have constant inputs of energy from the sun, and, in principle, we can empower the used water, nutrients and other materials towards an upgraded quality and a renewed functioning in the urban cycles. Like natural ecosystems, we have to learn to efficiently and sustainably use this available energy and resources to arrive at (peri-) urban systems in equilibrium.

Closing resource cycles is not a new concept. Reports from the nineteenth century already described how materials cycles for industrial processes were optimized (Desrochers 2000). In the last decade, closing cycles objectives have been present at different scales within the built environment, neighborhoods, industrial areas, cities or regions. In parallel, new environmental technologies and infrastructure arrangements, contributing to improved resource management, are being developed rapidly over the last years (Daigger 2009; Gikas and Tchobanoglous 2009; Wolfe 2008). Hence, this evidences the growing interest and increasing pressures in urban resource management.

4.1.2 Urban Harvest

Cities have, from a resource point of view, mainly been seen as resource consumers and waste producers. Large portions of the flows of wastewater, solid waste, demolished construction materials, etc. are exported out of the urban system, while others remain inside as urban 'stocks', as internal resource reservoirs (Brunner 2007). Looking at the urban networks some of the city outflows and stocks, often called waste, still have a remaining quality or a set of potentials that can be harvested and used within the city itself. Therefore, cities can be seen as producers of secondary resources which are material, water and energy outputs from human activities. Preliminary results have shown the large potential of cities as providers of their own resources by harvesting local secondary and renewable resources (see Chapter 3).

Current urban resource supply is mainly focused on quantitative provision of resources of a single quality. Analyzing the current urban water or energy systems, it becomes apparent that different activities require different resource qualities. However, our current urban infrastructure grids tend to provide only one single (generally high) quality, for example drinking water or electricity. Therefore, some of the activities will receive a higher quality than needed – a quality surplus. After a given activity is performed, the quality of the resource deteriorates and a remaining quality is left, the so called, un-used quality. In a linear open system with emissions, these remaining qualities will be wasted. In a cascading approach, a resource with lower quality – urban outflows and stocks – can still be harvested and used as input for a certain activity with a lower quality demand, as discussed in Chapter 3. To use resources efficiently, quality optimization is also needed for a fit-for-purpose supply. Currently, many societies are shifting from removal technologies to consumption reduction and recovery techniques, minimizing use and valorizing the resources' value (Daigger 2009; Guest et al. 2009; Jegatheesan et al. 2009). In addition integration of technical solutions and understanding of the urban metabolism is needed to deal with the complexity of sustainable urban resource management (Pahl-Wostl 2007).

Sustainable urban planning should aim for cities with a low resource use impact by integrating resource management and urban planning. The Urban Harvest Approach (UHA), as presented in this chapter and based on the urban metabolism concept, aims for improved resource management by closing urban cycles, applying innovative technologies and harvesting urban resources. UHA works on the principle that urban systems can minimize their dependency on external resources by strategic management of resources: minimizing demand, minimizing outputs and multi-sourcing, which can be characterized by the Urban Metabolic Profile (UMP). UHA studies primary and secondary resources available within the built environment, and does consider outflows as available secondary resources ready to be harvested and be reused in the urban environment and peri-urban surroundings. This approach can be developed at different scales: a house, a neighborhood, a city quarter, a city, or a city and its surroundings. This chapter demonstrates the UHA at the smallest scale "a house" for the resource "water". The applicability to two free standing houses in two different contexts – in the Netherlands and in Australia – is shown and measures are tested that yield improvements in the urban metabolic profile.

4.2 Method

The UHA has been developed to systematically investigate the available options for improved urban resource management. UHA integrates closing urban resource cycles by applying innovative technologies and harvesting local and renewable urban resources. In this approach, waste flows are not only key indicators of systems efficiency, but may also provide insights into potential infrastructural linkages for a more efficient urban metabolism. Indirect resource flows such as embedded energy or water footprints of products (Hoekstra and Chapagain 2007) are not taken into account in the UHA. Those indirect flows can be addressed by improving product design, for example using cradle to cradle concepts (Braungart et al. 2007), which is out of the scope of this approach.

In fact, UHA always starts with a baseline assessment, followed by implementation of three strategies. The first strategy is to minimize the demand. The other two strategies evaluate the potential to harvest resources within urban areas. The second strategy is to reduce outputs by cascading, recycling and recovery. The third strategy is to multi-source the remaining demand by using renewable and local sources. In the following, these strategies will be further explained.

4.2.1 Baseline assessment

The starting point of the UHA is a baseline study by preparing a mass flow analysis of the existing situation. The aim is to identify all the inputs and outputs of a defined urban system and to understand the current urban metabolism. The baseline study covers both, a demand inventory and an output inventory. The demand inventory quantifies the resource demand along with a hierarchical identification of the qualities required for the various uses. The output inventory describes the outgoing resource flows, their quantity and quality.

4.2.2 Demand minimization

Demand minimization is a first key activity in the UHA. Current urban consumption is generally characterized by a massive demand of resources and the production of huge outputs and stocks. As such, the UHA follows sustainable approaches as developed in solid waste management, which promotes minimization as the first step in the waste management hierarchy.

Demand minimization can be achieved by stimulating changes in human behavior or by technology implementation. The UHA focuses on technology implementation to reduce resource demands. It starts at the smallest scale possible, preferably the building level. After the base line assessment, UHA aims to select the main activities, which consume more than 10% of the current demand. Subsequently, technologies are identified that contribute to reduce those resource demands.

4.2.3 Output minimization

The second step in the UHA aims at minimizing outputs. This can be achieved by three strategies, recovery, cascading or recycling of the outputs. Cascading and recycling strategies refer to single flow analysis, without and with quality upgrading respectively. Meanwhile recovering refers to multiple flow analysis.

Cascading

Cascading refers to direct reuse of outputs for a similar purpose, however with a reduced quality. In cascading, a resource is being reintroduced in the system at lower quality. By cascading, the remaining quality of this resource is used. The baseline provides an overview of the outputs and their remaining qualities. These remaining qualities can be harvested and matched with the urban activities by using low quality flows for low quality demand activities. Examples of cascading are use of low polluted water for non-potable activities, or using waste heat of industries to heat households.

Recycling

Recycling refers to reuse of a particular resource flow after quality upgrading, which generally costs energy. Thus, higher quality resources are being reintroduced upstream into the cyclic system. To assess the feasibility for recycling, the baseline study should include the same parameters as for cascading. In addition, appropriate technologies for recycling have to be selected based on the local context. Within the UHA, preference is given to multi-purpose technologies that simultaneously recover other resources. Recycling is performed to produce the same or a similar product. Examples of recycling are grey water reclamation or using a heat pump to increase the temperature of a flow.

Recovery

Recovery refers to the extraction of useful substances from waste flows. Because there is a remaining quality, the recovered resource can be reintroduced into the system. Within the UHA, recovery refers to extraction of "products" that belong to other flows, for instance recovery of nutrients or heat from wastewater flows or recovery of nutrients from a bio-digester used for biogas production.

4.2.4 Multi-sourcing

After demand and output minimization, there may still be a remaining demand. Within the UHA, this will be supplied by using local and renewable sources, such as solar energy and rain water. Local resources have the advantage of minimizing transport costs, and minimizing external dependence.

The resources harvested by cascading, recycling, recovering and multi-sourcing can be reintroduced in the same system or be exported to another system. If re-introduced in the same system, they further reduce external inputs. The feasibility to use harvested flows does not only require data on quantity and quality, but also on temporal availability, spatial implications, impacts on other resource flows and people's acceptance. To quantify the effect of each strategy on the urban metabolism, the so called Urban Metabolic Profile (UMP) is introduced.

4.2.5 Urban Metabolic Profile

Current urban systems have two different impacts on the environment. The first is due to the extraction of resources, and the second is due to the release of wastes. The urban metabolic profile (UMP) provides information regarding the demand of resources and production of wastes or secondary resources and as such can be used to evaluate the possible combined strategies within UHA at different levels. Fig. 1a shows the variables that characterize the UMP. These variables are valid for the different spatial scales: building unit, block, neighborhood and city.

In the following, each of the variables is assumed to be larger or equal to zero. Although specific reference is made to building unit the same definitions and variables are applicable at all mentioned urban scales. As shown in Fig. 1a, a building unit has external, usually high quality inputs (*Ei*) that are related to the Demand (*D*), which depends on occupancy, life style, among other determinants. Cascade (*C*) refers to resources that are directly reused within the building unit, and Recycle (*R*) is the flow of resources that is treated and reintroduced in the building unit. Multisource (*M*) refers to local sources used in the building unit. Storage (*S*) is the amount of resources that is stored in the building unit. Waste exported (*We*) refers to the wastes produced by the building unit and exported. It is important to point out that, within the UHA Total input (*Ti*), $Ti = Ei+C+R+M$, can be larger than *D* due to harvesting of local resources and in that case there are possibilities of exporting resources. Exported resources (*Er*) refers to secondary resources that are harvested in the building unit and exported. The UHA aims to minimize *D*, *Ei* and *We* and maximize *C*, *R* and *M* at building, block and neighborhood level. UMP is done per flow (e.g. water, energy, or a given material). Therefore, recovery is not included in the UMP, because it refers to other flows. Recovery will be represented as multi-sourcing in the metabolic profile of the recovered flow.

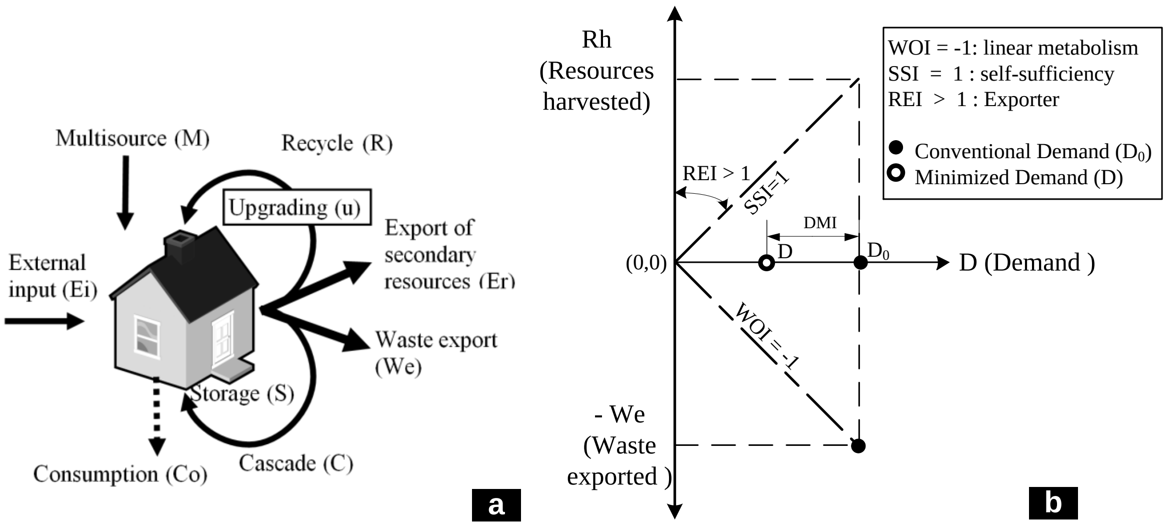


Figure 1 a) variables of the Urban Metabolic Profile (UMP) in a building unit; b) Visual representation of the UMP dashboard and the four indices: DMI, WOI, SSI and REI.

Based on the general mass balance: Storage (s) = Total inputs (Ti) – Total outputs (To) – Consumption (Co), at a specific instant in time, the mass balance equation can be written as:

$$\frac{ds}{dt}(t) = Ti(t) - To(t) - Co(t) \qquad (1)$$

Consumption (Co) is defined as the process of being consumed, converted to one or more different components, or diminished by e.g. decay. Therefore, Co is a fraction of the demand that is not available to be harvested.

For the system in Fig. 1a, without explicit reference to the time argument, $Ti = Ei + C + R + M$ and $To = C + R + We + Er$. Consequently,

$$\frac{ds}{dt} = (Ei + C + R + M) - (C + R + We + Er) - Co \qquad (2)$$

Defining in (2), the resources harvested Rh as,

$$Rh = C + R + M \qquad (3)$$

For a system in equilibrium, thus with $dS/dt = 0$, total inputs are equal to the sum of total outputs and consumption, so that $Ei + M = We + Er + Co$ and thus:

$$We = Ei + M - Er - Co \qquad (4)$$

Since Ti can be larger than D, Er can be expressed as:

$$Er = Ti - D \qquad (5)$$

with $Er>0$. Then from equation (2), with ds/dt=0, we also obtain that

$$We = D - C - R - Co \qquad (6)$$

and thus, replacing Eq. 6 in Eq. 4:

$$Ei = D - C - R - M + Er \qquad (7)$$

To relate these variables and to evaluate the different measures, the UMP per flow (water, nutrients of energy) is calculated. The UMP is described in terms of the demand (D), the waste exported (We) and the resources harvested (Rh). Hence, in this chapter, the urban metabolism of a given flow is expressed by the four indices: Demand Minimization Index (DMI), Waste Output Index (WOI), Self-Sufficiency Index (SSI), Resource Export Index (REI) and which are given by:

$$DMI = \frac{Conventional\ demand\ (D_0) - Minimized\ demand\ (D)}{Conventional\ demand\ (D_0)} \quad (8)$$

$$WOI = -\ \frac{Waste\ \exp orted\ (We)}{Minimized\ demand\ (D)} =_{[Eq.4]} -\ \frac{Ei + M - Er - Co}{D} =_{[Eq.6]} -\ \frac{D - C - R - Co}{D} \quad (9)$$

$$SSI = \frac{Resources\ harvested (Rh) - Exported\ resources\ (Er)}{Minimized\ demand\ (D)} =_{[Eq.3]} \frac{C+R+M-Er}{D} =_{[Eq.7]} \frac{D-Ei}{D} \quad (10)$$

$$REI = \frac{Exported\ resources\ (Er)}{Minimized\ demand\ (D)} =_{[Eq.5]} \frac{Ti-D}{D} \quad (11)$$

Fig. 1b shows the UMP dashboard. In the UMP dashboard, the demand (*D*) is projected on the horizontal axis. According to equation (9), waste exported (*We*) has a negative value and is represented in the vertical axis (down) and from equation (10) resources harvested (*Rh*) has a positive value and is represented in the vertical axis (up). Notice from Fig. 1b that the *DMI* is the relative change in the horizontal axis, which represents the change in the demand taking as reference the conventional demand (D_0). D_0 represents the demand when conventional technologies are implemented, therefore D_0 may vary according the local context. *WOI* is the slope between the origin (0, 0) and the point given by demand and waste exported (*D*, *We*) and *SSI* is the slope between the origin (0,0) and the point given by demand and resources harvested (*D*, *Rh-Er*). *REI* is the ratio of the Exported resources (*Er*) and the demand (*D*).

Notice from the definitions of *WOI* and *SSI* that for a given index and a given demand multiple solutions exist, as in each case we have one equation with at least two unknowns. For example, if *WOI*= –1, then from equation (9) it can be derived that *Ei*=*D* for *C*=*R*=*M*=*Er*=*Co*=0. This case represents the conventional “linear metabolism”. This linear metabolism can be also obtained, for *M*=*D* if *Ei*=*C*=*R*=*Er*=*Co*=0; or for *Ei*+*M*=*D* if *C*=*R*=*Er*=*Co*=0. Moreover, *WOI*=-1 can be obtained, when *Ei*+*M*-*Er*=*D*, which holds for *Co*=*C*=*R*=0. If, furthermore, *Er*>0: *Ei*+*M*>*D*, which indicates that there are flows passing through without being used in the system and that these flows are being exported as secondary resources. One of the aims of UHA is to minimize *Ei*, so that a direct feed-through from *Ei* to *Er* will be avoided. Hence, if *Ei* > 0 in order to meet the demand *D*: *Er* = 0. From the definition of *Er*, so that equation (6) holds, it follows that *WOI* ≥ -1, that is *We*≤*D*. In addition, *WOI*=0 when *D*=*C*+*R* and *Co*=0 or when *C*+*R*=*0*: *D*=*Co*. Notice that large values of *Co* imply lower amount of resource available to be harvested (*C* and *R*).

Recall that UHA aims to maximize *C* and *R*, and to minimize *D* including *Co*, so that lower values of *Co* will be preferred. Generalizing, if $C=R=Co=0$, then $WOI = -1$; and if $C>0$ or $R>0$ or $Co>0$, then $WOI > -1$. A similar analysis can be applied to equation (10). If, for instance, $SSI=1$ the area is self-sufficient, that is $D=Rh$ if $Ei=Er$, which may be equal to zero. If $Ei=Er > 0$, it implies, as shown above for *WOI*, that *Ei* is passing through without being used in the system. If $Rh>D$, $Er=Rh-D$ and hence, then REI>0, and thus the area can export resources. Recalling that the UHA aims to minimize *D*, *Ei* and *We* and maximize *C*, *R* and *M*, this provides restrictions to these multiple solutions. Fig. 2 shows the UMPs, following the hierarchy of measures proposed by the UHA. It is shown, how different strategies influence different indices of the UMP.

To summarize, UHA integrates three strategies: demand minimization, output minimization and multi-sourcing; and four levels: building, block, neighborhood and city. To evaluate a specific resource management, the UMP has been introduced. The UMP consists of *DMI*, *SSI*, *WOI* and *REI*. UMP facilitates comparison among the different urban flows. Moreover, UHA is applicable to different flows as water, energy and nutrients within the urban system.

4.2.6 Linkages with planning

UHA provides guidelines for improved urban resource management by implementation of (innovative) environmental technologies, and integration with urban planning. Potential harvest and restrictions vary according to the scale. Moreover, different measures can be adopted to optimize urban cycles for different spatial and temporal scales (Guest et al. 2009; Korhonen 2007; Pahl-Wostl 2007). It is important to evaluate different scales to achieve maximum benefits, because each resource has a different optimal scale for management. Therefore, when addressing different scales simultaneously, the need for coordination and thus for planning becomes evident (Pahl-Wostl 2007).

Fig. 3 summarizes the proposed approach to optimize the potential for closing cycles and shows the linkages among different urban functions. The UHA starts at the building unit because this is where a major part of the urban resource consumption actually takes place. At this level, human choices for resource consumption and disposal are made. The importance of focus on the building level has been acknowledged over the last decades, for example by the introduction of the energy efficiency label and the Leadership in Energy and Environmental Design (LEED) certification (Ding 2008).

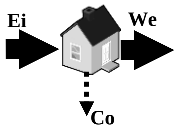
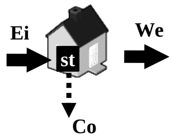
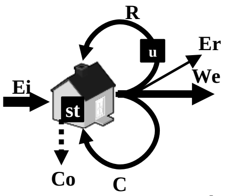
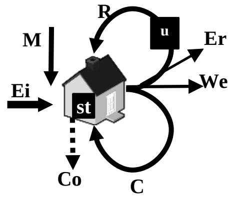
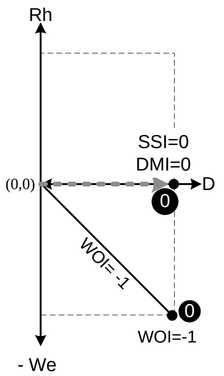
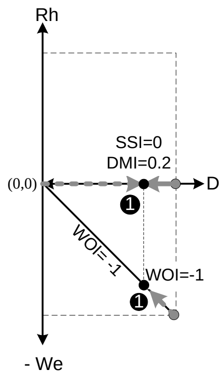
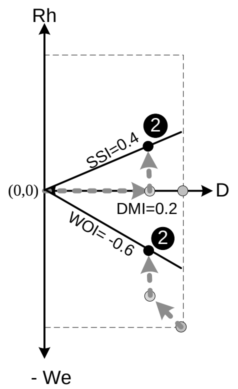
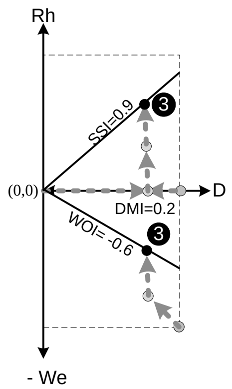
	Step 0	Step 1	Step 2	Step 3
	Baseline	**Demand minimization**	**Output minimization**	**Multisourcing**
		 st=saving technologies	 u=upgrading	
Strategies		Implementation of saving technologies (st)	Cascading: Direct reuse of resources Recycling : Reuse after upgrading (u)	Multisource by using local and renewable sources
Total Inputs (Ti)	*Ei*	*Ei*	*Ei, C, R*	*Ei, C, R, M*
Total Output (To)	*We*	*We*	*C, R, We, Er*	*C, R, We, Er*
Consumption	*Co*	*Co*	*Co*	*Co*
Resources harvested	$Rh = 0$	$Rh = 0$	$Rh = C + R$	$Rh = C + R + M$
Waste output Eq. (4, 6)	$We = Ei\text{-}Co$ $We = D_0\text{-}Co$	$We = Ei\text{-}Co$ $We = D\text{-}Co$	$We = Ei - Er - Co$ $We = D - Co - C - R$	$We = Ei + M - Er - Co$ $We = D - Co - C - R$
External input Eq. (7)	$Ei = D_0$	$Ei = D$	$Ei = D - C - R + Er$	$Ei = D\text{-}C\text{-}R\text{-}M\text{+}Er$
Remarks	Linear metabolism Single quality supplied	Linear metabolism with reduced flows Single quality supplied	Potential export of secondary resources, if $D < Rh$ Multiple qualities supplied	Potential export of secondary resources, if $D < Rh$ Multiple qualities supplied
UMP n Step number				
Indices (Eq. 8-11) $DMI=(D_0\text{-}D)/D$ $WOI=We / D$ $SSI = Rh\text{-}Er / D$ $REI=Er/D$	$DMI_0 = 0$ $WOI_0 = -1$ $SSI_0 = 0$ $REI_0 = 0$	$DMI_1 \in [0 , 1]$ $WOI_1 = WOI_0 = -1$ $SSI_1 = SSI_0 = 0$ $REI_1 = REI_0 = 0$	$DMI_2 = DMI_1 \in [0 , 1]$ $WOI_2 \in [-1 , 0]$ $SSI_2 \in [0 , 1]$ $REI_2 \geq 0$	$DMI_3 = DMI_{1,2} \in [0,1]$ $WOI_3 = WOI_2 \in [-1,0]$ $SSI_3 > SSI_2 > 0$ $REI_3 \geq REI_2 \geq 0$

Figure 2 UHA step by step and correspondent changes in the Urban Metabolic Profile (UMP) under steady state conditions.

Lifetime of assets is an important element of selecting measures for UHA. Typically, physical structures of cities have different lifetimes. For example buildings, roads and sewers wear out in 50-100 years (Kibert et al. 2000), while technical devices within buildings may last for 5-20 years. Thus, in-house and on-site technologies are quicker to implement and replace than technologies at larger scale. Moreover, because fewer stakeholders are involved in selecting these systems, their implementation can be done at a relative short time horizon. Meanwhile, modifications of resource systems at neighborhood or central urban level require longer time.

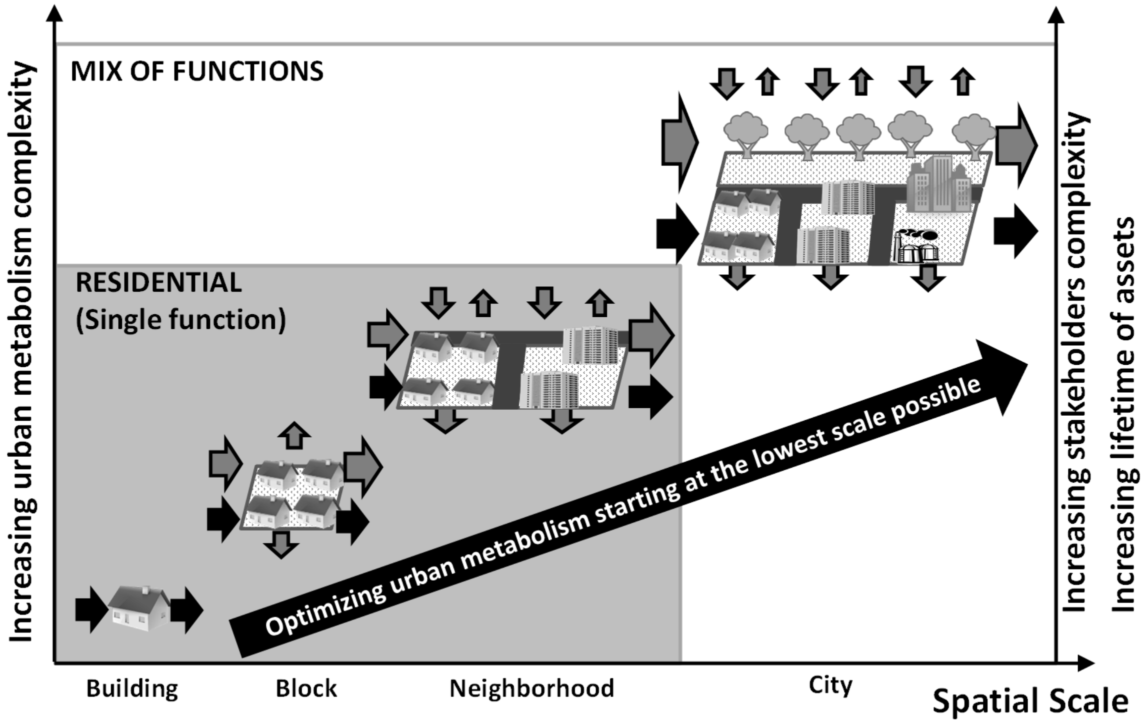


Figure 3 Bottom-up approach proposed by the Urban Harvest Approach to optimize the urban metabolism, starting at the lowest scale possible (building) and a subsequent stepwise scaling up to block, neighborhood and city level.

4.3 Applicability of the UHA for urban water flows at building level

The UHA provides general rules for resource management within the urban environment. Since different urban flows have different characteristics and dynamics, in particular the applicability for water flows at the building level will be evaluated in the next subsections.

4.3.1 Residential urban water

When comparing water demand versus actual water demand at the building level, it becomes clear that only a small percentage of (high quality) water is used for drinking and cooking. The rest is used for other purposes, mainly for personal hygiene and cleaning. The latter uses require a lower quality than water that is fit for human consumption.

During the various uses, water quality is definitely reduced by each utilization step. As a final output, water with lower quality – wastewater – is produced and discharged.

In the following, the consumption term is neglected (*Co*=0), as mainly the water quality deteriorates. After the assessment of the baseline, the UHA starts with demand minimization at building level addressing the major uses that consume more than 10% of the total demand. Available technologies for water demand reduction include: water saving shower heads, water saving taps, low water demand toilets. As a second step, water cascading and recycling are considered to reduce outputs. Water can be cascaded directly to fulfill activities with lower quality demand. For instance, low polluted grey water can be used for toilet flushing. However, the acceptance and technical applicability of this practice in developed countries is currently low. Regarding recycling, the state of the art technologies allow us to treat any quality of residential waste water to a desired level, allowing on-site recycling for different non-potable activities (Li et al. 2009). However, treatment implies the use of chemicals, energy and/or space (Makropoulos and Butler, 2010). Recovery of other products from the water flows, such as nutrients or heat, is also feasible, but this does not affect the volume of the water flows at building level. The third step is to fulfill the remaining demand by multi-sourcing. In general, there are various water sources in the urban environment, as for instance ground water, surface water and rain water. The preferred source is determined by the local context. The contribution to the total demand should be assessed based on availability, quality, storage and transport implications and the influence on the other urban flows.

4.3.2 Applicability of the UHA for urban water flows at building level for a case in the Netherlands and a case in Australia: results and discussion

This subsection describes the UHA for water for a standard free standing house in the Netherlands and in Australia.

Baseline assessment

Based on the average information for the Netherlands and for Australia (Melbourne), the conventional demand[9] in liters per person per day ($l\ p^{-1}d^{-1}$) and m³ per household per year ($m^3hh^{-1}yr^{-1}$) was estimated. Subsequently, the activities with largest demand were identified. From the baseline, as presented in Table 1, we found similar indoor water demand patterns for the two cases. In both cases, the activities with largest water demand were shower, toilet flushing and laundry machine.

[9] For the Netherlands, the conventional demand was calculated assuming the less efficient technologies installed at home from the survey of Foekema et al, 2008. For Melbourne, the conventional demand was assumed as the average of the year 2004. A survey from 2007 was available; however, due to temporal water use restrictions, water demand was low and there is no guaranty that when the restriction is over, the low demand is maintained.

Demand minimization

In both cases – water use for shower, toilet flushing and laundry machine – each accounts for more than 10% of the total demand. Table 2 shows the available technologies for water demand reduction. These technologies have different degrees of water use efficiency.

Table 1 Conventional (Con) and Minimized (Min) water demand in liters per person per day (l $p^{-1}d^{-1}$) and in m³ per household per year (m³ hh^{-1} y^{-1})

	Netherlands (2007) hh size: 2.3 people						Australia – Melbourne (2004) hh size 2.7 people					
Activity	Demand (l $p^{-1}d^{-1}$)		hh. Demand (m³ hh^{-1} yr^{-1})		% of total		Demand (l $p^{-1}d^{-1}$)		hh. Demand (m³ hh^{-1} yr^{-1})		% of total	
	Con	Min	Con	Min	Con	Min	Con	Min	Con	Min	Con	Min
Shower	63.8[a]	37.9	53.6	31.8	40	45	49.1[d]	32.4	48.4	31.9	32	41
Toilet flushing	56.4[b]	5.0	47.4	4.2	35	6	30.4[e]	3.4	30.3	3.3	20	4
Laundry machine	15.5[c]	15.5	13.0	13.0	10	19	40.4[f]	10.2	39.8	10	26	13
Dish washing, machine	3		2.5		2	4	2.7		2.7		2	3
Bath	2.5		2.1		2	3	3.2		3.2		2	4
Kitchen sink	8.8		7.4		5	11						
Bathroom sink	5.3		4.4		3	6						
Dish washing, hand	3.8		3.2		2	5						
Laundry, hand	1.7		1.4		1	2						
Sinks							26.6[g]		26.6		18	34
Total	160.9	83.5	**135**	**70.1**	100	100	152.8	78.8	**150.9**	**77.7**	100	100

Sources: Foekema et al. 2008 and Roberts 2005.
Recalculated to estimate conventional demand as follows:
[a] Average duration of shower: 7.9 min (Foekema et al. 2008); demand of conventional douche: 10.1 l/min (millieucentraal 2010), frequency 0.8 times per day (Foekema et al. 2008).
[b] Frequency of toilet use: 6.27 times per day (Foekema et al. 2008). Conventional toilet consumes in average 9 l per flush. (Kujawa-Roeleveld and Zeeman 2006).
[c] Conventional laundry 55.4 l/wash, frequency 0.28 times/day (Foekema et al. 2008).
[d] Average duration of shower: 7.1 min, frequency of showers per day: 0.76 , flow rate: 9.1 l/min, (Roberts 2005)
[e] Recalculated: frequency of toilet use: 4.2 times per day. Conventional toilet consumes in average 7.23 l per flush (Roberts 2005).
[f] Frequency 0.28 times/day (Roberts 2005).
[g] specifications for the different sinks were not available. This value includes kitchen and bathroom sinks.

To provide an overview of the maximum saving potential, vacuum toilets with a demand of 0.8 l per flush, a shower with a demand of 6 l/min and a washing machine with a demand of 9 l/kg load were considered. For both cases 4 kg/cycle were assumed (Pakula and Stamminger 2009). Using the most efficient appliances, the demand minimization was 48% for the Netherlands – from D_0=135 m³$hh^{-1}y^{-1}$ to D=70.1 m³$hh^{-1}y^{-1}$ – and 49% for Australia – from D_0=150.9 m³$hh^{-1}y^{-1}$ to D=77.7 m³$hh^{-1}y^{-1}$ as shown in Table 1.

Output Minimization

Output minimization can be achieved by cascading or recycling. Since, cascading does not include any treatment, it is restricted to a few activities. Meanwhile recycling implies treatment; therefore, it needs energy and materials. In urban areas, feasibility of the measures strongly depends on user acceptance, water usage patterns and availability of space. Cascading can for instance be done from shower to toilet. However, after demand minimization, toilet flush water demand is only a small percentage of the total demand. Consequently, the improvement in the total water balance is not significant, around 5%.

Table 2 Minimization technologies and demands

Appliance	Units	Rating				
		Rating (Dutch labeling for shower heads)				
		B - D	**S**	**A**	**Z**	
Shower	**l/min**	11.5 – 21.9	8.7-11	6.9 – 8.7	4.2-6.9	
		Toilet type				
		Conventional	**Low flush Two buttons**	**Urine diverting**	**Vacuum**	
Toilet	**l/flush**	6 to 12	4 large flush 2 small flush	4 to 6 large flush 0.2 small flush	0.8 to 2	
		Rating (Australian labeling WELS)				
		A	**AA**	**AAA**	**AAAA**	**AAAAA**
Shower	**l/min**	>12 to 15	>9 to 12	>7.5 to 9	>6 to 7.5	<6
Toilet	**l/flush** [a]	>5.5 to 6.5	>4 to 5.5	>3.5 to 4	>2.5 to 3.5	<2.5
Washing machine	**l/kg load**	>28 to 34	>22 to 28	>15 to 22	>9 to 15	<9

Sources: Kujawa-Roeleveld and Zeeman 2006; millieucentraal 2010; AS/NZS 6400:2005, Water efficient products – Rating and Labelling, Australian and New Zealand Standard.

[a] Average of four short and one long flush

Technologies for domestic water recycling were reviewed by Li et al. (2009). Treatment will depend mainly on Chemical Oxygen Demand (COD) concentrations: Low strength grey water (COD<300 mg/l) e.g. shower water; and high strength grey water (COD>300mg/l) e.g. mixed grey water, Table 3. For our cases, the technology selected will affect the *Rh*, *We* and therefore the *Ei*, *WOI*, *SSI* and *REI*. In the case of recycling low strength grey water with minimized demand, water from the shower is used for toilet flush and laundry machine. For the Netherlands, 31.8 $m^3hh^{-1}y^{-1}$ from shower is available to supply 17.2 $m^3hh^{-1}y^{-1}$. For Australia this is 31.9 $m^3hh^{-1}y^{-1}$ and 13.6 $m^3hh^{-1}y^{-1}$ respectively, see table 1. In the case of recycling high strength grey water, for example, water from shower and laundry, this can be fully recycled for the same purposes, creating a closed loop. This will lead to save 44.8 $m^3hh^{-1}y^{-1}$ of drinking water in the Dutch case and 41.9 $m^3hh^{-1}y^{-1}$ in the Australian case.

Multi-sourcing

For both cases, we investigated the potential of harvesting rainwater, to supply the remaining demand. In the Netherlands, the average yearly rainfall is 884 mm and in Melbourne 595 mm. For an average house of 60 m² roof area the maximum potential production of rainwater per year is for the Netherlands 53 $m^3hh^{-1}y^{-1}$ and for Australia 36 $m^3hh^{-1}y^{-1}$. On the basis of these and above mentioned data (Table 1), the UMP can be made (see Fig. 4). Both profiles show that demand minimization (step 1) causes a change in the *DMI* (equation 8) and between classes. Recycling of high strength grey water (step 2) improves *WOI* (Eq. 9). Note that multi-sourcing (step 3) will improve the SSI because the self-production is increased (Eq. 9); however, the *WOI* will remain the same (equation 8), because the output is not minimized. If all three strategies are applied, self-sufficiency can be achieved in both cases. Furthermore, in the Dutch case, there are even possibilities to export rain water (REI>0).

The UHA presented here is a structured approach to identify the influence of different measures for reduction of demand and waste production, and for multi-sourcing within the built environment. Furthermore, the proposed methodology to assess UMP (*DMI*, *SSI*, *WOI* and *REI*) provides key information on the urban metabolism.

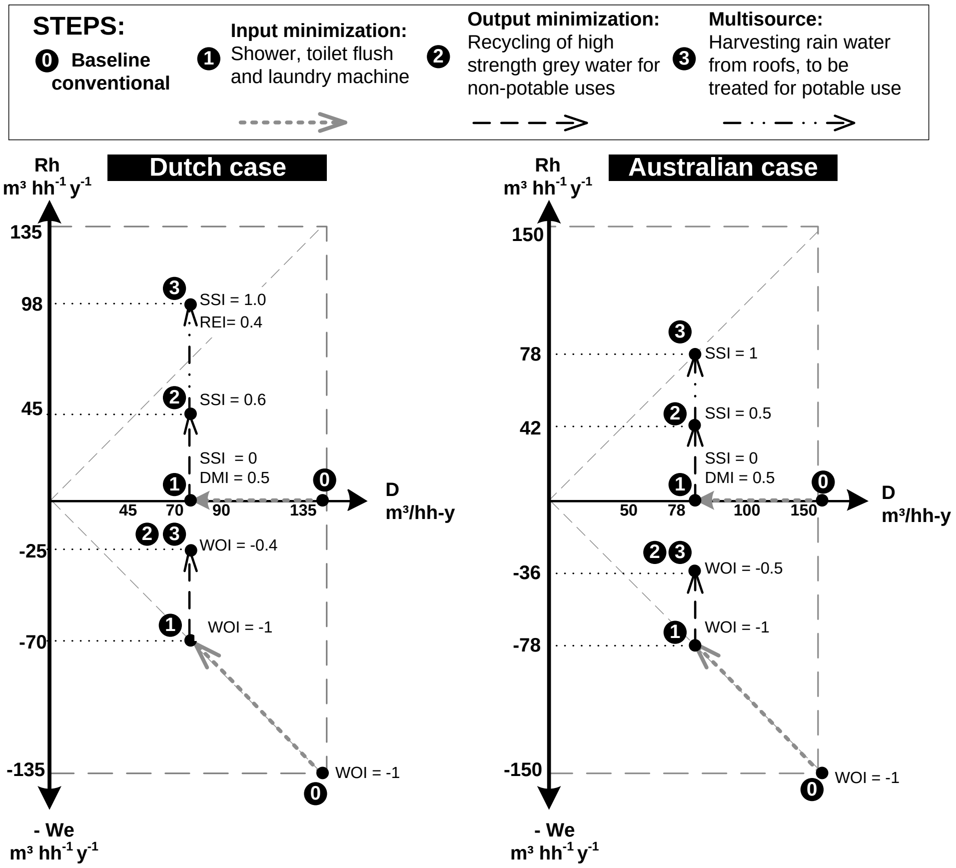
Looking at the results of the cases studied, *SSI*=1 implies that 100% of the total water demand can be supplied by local means by implementing the strategies described within the UHA. The results illustrated that we can see urban areas as reservoirs of resources that can be harvested and used to supply urban demands. Therefore, shortcoming of the existing resource management becomes evident. By analyzing the different UMP, it also becomes clear that implementation of single measures is not enough. In fact, a series of measures should be combined to achieve full self-sufficiency (*SSI*=1), in the hierarchy proposed in this chapter, thus first demand minimization, second output minimization and finally multi-sourcing.

Table 3 Proposed technologies for recycling of grey water for non-potable uses

Grey water type	Storage + pretreatment	Treatment	Filtration	Disinfection
Low strength	Sedimentation/screening	Chemical: Coagulation, ion exchange	Membrane	-
Low strength	Sedimentation/screening	Chemical: Coagulation, ion exchange	Sand	Disinfection
Medium and high strength	Sedimentation/screening	Biological (aerobic) RBC, SBR, CW[a]	Sand	Disinfection
Medium and high strength	Sedimentation/screening	Biological (aerobic) RBC, SBR, CW[a]	Membrane	-
Medium and high strength	Sedimentation/screening	Membrane bioreactor (MBR)	-	-

Source: Li et al. 2009

[a]RBC: Rotating biological contactor, SBR: sequencing batch reactor, CW: constructed wetland



	Step 0 - Baseline[a]	Step 1 – Demand minimization	Step 2 – Output minimization[b]	Step 3 - Multisourcing
	Netherlands			
[m³ hh⁻¹ y⁻¹]	D_0 = 135 Rh_0 = 0 We_0 = 135 Er_0=0	D_1 = 70.1 Rh_1 = 0 We_1 = 70.1 Er_1 = 0	D_2 = 70.1 Rh_2 = R = 44.8 We_2 = 25.3 Er_2 = 0	D_3 = 70.1 Rh_3= $R+M$ = 44.8+53=97.8 We_3 = 25.3 Er_3 = 27.7
[/]	DMI_0 = 0 WOI_0 = -1 SSI_0 = 0 REI_0 = 0	DMI_1 = 0.5 WOI_1 = -1.0 SSI_1 = 0 REI_1 = 0	DMI_2= 0.5 WOI_2 = - 0.4 SSI_2 = 0.6 REI_2 = 0	DMI_3= 0.5 WOI_3= - 0.4 SSI_3 = 1.0 REI_3 = 0.4
	Australia			
[m³ hh⁻¹ y⁻¹]	D = 150.9 Rh = 150.9 We = 0 Er = 0	D = 77.7 Rh = 77.7 We = 0 Er = 0	D = 77.7 Rh = R = 41.9 We = 35.8 Er = 0	D = 77.7 Rh = $R+M$= 41.9+36 = 77.9 We = 35.8 Er = 0.2
[/]	DMI_0 = 0 WOI_0 = -1 SSI_0 = 0 REI_0 = 0	DMI_1 =0.5 WOI_1 = -1.0 SSI_1 = 0 REI_1 = 0	DMI_2 = 0.5 WOI_2 = - 0.5 SSI_2 = 0.5 REI_2 = 0	DMI_3= 0.5 WOI_3 = - 0.5 SSI_3 = 1.0 REI_3 = 0

[a] Assumed Consumption (*Co*)=0.
[b] Only recycling, therefore, Cascading (*C*)=0.

Figure 4 UMPs for the Dutch and Australian case

Saving of water and an efficient reutilization of treated water and by-products is crucial. Sustainability of domestic water management could be reached through decentralization and separation of waste streams. Our study shows that a combination of state-of-the-art water saving technology, recycling and use of rain water results in a $SSI = 1$. Further optimization of the urban water cycle at building level can be achieved by increasing demand minimization. To increase demand minimization, implementation of water saving taps and dishwashers that are more efficient are needed. Moreover, if separation of waste streams is implemented, additional benefits can be reached. For instance, by separating urine and fecal matter, spread of pollutants can be prevented and nutrients can be recovered. Furthermore, if anaerobic digestion is used energy recovery is feasible as well (de Graaff 2010). Decentralization may also enhance the involvement of users in the prevention of pollution and in the proper functioning of the system. Moreover, regarding multi-source, new sources are being explored, for example high quality water generation from air.

4.4 Conclusion

The described approach relates urban characteristics to water harvesting potentials, thus aiming to foster a re-thinking of our current urban water systems. UHA can be used by urban planners and decision makers to understand the urban system and the internal flows within the same system and provide smart, customized solutions for existing and new urban areas. In aiming for sustainable development, it is evident that new approaches in urban resource management, such as Urban Harvest, novel city design and planning methods, need to be integrated.

Implementation of technology can have also drawbacks such as the rebound effect that is out of the scope of this chapter. Moreover, if technology implementation is combined with changes in user behavior, urban self-sustainability can be achieved.

The main shortcoming of current resource management in cities is to overlook self-producing potentials. The UHA proposed in this chapter, highlight that potentials are linked to local context and urban typology. Therefore, urban planning can contribute to facilitate linkages and synergies for harvesting of local resources towards sustainable cities. Further developing and testing for different urban typologies and different local context are important steps for future research. Further investigation on the dynamics of the flows is also required to evaluate storage implications and provide guidelines for design and operation. In addition to the incorporation of flow dynamics, for a flexible implementation at for instance block or neighborhood level, on-line estimates of flows and device parameters, preferably from a limited number of sensors, are needed, as well (see, for instance, Keesman (2011) for an overview of estimation techniques).

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Chapter 5

Evaluating the potential of improving the residential water balance at building scale

Abstract

Earlier results indicated that, for an average household, self-sufficiency in water supply can be achieved by following the Urban harvest Approach (UHA), in a combination of demand minimization, cascading and multi-sourcing. To achieve these results, it was assumed that all available local resources can be harvested. In reality, however, temporal, spatial and location-bound factors pose limitations to this harvest and, thus, to self-sufficiency. This chapter investigates potential spatial and temporal limitations to harvest local water resources at building level for the Netherlands, focusing on indoor demand. Two building types were studied, a freestanding house (one four-people household) and a mid-rise apartment flat (28 two-person households). To be able to model yearly water balances, daily patterns considering household occupancy and presence of water using appliances were defined per building type. A number of scenarios was defined including demand minimization, and light grey water (LGW) recycling potentially combined with rainwater harvesting (multi-sourcing) to cater for toilet and laundry water, second quality water (D_{Q2}). Results showed that water saving devices may reduce 35% of the conventional demand. Recycling of LGW can supply up to 36% of the conventional demand (83% - 100% of D_{Q2}) or up to 20% of the minimized demand (100% of D_{Q2}). For conventional demand, rainwater harvest may supply approximately 14% of the demand in case of the apartment flat and 18% in case of the freestanding house, respectively. To harvest these potentials, different system specifications, related to the household type, are required. Two constraints to recycle and multi-source were identified, namely i) to meet the demand given only by the grey water production and available rainfall; and ii) to harvest the potential given by the temporal pattern, and storage and treatment capacities.

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5 Harvesting urban resources towards more resilient cities

5.1 *Introduction*

In the transition towards more sustainable urban water systems, increasing attention is given to self-sufficiency (Rygaard *et al.*, 2011), and to a new planning and design paradigm to recover resources from wastewater (Guest *et al.*, 2009). This new paradigm considers the role of decentralized systems to address challenges faced by climate variability, population growth and urbanization (Makropoulos and Butler, 2010; Sharma *et al.*, 2010) as well as structural considerations that involve the form of urban development, patterns of land uses, types of land cover in the city, and the effect of lifestyles on water use (Guhathakurta and Gober, 2010).

Preliminary results for an average house in the Netherlands and Australia have shown that at household level, self-sufficiency can be achieved by following the Urban Harvest Approach (UHA): i.e. (i) minimizing demand; (ii) minimizing output; and (iii) multi-sourcing. These results are valid for an average household, assuming that all the available local resources can be harvested. In reality, there are limitations to harvest all the available local resources. The main limitations are spatial variations depending on building typology (e.g. single houses versus apartment blocks); seasonal and location-bound variations (e.g. yearly rain patterns, depending on locations) and temporal variations (demand and supply patterns that fluctuate through the day – day/night, within the week –working days/weekends, and within the year – seasons). Additionally, low acceptance of alternative sources for potable purposes also limits the potential for self-sufficiency.

This chapter focuses on the indoor water balance at building level and investigates the spatial and temporal limitations to harvest local water resources in the Netherlands. In this study, two building types were selected: a freestanding house and a mid-rise apartment flat. Yearly water balances were modeled based on daily time steps using different demand and supply patterns. Four demand patterns are defined at household level based on occupancy and the presence of water appliances according the building type. An additional pattern is evaluated for a flat to consider the effect of aggregating patterns. Different scenarios to improve the building water cycle were studied, following the hierarchy of measures proposed within the UHA. At first, this chapter introduces variations of the demand pattern related to the building type. Based on those variations, the different UHA measures (demand minimization, output minimization and multi-sourcing) are investigated (see Fig. 1). An important objective is to analyze the storage capacity required to match in-house demand – supply (grey water recycling) patterns and local water resources (precipitation) patterns. By investigating the influence of the building type on the variations of the supply and demand patterns and on the efficiency of the different UHA measures, customized solutions for design can be given for defined urban areas. Three scales are studied i) the subsystem level – collection and treatment of recycled water and harvested rain water; ii) the household level – including all indoor water flows – with a focus on the influence of occupancy on the water demand pattern, and iii) the building unit with a specific focus on the effect of aggregation of patterns on water balances. Notice that (i) the subsystem can be associated with (ii) the household level or with (iii) the building unit level.

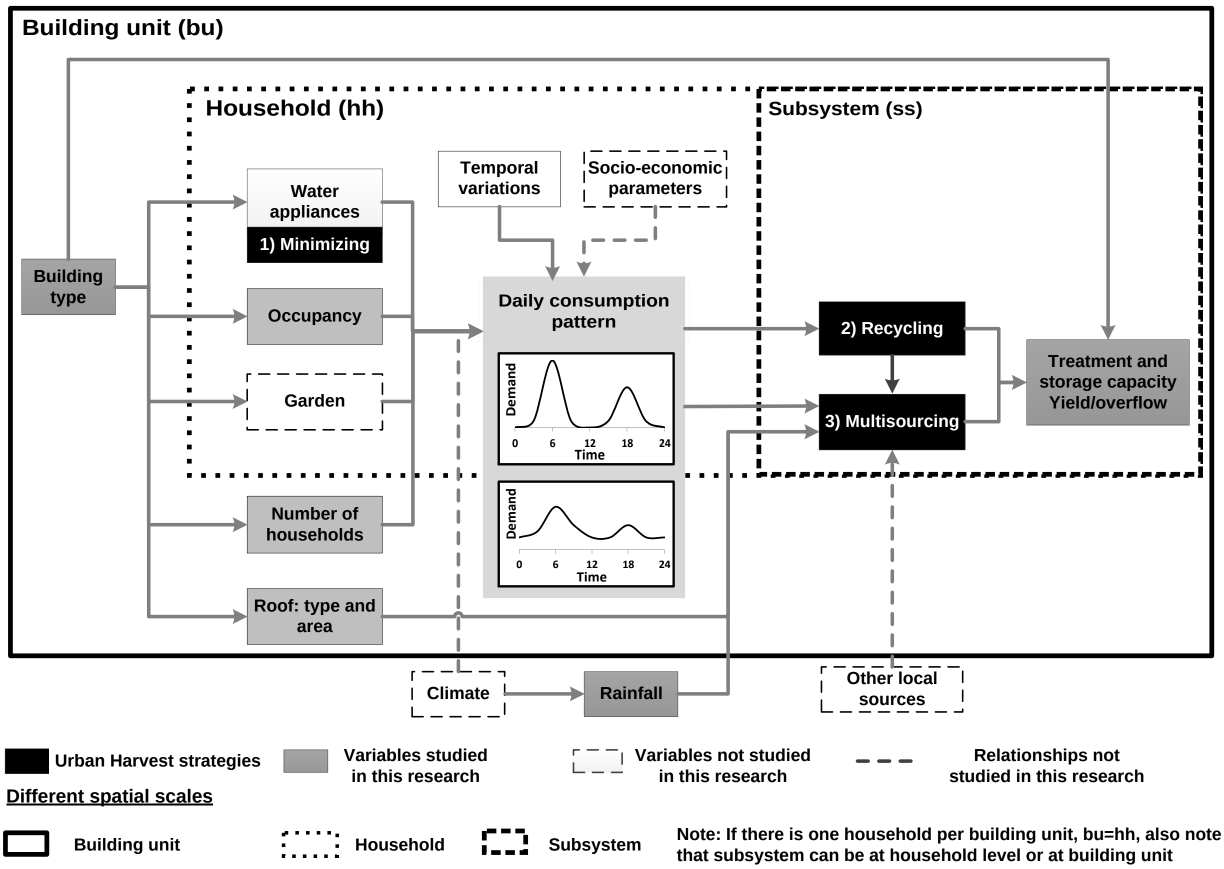


Figure 1 Variables influencing the water cycle at building level. In grey the main variables studied in this chapter: building type and demand pattern and rainwater harvesting; relationship with the Urban Harvest strategies; and the three study scales (i) subsystem, (ii) household and (iii) building unit level

5.2 Methodology

5.2.1 Urban Harvest Approach

Urban harvest steps

The Urban Harvest Approach (UHA) can be described in three steps: input minimization by implementation of more resource efficient technologies; output minimization by cascading and recycling of flows[10]; and multi-sourcing[11] of the remaining demand by harvesting local-renewable resources. In this chapter, we used UHA to study the urban water balance

[10] Cascading refers to direct reuse of waste flows, meanwhile recycling includes quality upgrading of the flow before reuse. In this chapter, to secure quality standards, we will only consider recycling. Recycled grey water will be used to supply non-potable activities.

[11] Although in the previous chapter, we assumed that rainwater harvesting can be treated for potables use. In this chapter, due to low acceptance of alternative sources for potable demand, we assume rainwater harvesting to supply non-potable activities.

at subsystem, household and building level, and to evaluate the potential for optimization. For this, a yearly water balance was prepared for the Netherlands, based on a survey of the daily residential in-house demand for the year 2010 (Foekema and van Thiel, 2011) and meteorological data from the weather station in Wageningen[12].

The study scenarios first consider input minimization for the largest flows (i.e. >10% of residential water demand). Secondly, wastewater from showering and bathing is assumed to be recycled to supply toilet flushing and laundry machine (Fig. 2), based on a quantitative, qualitative and temporal assessment (see Appendix A). Wastewater from the shower and bath is referred to as light grey water (LGW). LGW is the cleanest fraction of the residential wastewater. As a third step, rainwater harvesting is evaluated to supplement supply of LGW. Each of these three measures was modeled. In addition, the water balance for the subsystem, household and building unit was evaluated for different variables such as tank size, treatment capacity, inhabitants per household and roof area.

Because production of LGW and rainwater harvesting are neither simultaneous nor equal in quantity with actual demands for toilet flushing and laundry machine, it is necessary to introduce storage to balance supply and demand. Additionally, to secure quality standards, a treatment unit is required to upgrade water quality. In this chapter (Fig. 2), two storage units are considered[13]: $S_1^{S\&T}$, for LGW and $S_3^{S\&T}$ for treated LGW and rainwater, and the condition $S_1^{S\&T} = S_3^{S\&T}$ was used, as a first assessment. To minimize the number of variables, a plug-flow reactor ($S_2^{S\&T}$) was assumed to treat the LGW. Thus, hydraulic residence time – RT – and volumetric treatment capacity – k – define the volume of the treatment unit, $S_2^{S\&T} = RT \times k$.

As mentioned earlier, treated water from the shower and bath (d_{sho}) is used to supply water for toilet flushing (d_{toi}) and the laundry machine (d_{lau}) – see Fig. 2. Therefore, the recycling potential can be expressed as: $R_{pot}(t)=d_{sho}(t)$, and demand for second quality water is defined by: $D_{Q2}(t)=d_{toi}(t) + d_{lau}(t)$.

A general mass balance reads as: Storage = Total inputs (Ti) – Total outputs (To) – Consumption (Co). For the system in Fig. 2: $Ti = Ei_{Q1}+ Ei_{Q2} +M_{pot}$ and $To = d_{tap}+d_{lau}+ d_{toi} +O_1^{S\&T} +O_2^{S\&T}$. Considering Co=0 (i.e. no loss of water), and ds as the change of the volume stored in $S_1^{S\&T}$, $S_2^{S\&T}$ and $S_3^{S\&T}$, at a specific instant in time, the volumetric balance equation can be written as:

$$\frac{ds}{dt} = [Ei_{Q1}(t) + Ei_{Q2}(t) + M_{pot}(t)] - [d_{tap}(t) + d_{lau}(t) + d_{toi}(t) + O_1^{S\&T}(t) + O_2^{S\&T}(t)] \qquad (1)$$

[12] http://www.climatexchange.nl/projects/bsikme1/haarweg.htm
[13] The storage units were assumed to be ideal and closed, thus dead storage capacity (initial tank level set to zero) and evaporation were excluded in modeling.

Defining as objective that the demand condition ($D=D_{Q1}+D_{Q2}$) is always met gives

$$D(t) = Ei_{Q1}(t) + Ei_{Q2}(t) + R_{act}(t) + M_{act}(t) \tag{2}$$

Hence, there are two types of demand: potable (D_{Q1}) and non-potable (D_{Q2}). D_{Q1} represents the daily demand of potable water. Potable water is required for kitchen and bathroom taps (d_{tap}) and for shower and bath (d_{sho}), thus $D_{Q1}= d_{tap}+d_{sho}$. Meanwhile D_{Q2} represents the demand for non-potable activities. Non-potable water can be used for toilet flushing (d_{toi}) and laundry machine (d_{lau}), thus $D_{Q2}= d_{lau}+d_{toi}$.

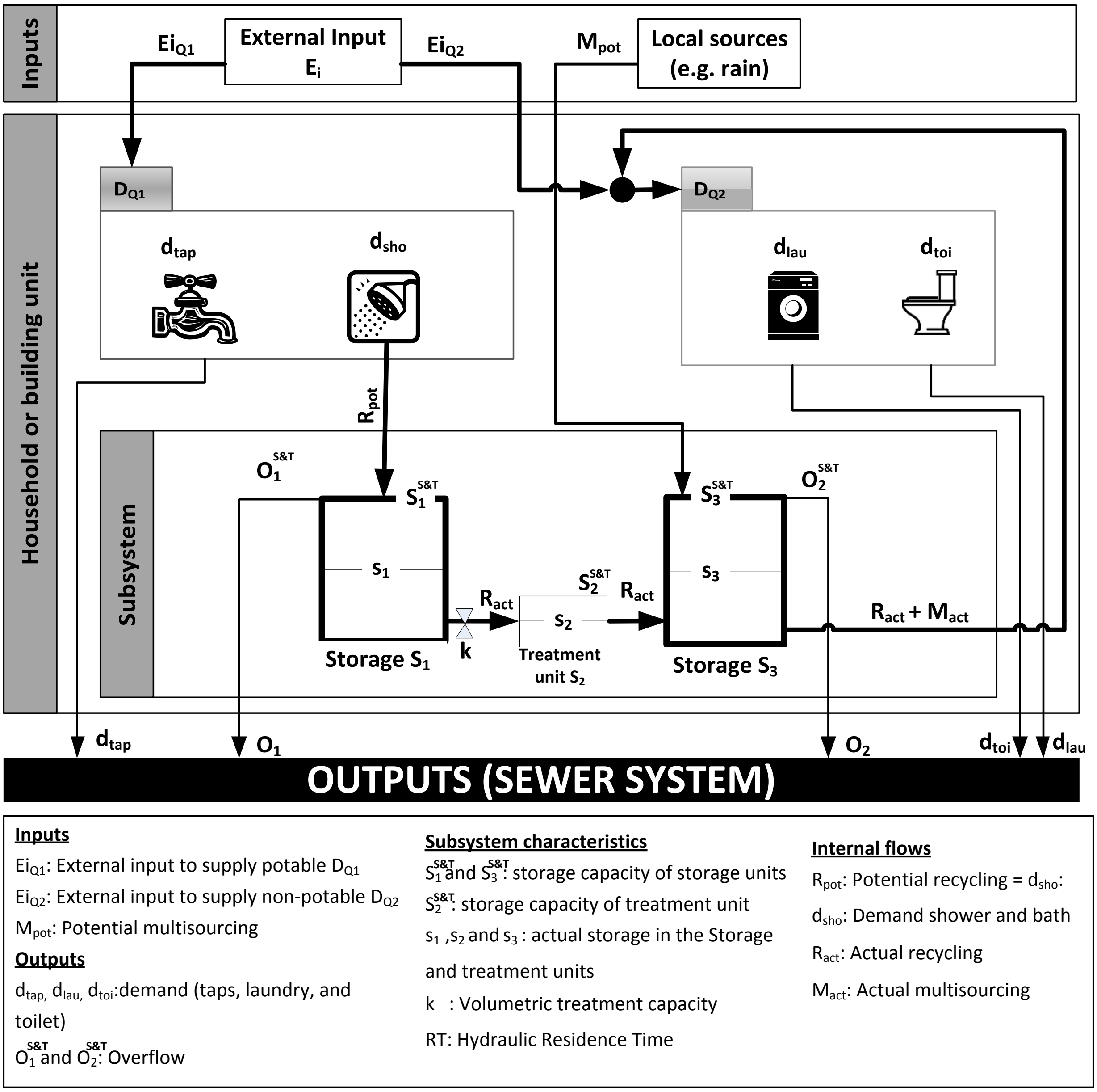


Figure 2 Schematic representation of the water system at household or building unit including subsystem for recycling LGW and harvesting rainwater, focused on indoor demand

The UHA focuses on technology implementation and does not consider any changes in human behavior. Notice from Fig. 2 that D_{Q1} is supplied by Ei_{Q1}, thus $D_{Q1}=Ei_{Q1}$. Then, D_{Q1} can only be minimized by installation of water saving technologies, the first step of the UHA. Note also that D_{Q2} is supplied by Ei_{Q2}, R_{act} and M_{act}, thus

$$D_{Q2}(t) = +Ei_{Q2}(t) + R_{act}(t) + M_{act}(t) \qquad (3)$$
$$\Rightarrow Ei_{Q2}(t) = D_{Q2}(t) - R_{act}(t) - M_{act}(t)$$

One of the objectives of the UHA is to minimize Ei_{Q2}. Ei_{Q2} can be minimized by implementing water saving technologies (minimizing D_{Q2}), by recycling (maximizing R_{act}) and by multi-sourcing (maximizing M_{act}), steps 1, 2 and 3 of the UHA. Export of resources is set to zero, to avoid flows passing through without being used in the system and being exported as secondary resources. Hence, the optimal case is when $Ei_{Q2} = 0$; $R_{act}+M_{act}=D_{Q2}$.
Additionally within the UHA, waste exported should be minimized. The waste exported (*We*) of the system can be written as:

$$We(t) = d_{tap}(t) + d_{lau}(t) + d_{toi}(t) + O_1^{S\&T}(t) + O_2^{S\&T}(t) \qquad (4)$$

Notice from Fig. 2 that $D=D_{Q1}+D_{Q2} = d_{tap}+d_{lau}+d_{toi}+d_{sho}$. Also note that $R_{pot} = d_{sho}$ and $R_{act} = R_{pot} - O_1^{S\&T}$. Thus, *We* can also be defined as:

$$We(t) = D(t) - R_{act}(t) + O_2^{S\&T}(t) \qquad (5)$$

Hence, to minimize *We*, in addition to minimizing *D*, the overflows $O_1^{S\&T}$ and $O_2^{S\&T}$ should be minimized resulting in maximized R_{act} and M_{act}, such that $R_{act}=R_{pot}$ and $M_{act}=M_{pot}$, by a proper choice of the storage capacities $S_1^{S\&T}$, $S_2^{S\&T}$ and $S_3^{S\&T}$. Selecting the optimal storage capacity involves tradeoffs, because it will directly depend on space availability and cost. Moreover, if the storage capacity is small, it will be most of the time full being volumetric effective, but leaving easily excess to overflow. If, on the other hand, the storage capacity is large then it will be able to capture larger yields. However, it is more difficult to be full or empty and then being less volumetric effective. Appendix B contains the model used for the subsystem.

Metabolic profile

To relate these variables and to evaluate the different measures, the so-called "metabolic profile" is calculated. The metabolic profile is described in terms of the demand (*D*), the waste exported (*We*) and the resources harvested (*Rh*). The metabolic profile is defined by four indices, i.e. Demand Minimization Index (*DMI*), Waste Output Index (*WOI*) Self-Sufficiency Index (*SSI*), and Resource Export Index (*REI*) as defined in Chapter 4:

$$DMI = \frac{Conventional\ demand\ (D_{con}) - Demand\ (D)}{Conventional\ demand\ (D_{con})} = \frac{\sum_{t=1}^{t=n} D_{con}(t) - D(t)}{\sum_{t=1}^{t=n} D_{con}(t)} \tag{6}$$

Where, D_{con} represents the demand when conventional technologies are implemented, while D is the actual demand.

$$WOI = -\ \frac{Waste\ exported\ (We)}{Demand\ (D)} =_{[eq.5]} -\frac{\sum_{t=1}^{n} D(t) - R_{act}(t) + O_2^{S\&T}(t)}{\sum_{t=1}^{t=n} D(t)} \tag{7}$$

In this chapter, we do not consider export of resources, therefore, Er=0; REI=0 and

$$SSI = \frac{Resources\ harvested\ (Rh)}{Demand\ (D)} = \frac{\sum_{t=1}^{n} R_{act}(t) + M_{act}(t)}{\sum_{t=1}^{n} D(t)} \tag{8}$$

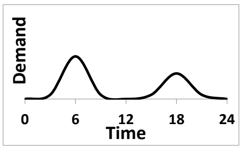
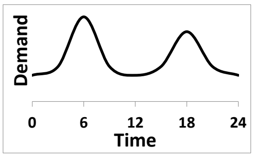
The indices *DMI*, *WOI* and *SSI* can be calculated for any given period (e.g. daily, weekly or yearly) and, based on data availability, different time steps can be used, as well. The metabolic profile can be calculated for a building unit (bu), household (hh) or subsystem (ss), where the subsystem is defined as the collection and treatment system for grey and rainwater. Since the water from the tap (d_{tap}) is not recycled, SSI_{bu}<1, additionally, SSI_{ss} > SSI_{bu} because the value of Rh is equal in both cases, but D_{bu}>D_{ss} *as* D_{bu}=D_{Q1}+D_{Q2}=D and D_{ss}=D_{Q2}. Thus, we can see that for the same scenario the subsystem has a large SSI_{ss}, but an overall low SSI_{bu}. This will depend on the ratio D_{Q2}/D.

5.2.2 Residential water demand

Spatial variations

Residential water demand is correlated with household size, presence of garden and type and number of water appliances (Fox *et al.*, 2009). At household level, the water pattern shows a high short-term variation. This high short-term variation, which is due to instant demand, is mainly present at "peak hours" and moments in which demand is zero. This variation is reduced at a larger spatial scale, in which more households are considered, due to aggregation of different patterns. In this case, the pattern is smoothed by reduced peaks and usually there is a base flow demand, see table 1. Generally, subsystems (e.g. recycling grey water for toilet) are considered the smallest scale for evaluation. To evaluate the efficiency of subsystems, the effect on the complete system – in this case in the building unit (bu) – needs to be considered, as well. We also compared the water cycle at household level to understand the differences provided by number of inhabitants and water appliances. Objectives of evaluating at building and at subsystem level are twofold: firstly to demonstrate that only results at subsystem level can be incomplete and secondly to show the applicability of the UHA for different scales.

Table 1 Description of the selected building units

	Free standing house	Mid-rise apartment flat
		
Roof area (m²)	60	640
Occupancy	1 family – 4 people	56 people: 28 apartments x 2 people
# of toilets	2 (1 in each floor)	28 (1 per apartment)
# of laundry machines	1 (in 1st floor)	28 (1 per apartment)
# of showers/bathtubs	1 (in 2nd floor)	28 showers (1 per apartment) – No bath
Roof type	Pitched	Flat
Grey water system	Single house collection	Shared collection
Rainwater collection	Single	Shared
Daily pattern demand		

Two building types were selected, including a free standing house with four occupants (a family with two children) and an apartment with two occupants (a couple without children). Using information from SenterNovem (2006) on reference houses for Vinex locations in the Netherlands, relevant characteristics as shown in Table 1 were defined. The building type also influences the number of water appliances, as for instance the number of toilets and the presence or absence of a bath. For this study, it is assumed that the apartments with two occupants do not have a bathtub.

Seasonal and location bound variations

Residential water demand is also linked to geographical location. Different countries have different per capita water use due to differences in weather, culture, water resources availability and socio-economic factors (Fox *et al.,* 2009). With respect to seasonal variations, the presence of garden or swimming pools may increase water demand during hot and dry periods. In general, during summer the frequency of activities like showering increases. However, detailed data are not available. This chapter focused on in-house water demand and seasonal effects on water demand were not taken into account.

Temporal variations

For recycling of grey water, which is a dependent source, it is important to analyze both the supply and demand pattern. The characteristics of these variations influence the time step (Δt) needed for modeling purposes. For this study, Δt=1 hour was selected. Residential water usage pattern may strongly differ because of the wide number of variables involved and because of the unpredictable nature of human behavior. Butler and Graham (1995) found that the household usage of different water appliances is quasi-random, with frequency of use being related to the time of day and with different characteristics (e.g.

quantity, quality, temperature). Due to the intermittent use and relatively short duration of water activities, the residential water pattern flows are subject to high fluctuation.

Several studies have found a bi-modal distribution for residential water demand with a morning and an afternoon peak. For the Netherlands, water demand can be related to whether people are at home or not and if they are asleep, getting up or preparing for bed (Blokker *et al.*, 2010).

5.3 Results

The three strategies proposed by the UHA - demand minimization, output minimization and multi-sourcing - were evaluated at different spatial scales. Moreover their effect on DMI, SSI and WOI was analyzed. Demand minimization is related to technologies used (conventional or water saving devices) and household occupancy. This was evaluated at subsystem level and at household level. Output minimization, in this case recycling, is related to household occupancy and the number of households connected to the subsystem. Thus, recycling is evaluated at subsystem, household and building unit. Finally, multi-sourcing of rainwater is related to the building, thus it was evaluated at subsystem and building level. Table 2 shows an overview of the scenarios, variables and scales studied. Recall that for the freestanding house, household and building level are the same.

Table 2 Description of the scenarios, variables and scales studied

Scenario (variables to be studied)	*Subsystem*	*Household*	*Household / building*	*Building unit*
	Two and four-pp	**Two-pp**	**Four-pp / Freestanding**	**Mid-rise flat**
Baseline assessment (sec 5.3.1)	X	X	X	
1.Minimization (sec 5.3.2) *(shower, toilet flushing and laundry machine)*	X	X	X	
2. Recycling (sec 5.3.3) *ƒ (k, $S_1^{S\&T}$, $S_3^{S\&T}$ and pattern)*	X	X	X	X
3. Minimization + Recycling (sec 5.3.3) *ƒ (k, $S_1^{S\&T}$, $S_3^{S\&T}$ and pattern)*	X	X	X	
4. Multi-sourcing (sec 5.3.4) *ƒ (k, $S_3^{S\&T}$, pattern, roof area and rainfall)*	X		X	X
5. Recycling + Multi-sourcing (sec 5.3.4) *ƒ (k, $S_1^{S\&T}$, $S_3^{S\&T}$, pattern, roof area and rainfall)*	X		X	X

5.3.1 Baseline – residential demand at household level

A water use survey, conducted in the Netherlands in 2010, found an average residential water demand of 124 l p^{-1} d^{-1} (Foekema and van Thiel, 2011). The activities with largest water demand are shower, toilet flushing and laundry machine. The survey did not report important differences between week days and weekend days but it reported on differences related to household size. For instance, larger households do laundry more frequent, while the total water demand per person is lower. Also, high correlations between households with children and bath use were found. Table 3 summarizes the water demand for two households, with two and four-people. Although, the demand per person per day are similar, the distribution of activities is different. The main difference is the bath, that in the four-people household accounts for 9% of the total demand, meanwhile due to our assumptions, in the two-people household it is zero.

Table 3 Water demand per person according household occupancy for the Netherlands, year 2010 (after Foekema and van Thiel, 2011).

	2 people				4 people			
Activity	Demand per time [l]	Usage frequency [times d^{-1}]	Demand [l $p^{-1}d^{-1}$]	%	Demand per time [l]	Usage frequency [times d^{-1}]	Demand [l $p^{-1}d^{-1}$]	%
Shower	56.8	0.8	45.5	36.5	68.7	0.7	48.1	40.0
Toilet flushing	5.75	6.64	38.2	30.6	5.74	5.4	31.0	25.7
Washing machine	55.6	0.3	16.0	12.9	55.6	0.2	13.3	11.1
Bath[a]	0	0.00	0.0	0	114.3	0.1	10.3	8.5
Sink	4	1.42	5.7	4.5	4	1.06	4.2	3.5
Other	-	-	5.3	4.3	-	-	5.2	4.3
Dishwashing (machine)	18.5	0.3	5.3	4.2	18	0.2	3.9	3.2
Dishwashing (hand)	9.6	0.5	4.4	3.5	8	0.1	1.0	0.9
Kitchen tap	-	-	3.2	2.6	-	-	2.7	2.2
Clothes washing (hand)	40	0.03	1.1	0.9	40	0.02	0.7	0.6
Total			124.7				120.4	

[a] For two-people household is assumed to be zero.

The survey also included usage frequency (Table 3) which changes according the household size. The usage frequency is important to determine the real daily demand. Fig. 3 shows the variations of the daily residential water demand over a year, for two and four-people households based on the data from Foekema and van Thiel, (2011). Fig. 3a and 3b shows the variations of the daily water demand. For a two-people household the average daily demand per household is 249 l varying from 157 to 347 l hh^{-1} d^{-1}. For a four-people household the daily average is 481 l hh^{-1} d^{-1} varying from 367 to 610 l $hh^{-1}d^{-1}$. For the four-people household, the demand presents a bi-modal distribution. The second peak in the Fig. 3b can be explained due to the bath, because it is a non-daily and large demand.

Fig. 3c and 3e show the variations over the year, sorted from lowest to highest daily variation showing the contribution per activity. In the vertical axis the value for daily demand is given, meanwhile in the horizontal axis the number of days is plotted, in total 365 days. Our focus is on water use for shower, toilet and laundry. Thus, in Fig. 3c and 3e, tap water use includes all the other activities. Looking at the total daily demand, it can be seen that few days have similar water demand. This variation in the daily water demand highlights the importance to investigate the dynamics of the urban water cycle. Isolating the demand for shower, toilet flush and laundry machine, and sorting them from lowest to highest demand, we obtain Fig. 3d and 3f. Demand and supply are not synchronized. Assuming that shower feeds simultaneously $D_{Q2,}$ for a two-people-household only 94 days the total demand D_{Q2} could be supplied, meanwhile for a four-people-hh 321 days the total demand D_{Q2} could be supplied. Additionally, when $d_{sho}>D_{Q2,}$ there will be a surplus. To match supply and demand, thus minimizing the surplus, storage is required.

5.3.2 Demand minimization

For the minimization step, the measures were focused on the activities with the largest demand, which are shower, toilet flushing and laundry machine. To provide an overview of the maximum saving potential, vacuum toilets with a demand of 0.8 l per flush, a shower with a demand of 6 l per minute and a washing machine with a demand of 9 l kg^{-1} and 4 kg per cycle were considered (Pakula and Stamminger 2009), see Table 4. Using the most efficient water appliances, the demand minimization indices were calculated. For the two-people household the D_{con}= 124.7 l p^{-1} d^{-1} after minimization is D = 79.8 l p^{-1} d^{-1}, thus, DMI_{hh} = 0.36 (which means a reduction of 36% in water use). For the four-people household D_{con}= 120.4 l p^{-1} d^{-1} and D=80.1 l p^{-1} d^{-1}, thus, DMI_{hh} = 0.34 (for the DMI_{ss} see table 5).

Table 4 Daily water demand in liters per person after demand minimization

	2 people				4 people			
Activity	Demand per time [l]	Usage frequency [times d^{-1}]	Demand [l p^{-1} d^{-1}]	%	Demand per time [l]	Usage frequency [times d^{-1}]	Demand [l p^{-1} d^{-1}]	%
Shower	46	0.8	36.5	46	46	0.7	37.0	46
Toilet flushing	0.8	6.64	5.3	7	0.8	5.4	4.3	5
Washing machine	45	0.3	13	16	45	0.2	10.8	13
Bath	0	0.00	0.0	0	114.3	0.1	10.3	13
Other activities			25.0	31			17.7	23
Total			79.8	100			80.1	100

Similar to Fig. 3, an overview of the water demand when demand minimization is implemented is shown in Fig. 4. Notice from Fig. 4d and 4f that supply from the shower is larger than demand from toilet flush and laundry machine. This means that self-sustainability for the subsystem can be achieved. However, if we consider the overall efficiency of the system, larger supply than demand implies that there are overflows, or in other words, waste output.

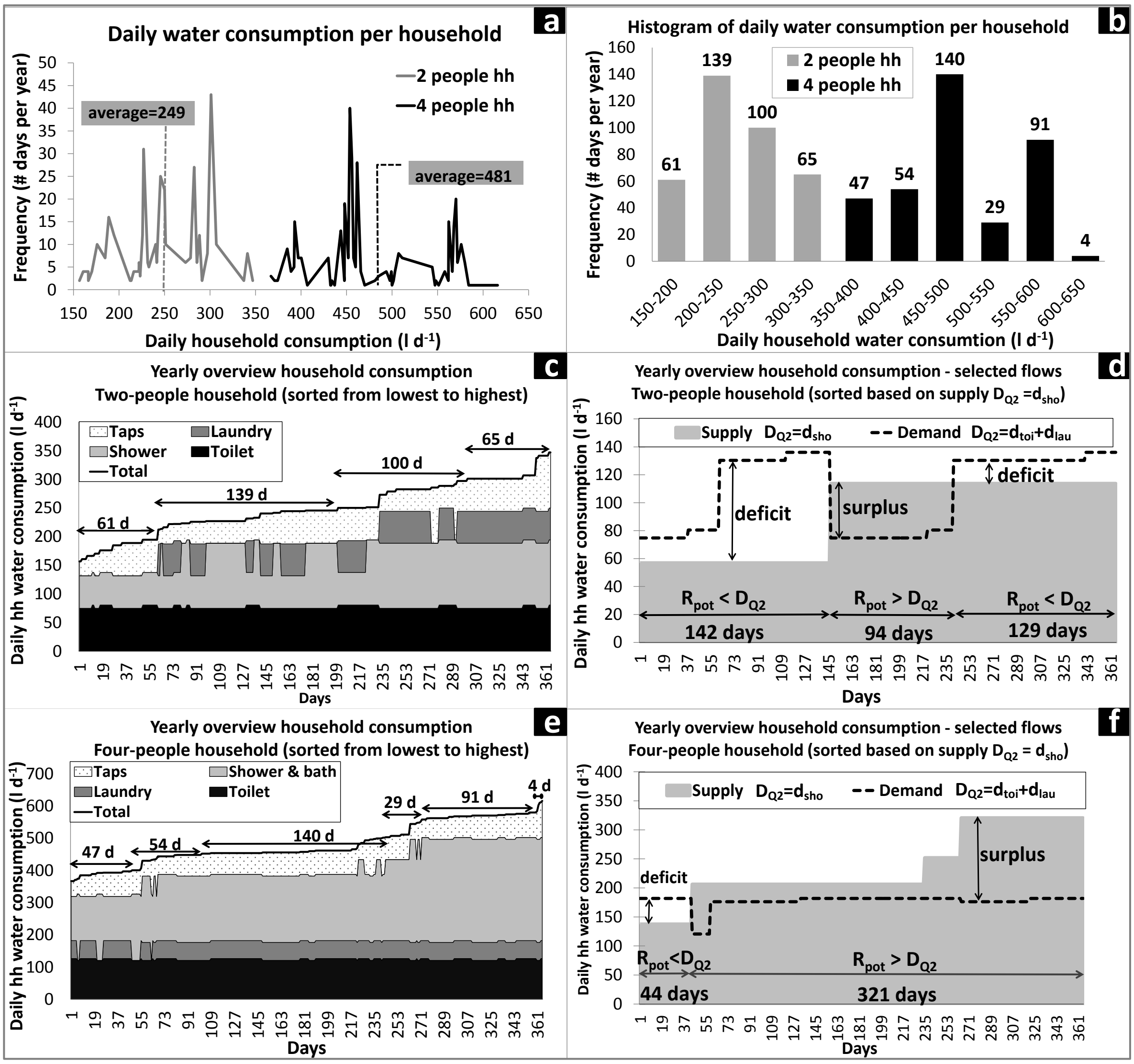


Figure 3 Daily demand for a year for two and four-people household based on Foekema and van Thiel (2011) water demand and frequency-2010. (a) Overview of variations of the daily water demand. (b) Histogram of daily water demand. (c), (e) Overview of the daily household water demand per activity, sorted from lowest to highest demand. (d), (f) Overview of activities with the largest demand and comparison of potential supply recycled water (shower + bath) and demand (toilet + laundry).

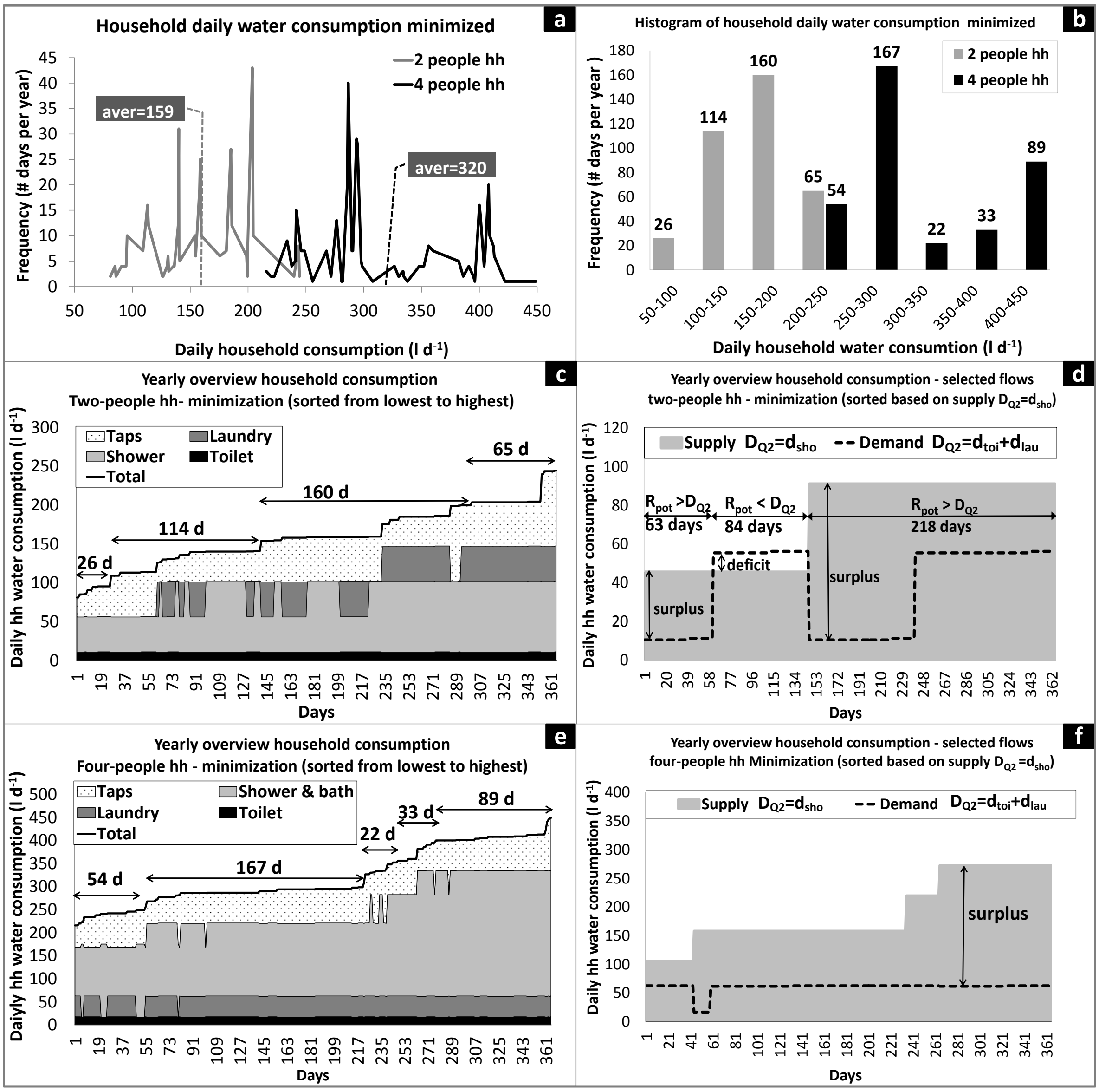


Figure 4 Overview of yearly distribution of minimized daily demand for two and four-people household (as described in Figure 3)

Table 5 shows the maximum potentials for the given scenarios, for steady state. These values show the importance of simultaneous evaluation at different scales e.g. household and subsystem. For conventional demand at subsystem level, self-sufficiency (SSI_{ss}) could be achieved or almost achieved. However, at household level SSI_{hh} is lower than 0.4. Additionally, looking at the *WOI*, when minimization is implemented, $WOI_{ss} > 1$, meaning that the overall waste of the subsystem is larger than the demand. These scenarios result in overflows (wastes) because, even with minimization, the water production from the shower is larger than the demand; this can be prevented by re-using this water for other activities, or by trying to influence user behavior and reduce shower demand.

Table 5 Maximum potentials for the given scenarios, and comparison at subsystem, household and building level

Scenario	Subsystem [a]		Household	Household / building	Building unit
	Two-pp	Four-pp	Two-pp	Four-pp / Freestanding	Mid-rise flat
Baseline assessment [m³ y^{-1}]	D_{Q2}=40	D_{Q2}=65	D=91 R_{pot} =33	D=176 R_{pot} =85 M_{pot} =48	D = 2548 D_{Q2}=1120 R_{pot} = 924 M_{pot} = 512
1.Minimization D, D_{Q2} and R_{pot} [m³ y^{-1}]	D_{Q2}=13	D_{Q2}=22	D=58 R_{pot} = 27	D=117 R_{pot} =69	D = 1624 R_{pot} = 756
DMI, SSI, WOI [-]	DMI = 0.68 SSI = 0 WOI = -1	DMI = 0.66 SSI = 0 WOI = -1	DMI = 0.36 SSI = 0 WOI = -1	DMI = 0.34 SSI = 0 WOI = -1	
2. Recycling [b]	DMI = 0 SSI ≤ 0.83 WOI ≤ -0.17	DMI = 0 SSI ≤ 1 WOI ≤ 0	DMI = 0 SSI ≤ 0.36 WOI ≤ -0.64	DMI = 0 SSI ≤ 0.37 WOI ≤ - 0.63	DMI = 0 SSI ≤ 0.36 WOI ≤ -0.64
3. Minimization + Recycling	DMI = 0.68 SSI ≤ 1 WOI ≤ 0	DMI = 0.66 SSI ≤ 1 WOI ≤ 0	DMI = 0.36 SSI ≤ 0.22 WOI ≤ - 0.78	DMI = 0.34 SSI ≤ 0.19 WOI ≤ -0.81	
4. Multi-sourcing [b]	DMI = 0 SSI ≤ 0.46 WOI = -1	DMI = 0 SSI ≤ 0.74 WOI = -1		DMI = 0 SSI ≤ 0.27 WOI = -1	DMI = 0 SSI ≤ 0.20 WOI = -1
5. Recycling + Multi-sourcing	DMI = 0 SSI ≤ 1 WOI ≤ -1	DMI = 0 SSI ≤ 1 WOI≤ -1		DMI = 0 SSI ≤ 0.37 WOI ≤ -0.63	DMI = 0 SSI ≤ 0.44 WOI ≤ -0.56

[a] At household or building unit level.
[b] Maximum values considering recycling on LGW for toilet flushing and laundry machine.

In reality, only a percentage of the potential can be harvested – the actual harvest – because of daily water demand patterns and restrictions given by the storage capacity of the subsystem. In the following sub-sections, daily patterns are described per household type for both conventional and minimized scenarios. Subsequently, recycling options are evaluated over a period of a year with an hourly time step. The first scenarios focus on evaluation at household level, while more advanced scenarios consider the effect of aggregation of patterns for the mid-rise flat to evaluate the effects at building unit level with multiple households.

5.3.3 Output minimization by recycling

Matching daily demand and supply patterns at household level

Residential water flows can vary significantly from day to day. Furthermore, daily water demand is un-evenly distributed during the day. For instance, for a household the minimum hourly flow is zero, and it is likely to be during the night. Therefore, to evaluate the efficiency of the measures and to estimate the storage capacity needed, it is important to investigate also the daily pattern. Since multiple patterns are present (Blokker et al. 2010), in particular one pattern was studied. The characteristics of the studied pattern are that the inhabitants shower between 7:00 – 8:00 (morning peak), do their laundry between 17:00 – 18:00 (afternoon peak) and toilet flushing distributed over the day (excluding night).

Type and number of water appliances are important to define the variations in the daily pattern. For instance, for a four-people household with two toilets, the toilet flush can be simultaneous at peak hours. Thus a four-people household can present a larger peak than a two-people household with one toilet.

Fig. 5 shows that actual recycling (R_{act}) is a function of storage capacity ($S_1^{S\&T}$,$S_2^{S\&T}$ *and* $S_3^{S\&T}$) and treatment capacity *k;* recall that, the volume of the treatment unit is determined by the retention time (*RT*) and the treatment capacity (*k*); $S_2^{S\&T}$ = *RT* x *k*. The maximum value for R_{act} is given by the lowest of R_{pot} or D_{Q2} values. For minimized flows, a small storage capacity is required to harvest all potential. Notice that similar subsystem configuration will perform different according occupancy and presence of water saving devices.

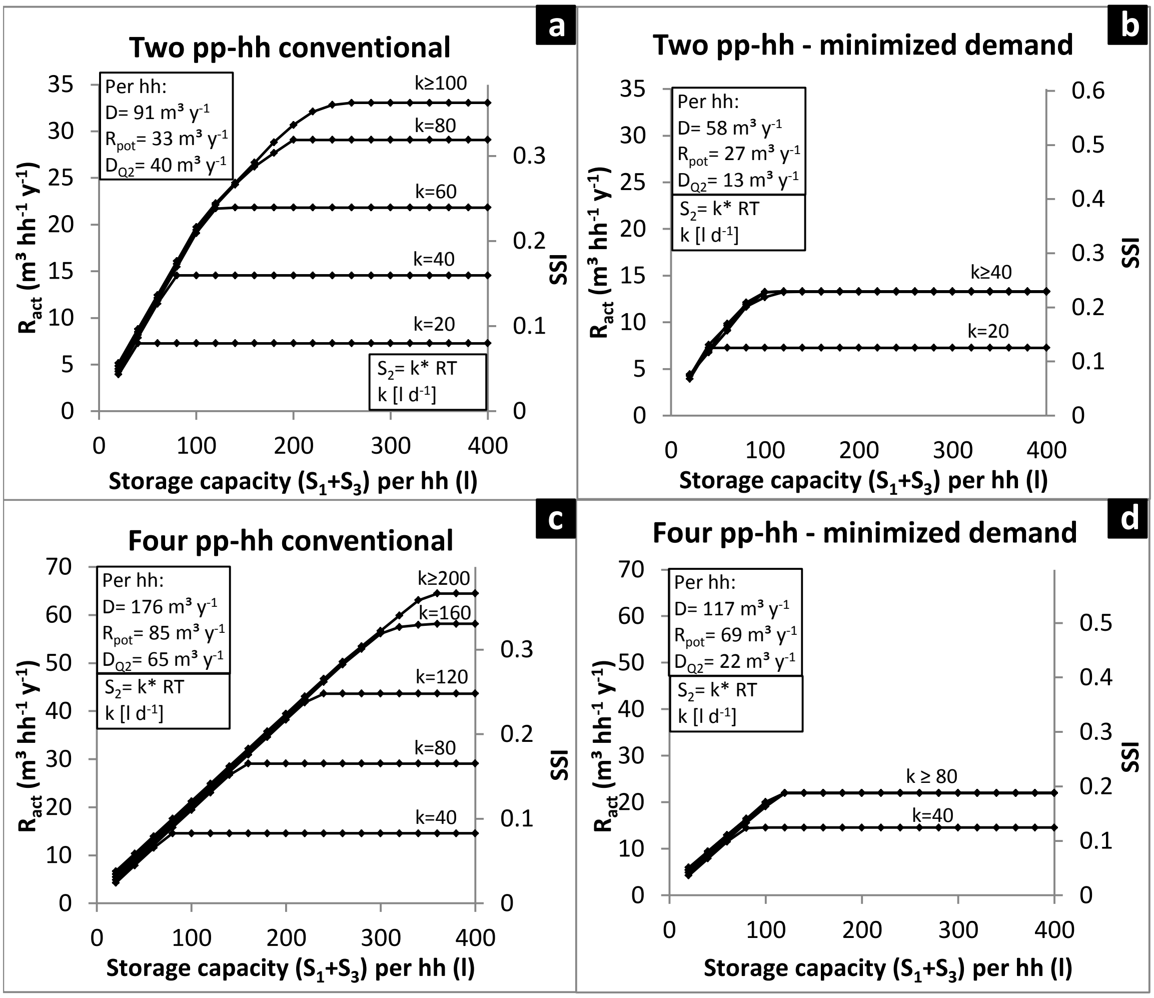
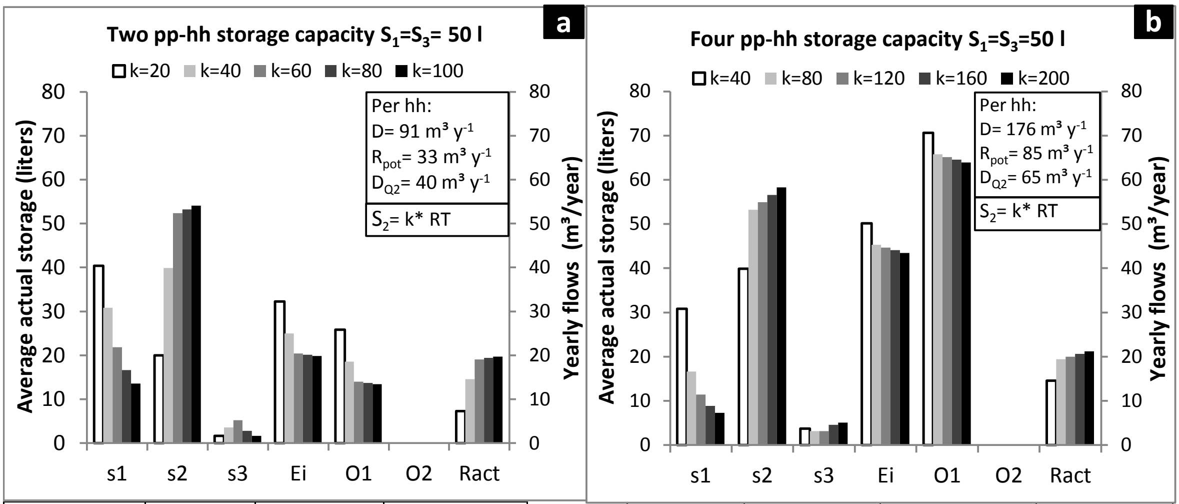


Figure 5 Actual recycling (R_{act}) for two and four-people household, for different k [l d^{-1}], different strategies and RT = 1 day. S_1 and S_3 are storage units and S_2 the treatment unit.

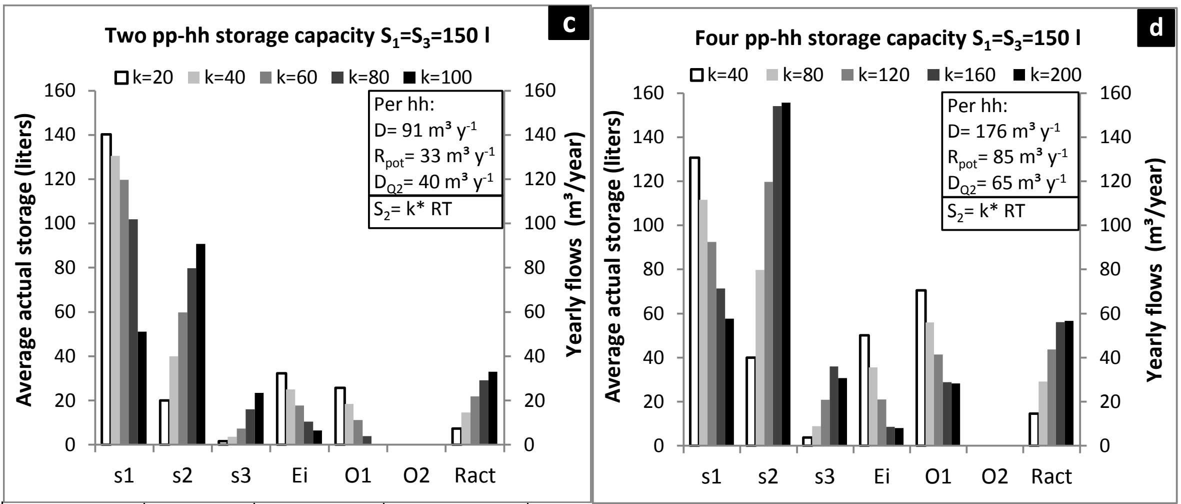
To visualize the changes in the subsystem, the different subsystem variables were plotted for the two households and for two storage capacities: 50 and 150 l. Fig. 6 shows the non-linear relationship between the variables. Fig. 6 also shows that s_1 and s_3 depend on *k*, $S_1^{S\&T}$

and the pattern. To evaluate the efficiency of the storage units, the volumetric efficiency (VE) was calculated. VE is the yearly average volume stored in the tank divided by the tank size, expressed in percentage. Fig. 6 shows that the assumption $S_1^{S\&T} = S_3^{S\&T}$, is not suitable for these cases, because it results in a low volumetric efficiency for the storage unit $S_3^{S\&T}$.



	VE s_1	VE s_2	VE s_3
k=20	80%	100%	4%
k=40	62%	100%	8%
k=60	44%	87%	10%
k=80	34%	66%	6%
k=100	28%	54%	4%

	VE s_1	VE s_2	VE s_3
k=20	62%	100%	8%
k=40	34%	66%	6%
k=60	22%	46%	6%
k=80	18%	36%	10%
k=100	14%	29%	10%



	VE s_1	VE s_2	VE s_3
k=20	93%	100%	1%
k=40	87%	100%	3%
k=60	80%	100%	5%
k=80	68%	100%	11%
k=100	34%	91%	15%

	VE s_1	VE s_2	VE s_3
k=20	87%	100%	3%
k=40	75%	100%	6%
k=60	61%	100%	14%
k=80	47%	96%	24%
k=100	39%	78%	21%

Figure 6 Subsystem behavior for a single apartment (two-people hh) and for the freestanding house (four-people hh). For two tank storage capacities $S_1^{S\&T} = S_3^{S\&T}$ = 50 and 150 l. S_1 and S_3 storage units and S_2 treatment unit. s_1,s_2 and s_3 correspond to the average volume in the storage units given in liters and the other variables are the total value in m³ for a year, and VE: Volumetric efficiency per storage unit. k is given in l d^{-1} per household.

Aggregation factor

As shown in Table 1 for the mid-rise flat, the most appropriate scale for collection and treatment of grey water is at building unit and not at household level. At building level with multiple households, the worst case scenario will be when all the households have identical demand. However, the probability that multiple households have identical demands is low. Thus there is an aggregation pattern. To evaluate how the aggregation of patterns influences the water cycle at building unit, the daily pattern was simulated using SIMDEUM (Blokker et al. 2010). By simulating 28 apartments with 365 patterns, we found that the morning peak is approximately 0.6 $m^3 h^{-1}$, which corresponds to a 12% of the daily demand, see Fig. 7a. To study the aggregation effect in the mid-rise building, the worst case scenario (*wcs*) was studied as well. The *wcs* considers simultaneous demand of the 28 apartments, following the pattern described in 3.3.1. The demand peaks were estimated, only considering the selected activities toilet, laundry and shower. Assuming that all the apartments have the same pattern, the morning peak for the flat is 3.5 $m^3 h^{-1}$. Therefore, the aggregation factor reduced the morning peak by 80%.

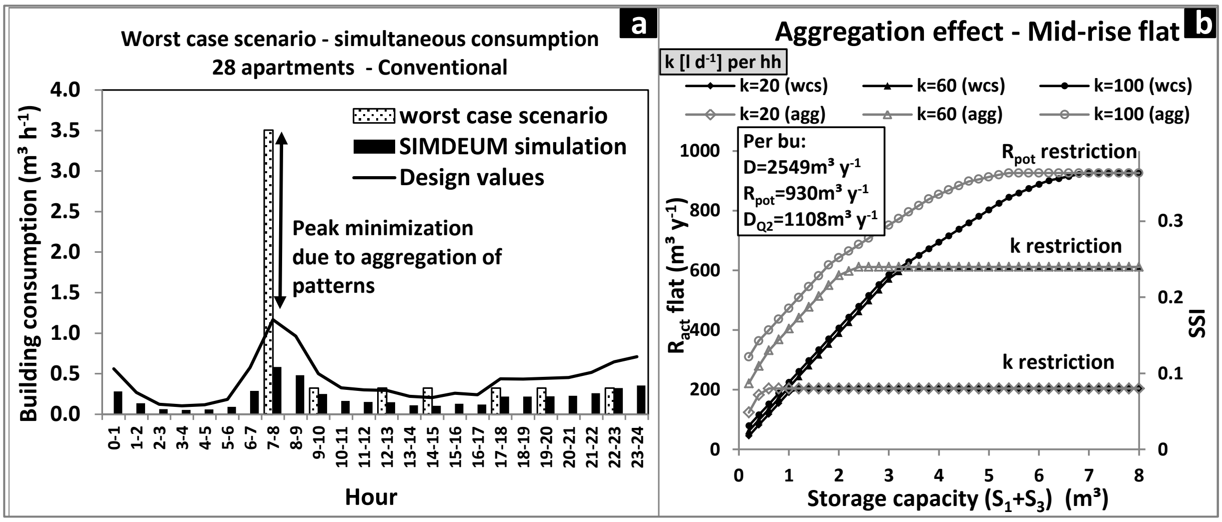


Figure 7 aggregation effect (a) one realization for daily pattern for the apartment flat with conventional demand for worst case scenario, simulation aggregating patterns using SIMDEUM and maximum design peak values. (b). Influence of the pattern on the R_{act} per building in a year – two daily patterns: worst case scenario (wcs), and aggregation (agg).

For design purposes, an aggregation pattern was defined, based on the SIMDEUM simulation and assuming a security factor of two for the peaks (see Fig. 7a maximum design values). For the morning, the maximum probable flow was defined at 1.2 $m^3 h^{-1}$. Again, multiple realizations are possible, only the design pattern is studied to evaluate the effect of aggregation versus the worst case scenario. The aggregated pattern was defined as follows: to minimize the morning peak – shower, 16% is assumed between 6:00 – 7:00, 32% between 7:00 – 8:00, 26% between 8:00-9:00, 13% between 9:00-10:00 and 13% between 21:00 – 23:00. And for toilet flush, the morning demand was assumed to be four times per person and it was distributed between 6:00 and 10:00 following the percentage distribution given by SIMDEUM. To minimize the afternoon peak, the toilet demand was distributed homogeneously between 17:00 and 22:00. For laundry, it was revised that the sum of toilet and laundry did not exceed the design flow of 0.8 $m^3\ h^{-1}$, the excess demand is allocated in the subsequent hour checking again that the design flow is not exceeded.

Then the aggregation effect was studied using two patterns: (i) worst case pattern and (ii) aggregation pattern. Fig. 7b shows that when considering aggregation for small storage capacities, actual recycling (R_{act}) can be up to three times the value of R_{act} for the *wcs* pattern. Thus, we can conclude that the pattern influences R_{act}. Patterns with softened peaks (aggregation pattern) have larger values of $R_{act.}$ When there are restrictions due to *k*, or R_{pot}, (horizontal part of the curves in Fig. 7b), the pattern becomes irrelevant.

5.3.4 Multi-sourcing

Multi-sourcing refers to the use of local and renewable sources. In this chapter, we focus on harvesting rainwater to cater for D_{Q2}. In this study, harvesting of rainwater is done at building unit scale. M_{pot} [l y^{-1}] of a roof can be estimated based on the local precipitation – P [mm y^{-1}], the roof area – A^{roof} [m^2] and the runoff coefficient – *RC* [-], as $M_{pot}=P\cdot A^{roof}\cdot RC$. The runoff coefficient is a dimensionless value that estimates the portion of rainfall that becomes runoff, taking into account losses due to spillage, leakage, catchment surface wetting and evaporation. Typical runoff coefficient values range between 0.7 and 0.9 (Farreny *et al.* 2011).

Following UHA, multi-sourcing is used to supply the remaining demand. For the scenarios with minimization, recycling of LGW could fully supply D_{Q2}. Thus, to evaluate the potential of harvesting rainwater, only the conventional scenarios were studied. Rainwater collection can only be done at building unit level. For the apartment flat, the aggregated pattern was used. The harvesting potential of rainwater was evaluated for different yearly rainfall conditions, measured during the last 25 years. For the average year, the rainfall records of the year 2010 (811mm) were used; for a dry year, the year 1996 (573 mm) and for the wet year, the year 1998 (1050 mm) were used, respectively. In Fig. 8, three scenarios are plotted: i) only recycling, ii) only multi-sourcing, iii) recycling and multi-sourcing. For the scenarios including recycling, two storage units ($S_1^{S\&T}$ and $S_3^{S\&T}$) and a treatment unit ($S_2^{S\&T}$) are required. For $S_2^{S\&T}$, a treatment capacity of 40 l per person per day was assumed, i.e. treatment capacity k=160 l d^{-1} for the freestanding house and k=2240 l d^{-1} for the mid-rise apartment flat. For only multi-sourcing a single tank is considered ($S_3^{S\&T}$), thus $S_1^{S\&T}$=0.

Fig. 8 shows resources harvested (*Rh)* per scenario: recycling, multi-sourcing and both. A comparison between recycling and multi-sourcing shows that for the same storage capacity, recycling is more beneficial. If recycling and multi-sourcing are combined, the maximum value for *Rh* is achieved with a smaller storage capacity. The multi-sourcing scenario shows that the value of *Rh* is highly sensitive to yearly variations in precipitation. This sensitivity decreases when recycling and multi-sourcing are combined.

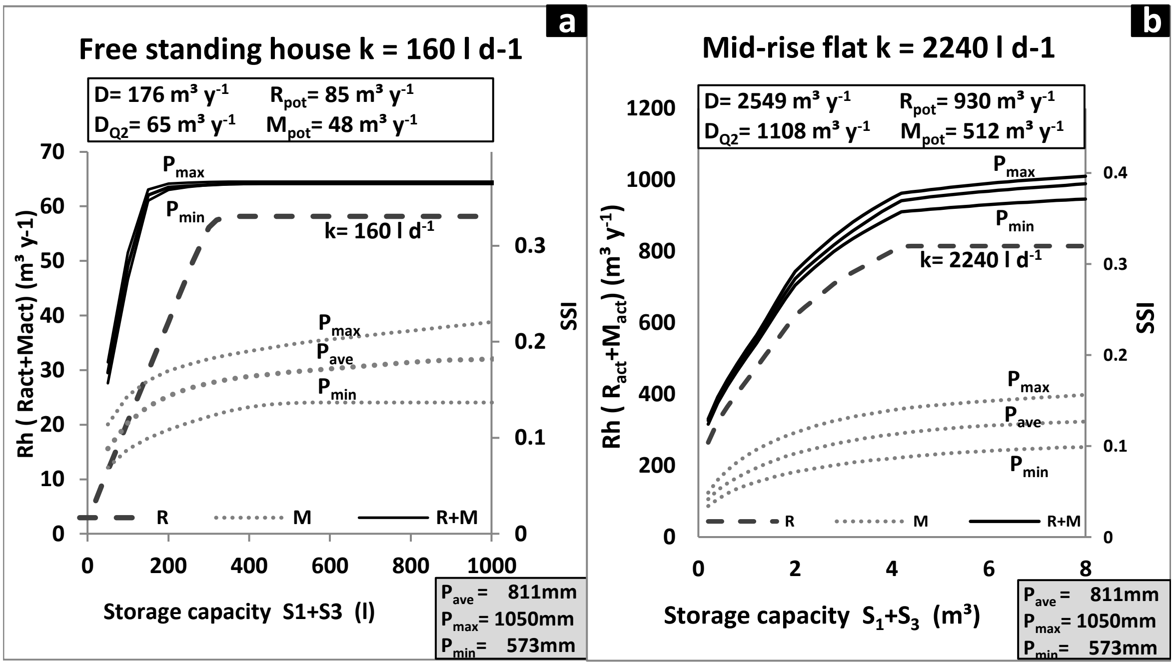


Figure 8 Comparison of recycling (R) and multi-sourcing (M) measures at building level for the conventional demand and sensitivity evaluation to changes in the rainfall pattern. k is given in l d^{-1} per building unit.

5.4 Discussion

The Urban Harvest Approach (UHA) presented here is a structured approach to identify the influence of different measures for reduction of demand and waste production, and for multi-sourcing at building unit scale. Furthermore, the proposed methodology to assess the metabolic profile (*Demand Minimization, Self-Sufficiency and Waste Output Indices*), provides key information on resource use.

This chapter aimed to test our hypothesis: urban areas as reservoirs of resources that can be harvested and used to supply urban demands and to develop improved understanding of process dynamics relevant for resources management at different scales. We have studied the urban water balance at building level and evaluated implementation of various measures: demand minimization, recycling of light grey water and harvesting of rainwater to supply non-potable demand.

We studied two household types in the Netherlands, i.e. two and four-people households. Although the yearly water demand per person is similar for both households, comparison of the temporal patterns showed that they do not satisfy the superposition principle, meaning that the water demand pattern of the four-people households is not two times the pattern of the two-people households. This shows that per capita water use is influenced by household size and that aggregated temporal patterns are non-linear. Non-linearity is, among others, caused by differences in (use frequency of) water appliances related to household size and family composition (adults/children).

Results showed, in both cases, that approximately 35% of the conventional demand may be reduced by implementing water saving devices (shower, toilet and laundry), indicating that demand minimization is a crucial measure towards a more efficient urban water cycle.

To minimize demand and waste flows, in this chapter non-potable demand (D_{Q2}) is supplied with local and renewable resources. Results showed that, even when resources are available to achieve local self-sufficiency on an average yearly basis, temporal supply-demand patterns and restrictions given by the spatial scale and building typology, may cause that only a percentage of the demand is supplied. Thus, temporal patterns of demand and supply should be studied carefully to determine storage requirements and to achieve maximum benefits.

Overall, our results show that there are two types of constraints to satisfy water demand with local resources at the building level. The first type is related to the availability of local resources. In this chapter, constraints to meet D_{Q2} are caused by disparity between grey water production patterns (R_{pot}) and demand patterns and to limited availability of rain water (M_{pot}) related to local context (i.e. climate, roof areas). The second type follows from the first and is caused by practical limitations in harvesting the recycling and multi-sourcing potentials – R_{pot} and M_{pot}. In this chapter, the harvest of R_{pot} and M_{pot} are constrained by the storage capacities that are required to cater for the mismatch in water harvested and demand patterns, which is linked to the availability of space in the building unit.

For cases with conventional demand, recycling of light grey water (R_{pot}) may cover approximately 36% of the demand (D), for both households. To reach this percentage, so that R_{act}=R_{pot}, different variables play a role. For a two-people household, a storage capacity of 240 l, and a volumetric treatment capacity of 100 l d^{-1} per hh is required. Meanwhile for the four-people household a storage capacity of 360 l and a treatment capacity of 200 l d^{-1} per hh is required. For the cases with minimized demand, R_{pot} may cover approximately 20% of the demand. In this situation, a storage capacity of 120 l is sufficient for both households, and treatment capacities of 20 and 40 l d^{-1} per hh for the two and four-people hh are required, respectively. When evaluating the effect of aggregation of patterns at flat level, for the 28 apartments, with a volumetric treatment capacity of l00 l d^{-1} per hh, a storage capacity of 5.4m³ is required, this means 200 l per household. Thus, aggregation of patterns leads to a reduction of 17% in the required storage capacity.

For both type of households, when demand minimization is implemented, recycling of light grey water covers D_{Q2}, and approximately 20% of D, even resulting in a surplus of treated water. This surplus of water can be used for ex-house activities, which are not considered in this chapter.

Multi-sourcing was investigated at building level, while assuming conventional water demand. The results showed that M_{act} is largely influenced by the available storage capacity. For the freestanding house, although M_{pot} may cover up to 27% of the demand (D), a storage capacity of 1 m³ limits M_{act} to 14 - 22%. For the apartment flat, M_{pot} may cover up to 20%, however, a storage capacity of 8 m³, (300 l hh^{-1}), limits M_{act} to 10% -16%. Combining grey water recycling and multi-sourcing provides a more reliable solution. For the freestanding house, a storage capacity of 200 l can supply 37% of the demand (D), while for the apartment flat, 1 m³ can supply 38% of the demand (D).

Results of the modeling study showed that dimensioning of the storage capacity requires to consider treatment requirements, daily water supply-demand patterns and the presence of saving devices, in addition to the physical space available.

Against our hypothesis: "urban areas as reservoirs of resources that can be harvested and used to supply urban demands", we can conclude that urban water demand can indeed largely be satisfied by a combination of demand reduction, output minimization and multi-sourcing. The study shows that building type and household size influence the pattern and the efficiency of the different measures. The results show that although implementation of single measures is not enough, demand minimization is the significant step to achieve local self-sufficiency cycle in residential areas.

This study selected two building types and household sizes. Other urban typologies may give different results, due to differences in water demand patterns and local potential for recycling and multi-sourcing. Implementation of water saving technologies may have rebound effects that are not considered within the scope of this study.

Our results confirm that grey water recycling is feasible and can contribute to sustainable water management (Pidou *et al.*, 2007). Treated urban wastewater provides a dependable water supply relatively unaffected by periods of drought or low rainfall (EEA, 2009). The characteristics and treatments of grey water have been extensively studied by Li *et al.* (2009) and Pidou *et al.* (2007). They recommend as first step pre-treatment, followed by treatment which can be chemical or biological, after that filtration with sand or membranes and finally disinfection. Possibly cheap, robust and low-energy demanding microbial quality enhancement technologies, currently under development, may also provide solutions for grey water reuse e.g. using fluidized bed electrodes (Racyte *et. al*, 2011). In this study, we assumed that multi-sourcing provides water of secondary quality. Current research is, however, exploring decentralized options to produce drinking water, e.g. producing drinking water from hydrogen fuel cells (Hristovski *et al.* 2009). Further studies should describe a yet completer urban water cycle including, for instance, evapotranspiration, infiltration and other building types such as duplex, or row houses. Different scales may have different potentials but at the same time different tradeoffs.

5.5 Conclusions

The Urban Harvest Approach considers urban areas as reservoirs of resources that can be harvested and used to satisfy urban demands. As shown in this paper, up to 100% of current demand for laundry and toilet water could easily be supplied by local resources. Urban characteristics, i.e. household occupancy and building type, influence the demand and production of water of secondary quality. This study showed that different building types, associated with different occupancies, showed different demands and different temporal patterns. This is essential information to design and optimize recycling and multi-sourcing measures. Demand minimization is the most effective measure to start reducing the dependence of urban environments for external, high quality water resources. Variations in daily production and demand patterns of individual flows showed large effects on the efficiency of the resources harvested. Additionally, spatial scale is really important; different scales might provide a complete different overview of the use of water resources. Therefore, different scales should be evaluated simultaneously when optimizing urban water flows. Further research is needed to properly understand the complexity of the urban water balance and to control the system in real-time. In aiming for sustainable development, it is evident that new approaches in urban resources management, such as the Urban Harvest Approach, novel city design and planning methods, need to be integrated to provide customized solutions for existing and new urban areas.

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Appendix A

To evaluate the different scenarios, 4 different categories were defined:
++ very good, + good, – bad, – – very bad. The categories for grey water are described in table A1. And the categories to evaluate rainwater are described in table A2.

Table A1 Categories for evaluating grey water flows

Parameter	**Grey water Assessment**			
	++	**+**	**–**	**– –**
Original Quality	Slightly polluted: Light grey water from shower	From slightly: polluted to polluted Grey water from shower and laundry	Polluted: Grey water from shower, laundry and bathroom taps	Heavily polluted: Total grey water: shower, laundry, bathroom and kitchen taps
Quantity	15%> of the total demand	15%<, >10% of the total demand	10%<, >5% of the total demand	5%< of the total demand
Temporal	6 or 7 days a week	5 or 4 days a week	2 or 3 times a week	Less than once a week

Table A2 Categories for evaluation of rainwater

	Rainwater assessment			
	++	**+**	**–**	**– –**
Original Quality [a]	Slightly polluted	From slightly polluted to polluted	Polluted	Heavily polluted
Quantity [b]	1000 >	1000 - 750	750 - 250	250 <
Temporal	Evenly distributed over the year	Dry winter / dry summer	Dry period longer than 3 months	Dry period longer than 6 months

[a] Function of the roof material.
[b] Yearly rainfall in mm/y

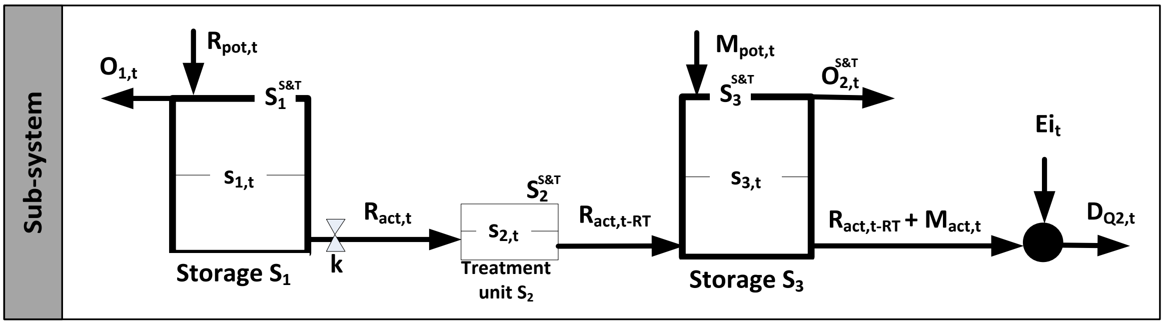
For the Netherlands, the assessment is presented in table A3.

Table A3 Evaluation of potential for reuse of the different flows for The Netherlands

	Grey water				**Rainwater**
	Bathroom	**Laundry**	**Kitchen**	**Mixed**	
Quality	+ +	+	+	- -	+ +
Quantity	+ +	+	- -	+ +	+
Temporal	+ +	-	+ +	+ +	+ +

Appendix B

Description of the subsystem model.



Storage 1

$$R_{act} = k$$
$$s_{1,t} = s_{1,t-1} + R_{pot,t} - R_{act,t}, O_{1,t}^{S\&T} = 0$$
$$if \;\; s_{1,t} > S_1^{S\&T} \Rightarrow O_{1,t}^{S\&T} = s_{1,t} - S_1 \Rightarrow s_{1,t} = S_1^{S\&T}$$
$$if \;\; s_{1,t} < 0 \Rightarrow R_{act,t} = s_{1,t-1} + R_{pot,t}, s_{1,t} = 0$$

Treatment Unit

$$for \; t \le RT$$
$$R_{act,t-RT} = 0$$
$$s_{2,t} = s_{2,t-1} + R_{act,t} - R_{act,t-RT}$$

Storage 3

$$s_{3,t} = s_{3,t-1} + R_{act,t-RT} + M_{pot,t} - D_{Q2,t}, O_{2,t}^{S\&T} = 0$$
$$if \;\; s_{3,t} > S_3^{S\&T} \Rightarrow O_{2,t}^{S\&T} = s_{3,t} - S_3^{S\&T} \Rightarrow s_{3,t} = S_3^{S\&T}$$
$$if \;\; s_{3,t} < 0 \Rightarrow R_{act,t-RT} + M_{act,t} = s_{3,t-1} + M_{pot,t} + R_{act,t-RT}$$
$$\Rightarrow s_{3,t} = 0; Ei_t = D_{Q2,t} - R_{act,t-RT} - M_{act,t}$$

Chapter 6

Evaluating the potential of improving the residential water balance at block scale

Abstract

Decentralized systems play a central role in the new paradigm towards sustainable urban water management. Planning decentralized systems requires understanding of the influence of the urban characteristics such as building type and land cover, on the urban water cycle. Previous chapters investigated the implementation of strategies at building unit, concluding that the water resource efficiency is larger for multiple households than for single households. This chapter studies the potential of improving urban water cycles at city block scale. Two different city blocks were analyzed; a low-density city block composed of freestanding houses and a high-density block composed of middle-rise apartment flats. Seasonal dynamic water balances were investigated for different scenarios, considering occupancy, conventional and saving water appliances, as well as percentages of permeable and impermeable surfaces as modeling parameters. Results showed significant variations in the water cycle due to seasonal variations and block type. Import of drinking water represents up to 40% of the total input in the low-density block, and up to 80% of the total input, in the high-density block. For the low-density block, 18% input minimization and self-sufficiency was achieved. And the waste output index WOI (waste/demand) was reduced from 97% to 73%. For the high-density block, 23% input minimization, 18% self-sufficiency, and WOI reduction from 123% to 104% was achieved. Three main options are identified to improve the water cycle at block scale: (i) technology implementation, e.g., water saving devices or decentralized wastewater treatment technologies; (ii) modifications in the building unit envelope, e.g., green roofs; and (iii) changes in the urban surfaces to increase storage capacity by selecting permeable materials.

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6 Harvesting urban resources towards more resilient cities

6.1 *Introduction*

Over the last decade a new paradigm for a sustainable urban water management has emerged as response to pressures such as population growth, increasing urbanization and climate change. In this new paradigm, decentralized systems play a central role (Guest et al., 2009, Rygaard et al., 2011). In this study, decentralization refers to on-site technologies at building, city block or neighborhood scale. Compared with centralized technologies for managing urban water, at city or regional levels; decentralized water infrastructure is relatively untried and unproven (Makropoulos and Butler, 2010). Decentralized systems, however, have proved to be sustainable options from the point of view of resources use, enabling recovery of nutrients and energy, and limiting the spread of pollutants (de Graaff, 2010; Kujawa-Roeleveld and Zeeman, 2006). Currently, despite the availability of a large range of centralized and decentralized technologies, we still lack tools to select the optimal scale of management and the most appropriate technology for a given urban context with specific building typology, land cover, water use patterns and climatological conditions.

Improving urban residential water cycles requires information about the varying use and availability of water. Water demand and water supply are often closely monitored. Conversely reliable data on water outflows are less available and highly variable, because evapotranspiration, runoff, groundwater recharge and leakage are not well known in most cities (Pataki et al., 2011). Moreover, little attention has been given to the way in which urban water demand varies across urban areas and how this may be used to shape a new approach to the planning, infrastructural design and management of water in an urban environment (Troy and Holloway, 2004). These variations in urban water demand are typically related to urban characteristics as, e.g. building type, presence of gardens or green areas and impermeable surfaces. These variations become highly relevant when planning and designing at small spatial scale, for instance at city block scale.

The Urban Harvest Approach (UHA) is a bottom-up approach, starting from the building unit to city scale. The UHA encompasses a hierarchy of measures to optimize urban resources management. The hierarchy of measures proposed is: i) minimizing demand; ii) minimizing output; and iii) multi-sourcing using local and renewable resources. Previous chapters investigated the implementation of strategies at building unit, concluding that efficiency is larger for building units with multiple households than for building units with a single household. This chapter studies the potential of improving urban water cycles at city block scale[14] by taking into account household and building typology and by including spatial and temporal climatological factors, such as evapotranspiration and precipitation.

[14] A city block is the smallest area that is surrounded by streets. Blocks are the space for buildings within the street pattern of a city; they form the basic unit of a city's urban fabric. Blocks may be subdivided into any number of smaller lots or parcels of land usually in private ownership, though in some cases, it may be other forms of tenure.

In this chapter, two different city blocks were analyzed; a low-density city block composed of freestanding houses and a high-density block composed of middle-rise apartment flats. Seasonal dynamic water balances were investigated based on hourly time steps for different scenarios. The different scenarios to improve the residential water cycle at city block scale were studied quantitatively, following the hierarchy of measures proposed within the UHA. The scenarios consider occupancy, conventional and saving water appliances, as well as percentages of permeable and impermeable surfaces. Due to the high complexity of the urban environment and the urban water cycle, it is not realistic to quantify each individual point source or sub-area of recharge. Thus, this chapter addresses estimates and provides a methodology for a preliminary assessment of the water balance and potential improvements at city block scale.

6.2 *The urban water cycle at city block scale*

In urban areas, the water exchanges are much more complex than in natural areas, due to the large heterogeneities of surfaces and the introduction of new water collection and conveyance systems. Some of the processes, such as urban surface runoff, water infiltration through the roads, water storage on artificial surfaces and groundwater infiltration into the sewer network are difficult to quantify (Lemonsu et al., 2007). Thus these processes are also difficult to optimize because of their complex interrelationships and their dynamic behavior.

Often the urban water balance is described by two different approaches. The first approach, with a focus on the nature-driven processes, describes the urban water cycle in terms of precipitation-evapotranspiration-runoff and infiltration. The second approach, with a focus on the man-made water infrastructure, includes the input of water provided by the drinking water system and the output via the domestic wastewater stream, but generally it does not include recycling and harvesting options.

To bridge the gap between the natural and man-made approach, some linkages to urban typology can be made based on the urban transect concept (Duany and Talen, 2002). For instance, areas with high percentage of impermeable areas are often located close to the city center and related to high densities and high rise buildings. Meanwhile low percentage of impermeable areas are often located in the sub-urban area and related to low densities and single family houses. In general, high-impermeable urban areas are associated with larger runoff, higher population density, higher buildings; and lower infiltration, lower evapotranspiration and smaller household size than low-impermeable urban areas. This chapter includes the interactions between the natural- and man-driven processes, as well as wastewater recycling and rainwater harvesting options. Fig. 1 shows the variables that affect the water cycle at city block scale, including the UHA strategies, and their relationships. Additionally the linkages between the building unit and the block scale are indicated. The urban water cycle model used in this study is shown in Fig. 2. A general volume balance for a dynamic system with actual amount of water stored (*s*) reads as:

ds/dt = Inputs – Outputs - Consumption *(1)*

In the next sections, each of these terms will be specified in more detail.

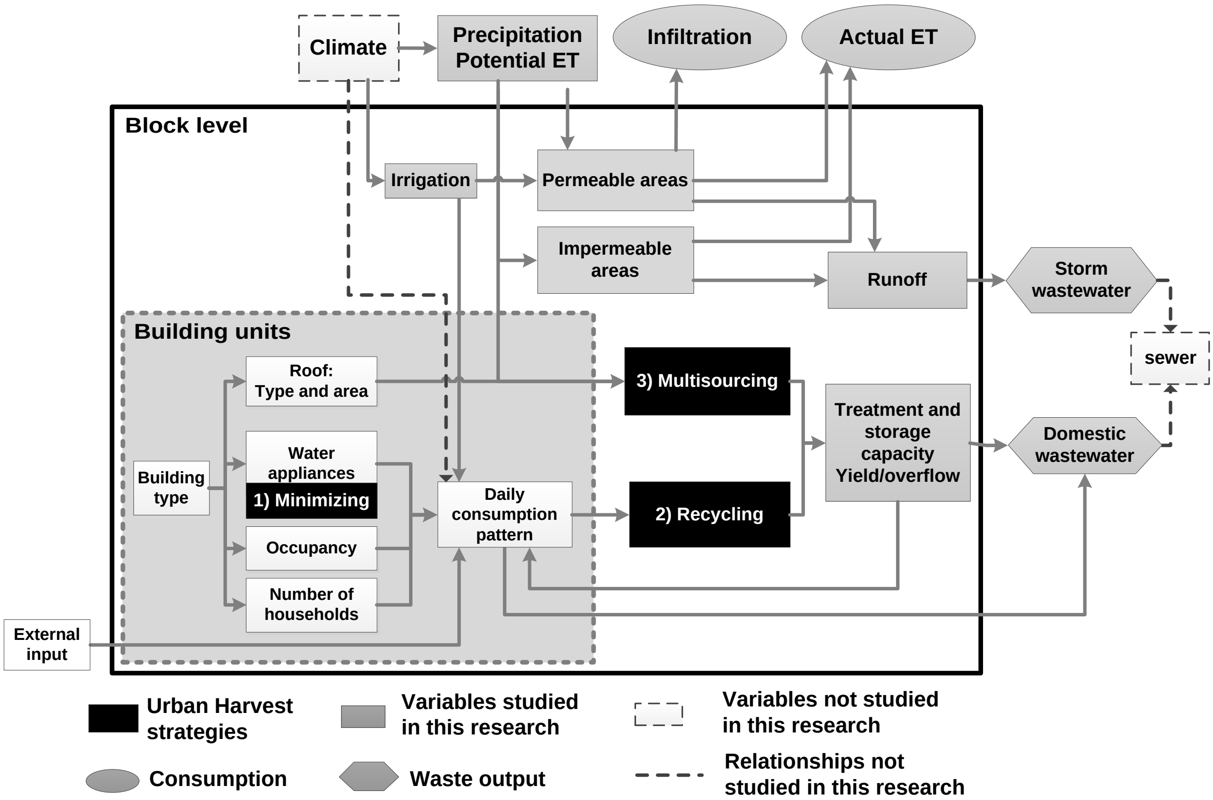


Figure 1 Schematic representation of the relationship between the different variables of the water cycle at block scale.

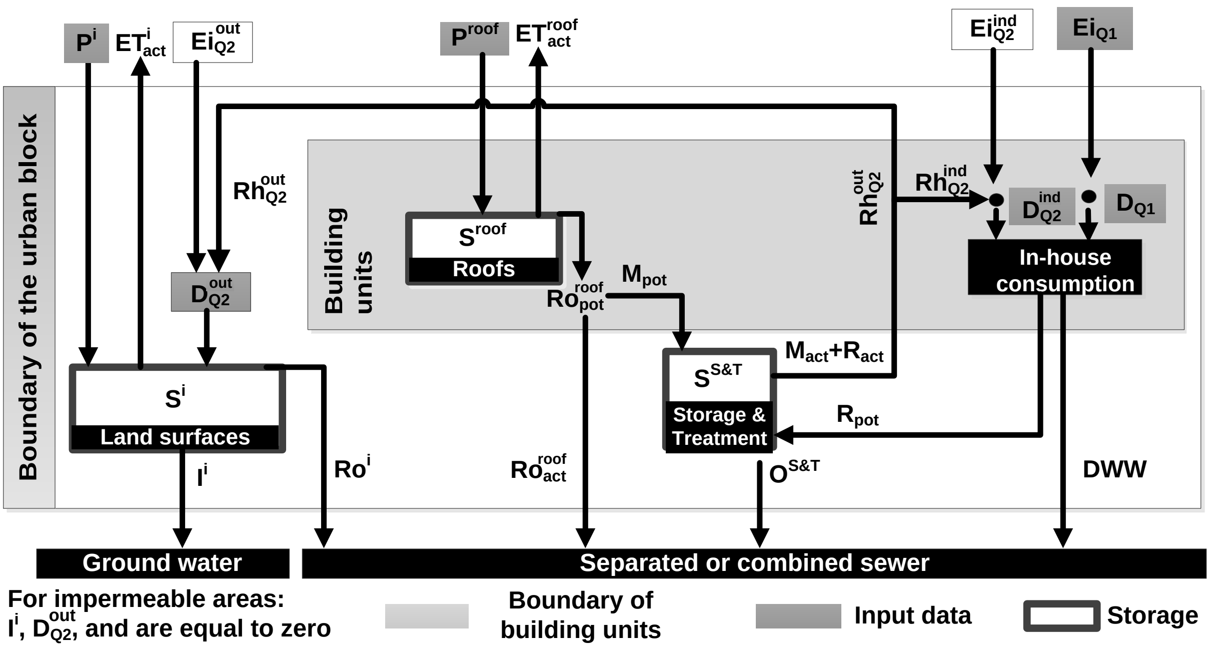


Figure 2 Schematic representation of the urban water cycle at block scale.

6.2.1 Storage

The term *ds/dt* in Eq. (1) is the change in storage per unit of time, in our case the water volume. We distinguish between three different types of storage at city block scale: surface depression storage, roof storage and storage in tanks/treatment units, see Fig. 2. Surface depression storage is the water that is retained in small depressions on the surfaces, preventing the water from running off. This water will eventually infiltrate or evaporate. Roof storage is the water that is retained at roof surfaces. Roofs capture the precipitation and redirect it to the sewer or to a collection tank allowing multi-sourcing (using precipitation water in addition to tap water). Appendix A shows the values for storage capacities of different surfaces reported in the literature. Tanks and treatment units are man-made infrastructures to collect and treat water. Thus in Eq. (1), *s* is the sum of volumes of water stored on the different surfaces, on the roofs and in the tanks and treatment units. Water stored in the sewer system and in the ground are considered outside the system boundary, and not managed at block scale, see Fig. 2.

6.2.2 Inputs and outputs

There are two main inputs of water in conventional urban systems at block scale: precipitation (*P*) and external input (*Ei*) – provided by the drinking water network. There are two main waste outputs (*We*) directly related to the inputs; runoff (*Ro,* excess rainwater leaving the area), and domestic wastewater (*DWW*). These two outputs are collected in combined or separated sewers. There are two main alternative inputs at block scale, namely, recycled wastewater (R_{pot}) and harvested rain water (M_{pot}) from roofs. Runoff from the land surfaces is not harvested for further (re-)use due to quality requirements. Runoff is often described using the runoff coefficient (*RC*). *RC* is defined as the proportion of rainfall that contributes to runoff from the surface, *RC=Ro/P* (Butler and Davies, 2000). The appendix A shows typical values for *RC*.

In urban areas, we consider two types of demand: potable (D_{Q1}) and non-potable (D_{Q2}). D_{Q1} represents the daily demand of potable water. Potable water is required for kitchen and bathroom taps and for shower and bath. Meanwhile D_{Q2} represents the demand for non-potable activities. D_{Q2} is divided into indoor (D_{Q2}^{ind}), e.g. toilet and laundry; and outdoor (D_{Q2}^{out}), e.g. garden irrigation. Thus, using R_{pot} and M_{pot} to supply D_{Q2} will lead to a reduction in *Ei* and in the domestic waste water (*DWW*).

In this chapter, we focus on water resource management in build infrastructure. Therefore, we only consider harvesting of rain water from roofs, and non-harvested water is discharged to the sewer. The potential harvest from roofs (M_{pot}) is given by $M_{pot} = Ro_{pot}^{roof} - Ro_{act}^{roof}$ with $M_{pot} \leq Ro_{pot}^{roof}$; and if M_{pot} = 0 (no harvesting), then $Ro_{act}^{roof} = Ro_{pot}^{roof}$.

6.2.3 Consumption

Consumption (*Co*) in Eq. (1) is defined as the sum of processes that lead to water leaving the block system becoming unavailable to be harvested to supply D_{Q1} or D_{Q2}. At block scale, two processes are considered; i) evaporation and evapotranspiration (*ET*), which has also a cooling effect in urban areas and ii) infiltration (*I*) which recharges subsurface groundwater resources, hence, $Co = ET + I$.

Evaporation is the process occurring along the water-air or soil-air interface by which water transforms into water vapor escaping into the atmosphere. And transpiration is the process of vaporization of water at the surface of plant leaves after the soil water has been transported through the plant. For simplification, transpiration is combined with evaporation from water and soil surfaces into evapotranspiration (Marsalek et al., 2008). In this paper, *ET* refers to evaporation from permeable and impermeable surfaces and evapotranspiration from green areas. We use the Penman-Monteith method (FAO, 1988) to calculate the reference evapotranspiration. And we assumed the reference evapotranspiration as potential evapotranspiration (ET_{pot}). The actual evapotranspiration (ET_{act}) is determined by the water availability on each of the surfaces and roofs. The stored water on the surface "*i*" is given by s^i. Then, if $s^i \geq ET^i_{pot}$: $ET^i_{act} = ET^i_{pot}$; and if $s^i < ET^i_{pot}$: $ET^i_{act} = s^i$.

Infiltration (*I*) refers to the process of water passing through the ground surface into the pores of the soil, and entering the groundwater system. *I* depends on soil type, structure and compaction, initial moisture content, surface cover and the depth of the water layer in the soil (Butler and Davies, 2000). The infiltration rate tends to be high initially, but decreases exponentially to a final quasi-steady rate when the upper soil zone becomes saturated. Some standard values used to estimate infiltration are presented in Appendix A. In this study, infiltration is assumed to be constant over the hourly time step. Infiltration at a given time step is a function of the stored water in the permeable surfaces, which infiltrates at the maximum rate of the soil infiltration capacity ($I \leq k_{soil}$), both given in mm/h.

The water balance at block scale can be derived from the balances of each of the storage units and can be written as:

$$\frac{dS}{dt} = [P^{roof} + \Sigma P^i + Ei^{out}_{Q2} + Rh^{out}_{Q2} + Ei_{Q1} + Ei^{ind}_{Q2}] - [\Sigma Ro^i + Ro^{roof}_{pot} + ET^{roof}_{act} + \Sigma ET^i_{act} + \Sigma I^i + DWW] \quad (2)$$

Appendix B shows the balances for each unit and the deduction of equation 2.

6.2.4 Urban water cycle and the urban harvest approach

As already mentioned in the Introduction, the Urban Harvest Approach (UHA) consists of three steps: (i) input minimization by implementation of more resource efficient technology; (ii) output minimization by cascading and recycling of flows[15]; and (iii) multi-sourcing of the remaining demand by harvesting local-renewable resources.

The UHA focuses on sustainable water management by technology implementation and does not consider any changes in human behavior. Fig. 2 shows that D_{Q1} is supplied by Ei_{Q1}, thus $Ei_{Q1}= D_{Q1}$. Then, Ei_{Q1} can only be minimized by installation of water saving technologies, the first step of the UHA. Besides D_{Q2} is equal to $D_{Q2}^{ind} + D_{Q2}^{out}$ and it is supplied by Ei_{Q2}^{ind}, Ei_{Q2}^{out}, R_{act} and M_{act}, thus, $D_{Q2} = Ei_{Q2}^{ind} + Ei_{Q2}^{out} + R_{act} + M_{act}$. Hence, Ei_{Q2} can be expressed as:

$$Ei_{Q2} = Ei_{Q2}^{ind} + Ei_{Q2}^{out} = D_{Q2} - R_{act} - M_{act} \quad (3)$$

And since $D= D_{Q1}+ D_{Q2}$, we arrive at

$$D = Ei_{Q1} + Ei_{Q2} + R_{act} + M_{act} \quad (4)$$

One of the objectives of the UHA is to minimize Ei_{Q2}. Eq. (3) shows that Ei_{Q2} can be minimized by implementing water saving technologies (minimizing D_{Q2}), by recycling (maximizing R_{act}) and by multi-sourcing (maximizing M_{act}), the three steps of the UHA. Export of resources is set to zero, to avoid flows passing through without being used in the system and being exported as secondary resources. Thus, the optimal case is when $Ei_{Q2} = 0$, so that $R_{act}+M_{act}=D_{Q2}$.

Additionally within the UHA, waste export should be minimized. The waste exported (*We*) of the system can be written as:

$$We = \Sigma Ro^{i} + Ro_{act}^{roof} + DWW + O^{S\&T} \quad (5)$$

From the balance at building unit, $DWW = D_{Q1} + D_{Q2}^{ind} - R_{pot}$. Consequently,

$$We = \Sigma Ro^{i} + Ro_{act}^{roof} + D_{Q1} + D_{Q2}^{ind} - R_{pot} + O^{S\&T} \quad (6)$$

Hence, to minimize *We*, three options are identified: i) minimizing indoor demand ($D_{Q1} + D_{Q2}^{ind}$) by implementing water saving devices, ii) minimizing runoffs ($Ro_{act}^{roof} + Ro^{i}$) by replacing impermeable by permeable areas, which will result in larger infiltration and evapotranspiration values, and iii) minimizing overflow from the treatment facility resulting in $R_{act} + M_{act} = R_{pot} + M_{pot}$, by a proper choice of the storage capacity. As the demand and the meteorological inputs are time-varying, a proper choice can only be made by dynamic modeling of the system.

[15] Cascading refers to direct reuse of waste flows, meanwhile recycling includes quality upgrading of the flow before reuse. In this paper, to secure quality standards, we will only consider recycling.

To relate the different variables of the water cycle and to evaluate the different measures, the so-called "metabolic profile" is calculated. The metabolic profile is described in terms of the demand ($D=D_{Q1}+D_{Q2}$), the waste exported (*We*) and the resources harvested (*Rh*). The metabolic profile is defined by three indices, i.e. Demand Minimization Index (*DMI*), Waste Output Index (*WOI*) and Self- Sufficiency Index (*SSI*), as defined in Chapter 4. The DMI is defined as,

$$DMI = \frac{Conventional\ demand\ (D_{con}) - Demand\ (D)}{Conventional\ demand\ (D_{con})} = \frac{\sum_{t=1}^{n} D_{con}(t) - D(t)}{\sum_{t=1}^{n} D_{con}(t)} \quad (7)$$

Where D_{con} represents the demand when conventional technologies are implemented, while *D* is the actual demand. Furthermore,

$$WOI = -\frac{Waste\ exported\ (We)}{Demand\ (D)}$$
$$=_{[eq\ 6]} -\frac{\sum_{t=1}^{n}[\Sigma Ro^{i}(t) + Ro_{act}^{roof}(t) + D_{Q1}(t) + D_{Q2}^{ind}(t) - R_{pot}(t) + O^{S\&T}(t)]}{\sum_{t=1}^{n} D(t)} \quad (8)$$

In this chapter, we do not consider export of resources, therefore (Er=0: REI=0) and

$$SSI = \frac{Resource\ harvested\ (Rh)}{Demand\ (D)} = \frac{\sum_{t=1}^{n}[R_{act}(t) + M_{act}(t)]}{\sum_{t=1}^{n} D(t)} \quad (9)$$

In this study, two block types relevant for the Netherlands were defined to evaluate the potential of improving the residential water cycle at that scale. Following the UHA, first, we prepared a baseline assessment for selected blocks. The indoor water demand of each of the blocks was simulated using the software SIMDEUM[16] (Blokker et al., 2010). Data from the meteorological station in Wageningen[17], the Netherlands, were used to determine precipitation and reference evapotranspiration using the Penman-Monteith equation (FAO, 1988). Seasonal dynamic water balances were evaluated to gain insight into the temporal variations within the year. For the baseline of the conventional system, recycling and multi-sourcing were set to zero. The sensitivity of the seasonal water balance to two extreme values of two critical parameters was evaluated: the soil infiltration capacity, k_{soil} = 0.1 and 5 mm/h, and the storage capacity of green areas, S^{green} = 10 and 100 mm. Four cases were defined by combining these boundaries. Seasonal variations on the water balance were studied; with and without irrigation. When there is no irrigation of green areas $D_{Q2}^{out} = 0$ and $D = D^{ind} = Ei = DWW$, meanwhile for the cases with irrigation $D_{Q2}^{out} > 0$, $D = Ei = D^{ind} + D_{Q2}^{out}$ and $DWW = D^{ind}$. Irrigation was set to occur after each 156 hours of dry weather, with an amount filling 80% of the storage capacity.

[16] SIMDEUM is a software developed by the water cycle institute (KWR), it simulates daily patterns for different household types in The Netherlands.
[17] http://www.met.wau.nl/haarwegdata/

Secondly, the variation of the water cycle in the green areas was studied for different values of k_{soil} and S^{green}. Seasonal variations for the green areas of a low-density block were compared for irrigated and non-irrigated conditions. Thirdly, the strategies proposed by the UHA, namely demand minimization, output minimization and multi-sourcing, were investigated for selected values of k_{soil} and S^{green} for the two blocks. Four scenarios combining the UHA strategies were studied and the metabolic profiles calculated. Here, changes in slope are not considered due to the small scale and the case study selected in the Netherlands, representing a flat Delta area.

Two different city blocks in The Netherlands were analyzed; a low-density city block composed of freestanding houses and a high-density block composed of middle-rise apartment flats. Seasonal water balances were investigated based on hourly time steps for different scenarios following the hierarchy of measures proposed by the UHA. For the low-density block, 20% impervious and 80% pervious area was assumed. And for the high-density block, 80% impervious and 20% pervious area was assumed. Impervious percentage refers to roof areas, meanwhile pervious percentage was assumed as green areas. Table 1 shows the characteristics of the two block types.

Table 1 General characteristics of the two selected blocks

	Low-density block	High-density block
Total block area (m²)	2500	2500
House typology	Free standing house	Mid-rise apartment flat
Roof area per building unit (m²)	63	670
Number of building units per block	8	3
Number of households per building unit	1[a]	28[b]
Total block population	32	168
Density (p/ha) [dwelling/ha]	128 [8]	672 [336]
Daily water demand indoor per capita (l)	111	105
Impervious percentage [c]	20%	80%
Pervious percentage [c]	80%	20%

[a] Household with two adults and two children.
[b] Household with two adults full time working.
[c] In this chapter impervious area refers to roof area and pervious areas refers to green areas.

6.3 *Results and Discussion*

6.3.1 Sensitivity analysis

First a sensitivity analysis was performed considering a conventional situation for the two blocks. For that, the indoor water demand of each of the blocks was modeled for a period of three months with hourly time steps using the software SIMDEUM (Blokker et al., 2010), see Fig. 3. In the Netherlands seasonal changes in indoor water demand can be neglected (Foekema and van Thiel, 2011). Thus, the same indoor water demand pattern was used for the different seasons.

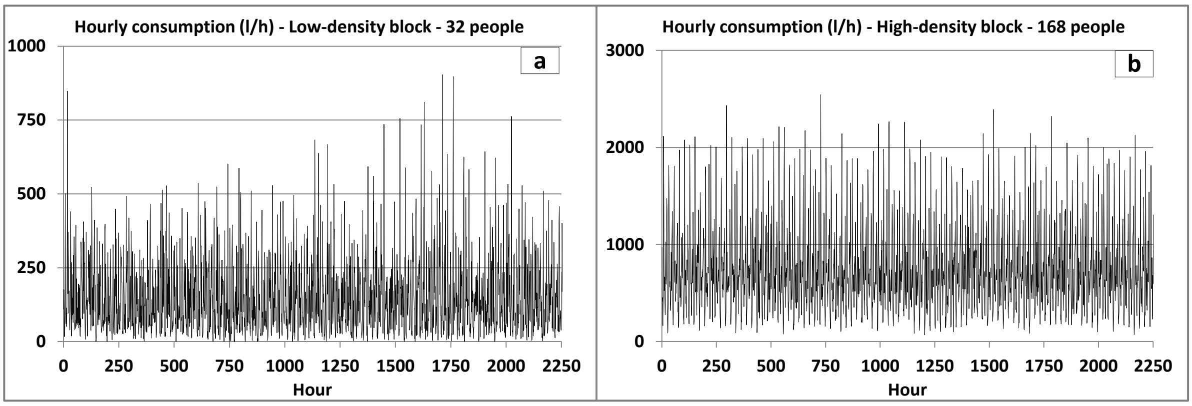
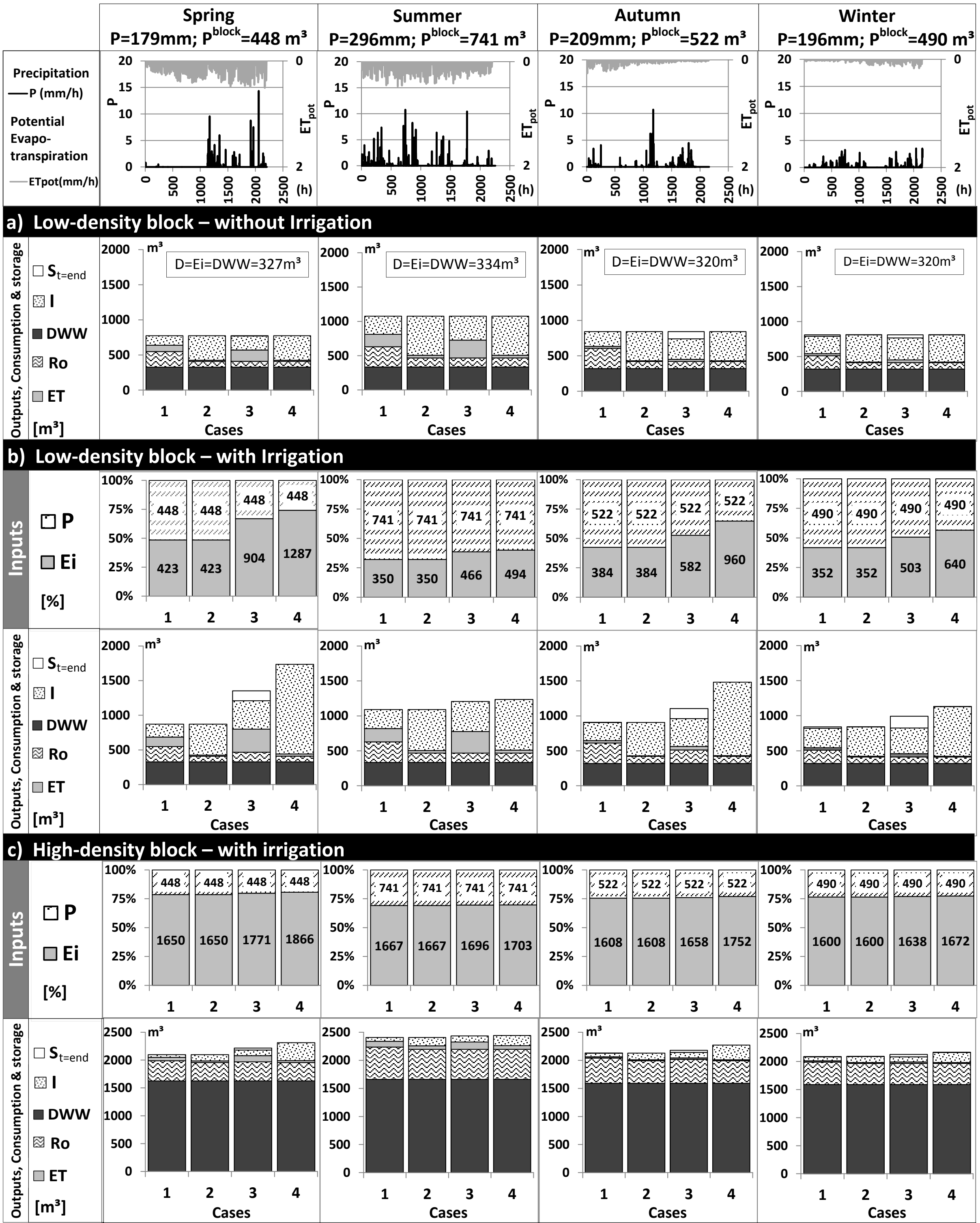


Figure 3 Hourly demand pattern for a season for the two blocks. a. Low-density and b. High-density block

An average year was selected, from March 2007 till March 2008, to evaluate the influence of the seasonal variations of the climate related parameters. Firstly, the sensitivity of the seasonal water balance to changes in k_{soil} and S^{green} was evaluated. Four cases were defined by combining two extreme values of the soil infiltration capacity, k_{soil} = 0.1 and 5 mm/h, and the storage capacity of green areas, S^{green} = 10 and 100 mm. Fig. 4 shows the seasonal balances for the low-density block for non-irrigated and irrigated conditions and for the high density block for irrigated conditions.

For the low-density block without irrigation, ($D_{Q2}^{out} = 0$; D=Ei=DWW), the external input Ei represents 31-42% of the total inputs (not shown here). Fig. 4a shows, as expected, that infiltration I and evapotranspiration ET are mainly influenced by k_{soil} and by seasonal changes in precipitation P and ET_{pot}, meanwhile the influence of S^{green} is lower. Runoff (Ro) changes seasonally, with runoff coefficient RC relatively constant, approximately 18% of the precipitated water for cases two to four during the whole year. For case one, RC varies seasonally from 39 to 55%. For the cases with irrigation, Fig. 4b, Ei can vary seasonally from 32 to 75% of the inputs. The maximum value for irrigation is during spring, with $D_{Q2}^{out} = 960m^3$ for case 4. Irrigation combined with large S^{green} enhances ET_{act}, mainly during spring and summer. As expected, I increases with increments in the amount of water irrigated.

For the high-density block without irrigation, there are no significant variations among the cases, mainly because green areas are a small percentage of the total area. Hence, this case is not presented in Fig. 4. Runoff coefficient RC is approximately 80% for all the scenarios and for the different seasons. For the cases with irrigation, Fig. 4c, the maximum value for irrigation is during spring, $D_{Q2}^{out} = 240\ m^3$, which is approximately 10% of the total inputs. Due to the high population density and related production of domestic waste water (DWW), external input Ei (Ei= DWW) represents between 68 and 80% of the total inputs. For the high-density block, infiltration I and the actual evapotranspiration ET_{act}, represent a small percentage of the water balance. For the studied cases the maximum consumption, $I + ET_{act}$, was 15% of the total water budget.



Cases		1	2	3	4
Soil infiltration capacity	k_{soil} (mm/h)	0.1	5	0.1	5
Storage capacity green areas	S^{green} (mm)	10	10	100	100

Figure 4 Seasonal balances for the two blocks to evaluate the sensitivity of the variables. k_{soil} = 0.1 and 5 mm/h; and storage capacity of green areas, S^{green} = 10 and 100 mm

It is important to know the soil infiltration capacity k_{soil} and the green surface area S^{green} when evaluating the water balance of a block, especially those with a large percentage of green areas. A series of dynamic simulations were performed to understand the relationship between ET_{act}, I, and S^{green} and irrigation in the green areas for the low-density block. Fig. 5 shows the results for spring and winter for non-irrigated and irrigated low-density green areas, Appendix C shows the yearly overview. Below we discuss the effects on the water balance in terms of Infiltration, Evapotranspiration, and Surface runoff.

Infiltration

I is determined by k_{soil} and the remaining water stored after evapotranspiration. Fig. 5 shows that for the cases with no irrigation ($D_{Q2}^{out} = 0$), precipitation will mainly determine the infiltration values, changing seasonally from 350 in spring to 570 m³ in summer. If there is irrigation, more water will be available and I increases up to 1292 m³ in spring. From Fig. 5 it can be concluded that I is proportional to S^{green} and to the number of irrigation events during the season.

Evapotranspiration.

Potential evapotranspiration ET_{pot} is on average 0.08 mm per hour in spring and summer and 0.01 mm per hour in autumn and winter. Actual evapotranspiration ET_{act} depends on the available water stored in the upper layer of the subsurface. Water stored in green areas, infiltrates or evaporates. Thus, if $k_{soil} >> ET_{pot}$, the sensitivity to S^{green} is lower. Fig. 5 also shows a strongly decreasing change of I and ET_{act} when k_{soil} is approaching low values close to zero. This reduction of I and ET_{act} is compensated by an increment of Ro.

Runoff

The results show that Ro^{green} can be generally regarded as zero for green areas. Only at very low values of k_{soil} and/or limited storage capacity smaller than a few mm (soil layers of less than a few cm thickness on top of low permeable subsurface matrices), runoff becomes significant, for the climatic conditions modeled. It is important, however, to recall that we neglected soil saturation, since we assumed a constant soil hydraulic conductivity given by (k_{soil}). For heavy precipitation events as under tropical conditions, after a certain value, the soil saturates and the subsequent precipitation will become runoff. Hence, for a more detailed design under heavy rainfall conditions, it is needed to combine continue–yearly–balances models with event-based models to evaluate the actual runoff.

6.3.2 Baseline and demand minimization

Effect of block density on baseline water dynamics

To further study the water balance of the two blocks, we assumed that S^{roof}= 0.25 mm, S^{green} = 25 mm, k_{soil} = 0.5 mm/h and that irrigation starts after 156 dry hours, filling 80% of S^{green}. Fig. 6a and 6b shows the comparison of the water balance for the low- and high-density block for the conventional demand. For the low-density block, the external input (Ei) varies seasonally. The average *Ei* was 455 m³/season, ranging from 374 to 567 m³/season. These seasonal variations are due to garden irrigation. In the studied year, spring was a dry season and required garden watering, meanwhile, the summer was wet and had a low garden irrigation demand (D_{DQ2}^{out}). Consumption (*Co*) also varies seasonally, mainly driven by the seasonal changes of evapotranspiration. For the studied year, the nature-driven flows have a slight predominance on the water balance, P = 2201 m³/y (55% of the inputs) and *Co* = 2279 m³/y (57% of *We* + *Co*). Meanwhile, the human-driven flows (*Ei*) are 1821 m³/y (45% of the inputs) and *We* is 1715 m³/y (43% of *We* + *Co*).

For the high-density block, *Ei* shows minor seasonal variations, ranging from 1612 to 1686 m³/season, because garden irrigation represents only a small percentage of the water demand. In this block, *Co* varies seasonally from 128 to 217 m³/season, reflecting the increment in evapotranspiration during spring and summer. For the studied year, precipitation (*P)* was found to be 2201 m³/y (26% of the inputs) and Consumption (*Co*) reached 682 m³/y (8% of *We* + *Co*). Meanwhile, the human-driven flows *Ei* amount to 6603 m³/y (74% of the inputs) and waste exported *We* was 8116 m³/y (92% of *We* + *Co*). This shows that the water cycle of the high-density block is dominated by the human-driven flows.

Comparing the water balance of the two blocks, Fig. 6a-b, there are several non-linear relationships, as a result of e.g. constraints on the infiltration and storage capacity. Although the population in the high-density block is 5.25 times the population in the low-density block, the yearly demand of the high density block is only 3.6 times higher than in the low-density block. Moreover, looking at the total in – and out – flows of the blocks, they are approximately 1000 m³/season for the low-density block and 2000 m³/season for the high-density block. The waste exported of the high-density block is 4.7 times larger than the waste exported of the low-density demand because of the differences in gardening irrigation, evapotranspiration, infiltration, and domestic demand.

Demand minimization

The first strategy in the UHA is demand minimization, focusing on the largest demand at household level ($D_{activity}$ > 10%). By implementing water saving technologies to reduce shower, toilet and laundry demand; the indoor household demand can be reduced up to 23% for the two-people household and 25% for the four-people household, see Appendix D. Fig. 6c and 6d show the effect of demand minimization for the two blocks per season on the water balance of the block. Demand minimization reduces *Ei*, *We* and the percentage of the human-driven flows in the urban water balance.

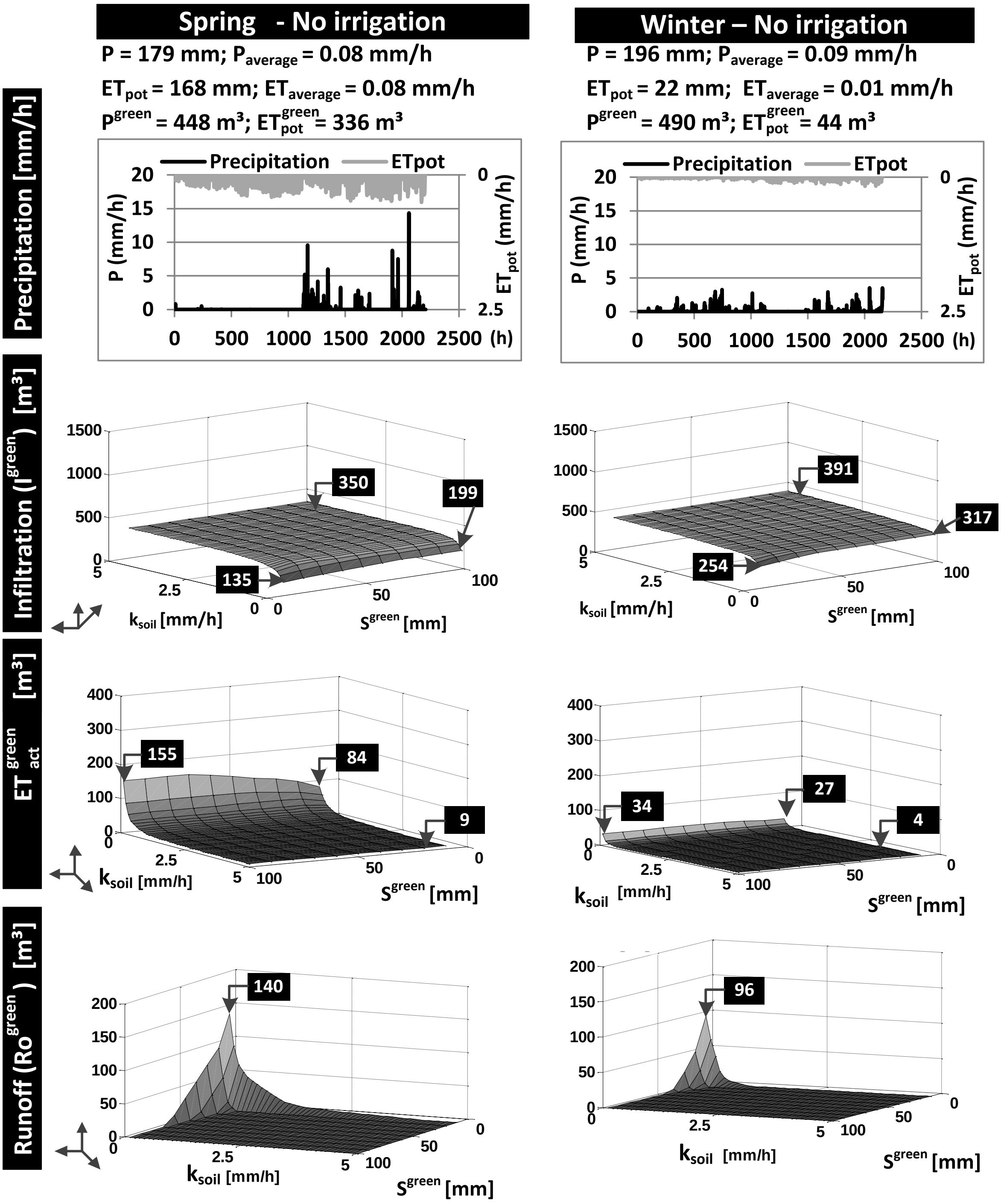


Figure 5 Seasonal simulation for the green areas (2000m²) of the low density block to evaluate the sensitivity of the water balance to k_{soil} = 0.1 – 5 mm/h and, S^{green} = 10 – 100 mm without irrigation (left) and with irrigation(right), assuming irrigation after 156 dry hours filling 80% of S^{green}

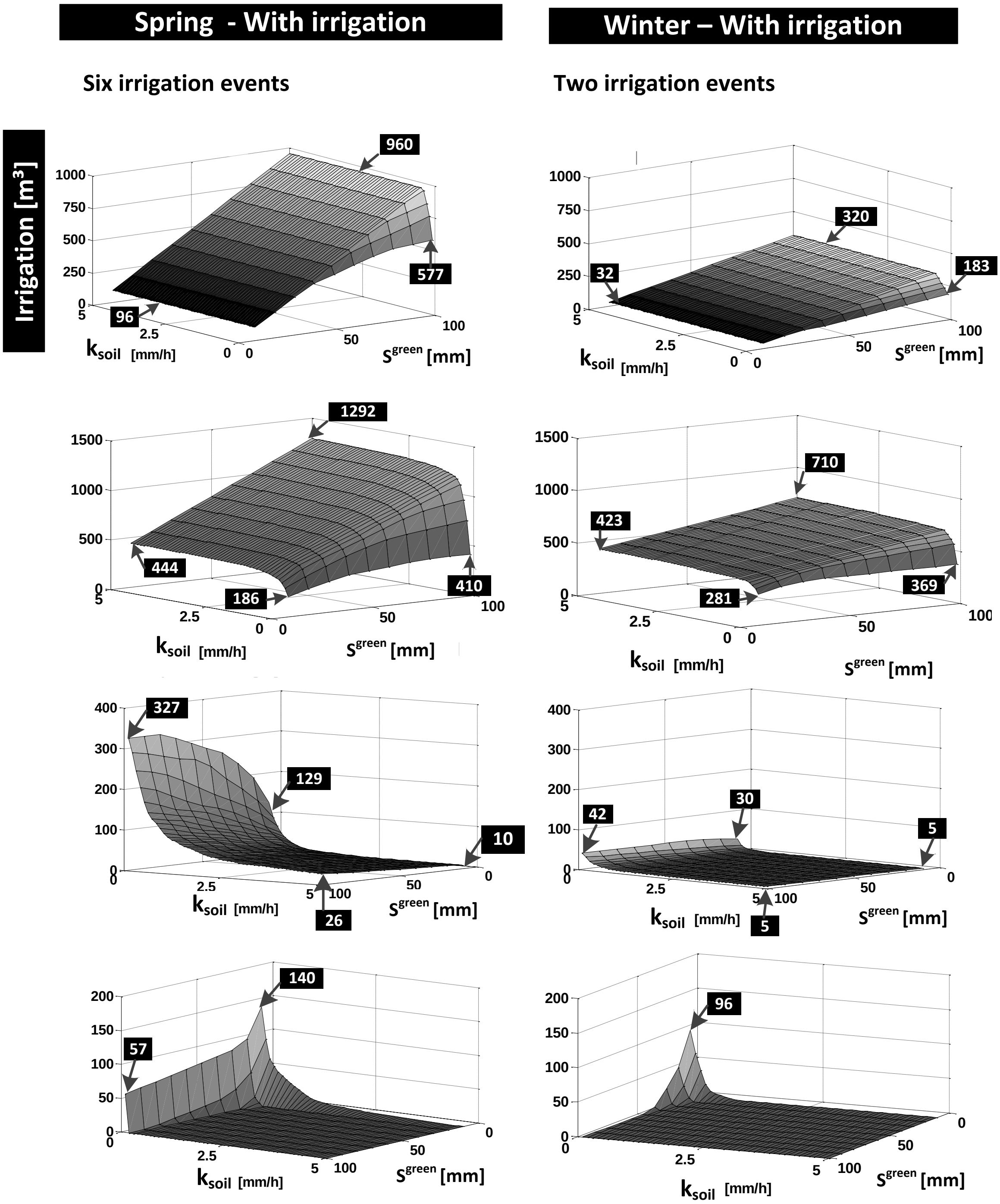


Figure 5 (Continuation)

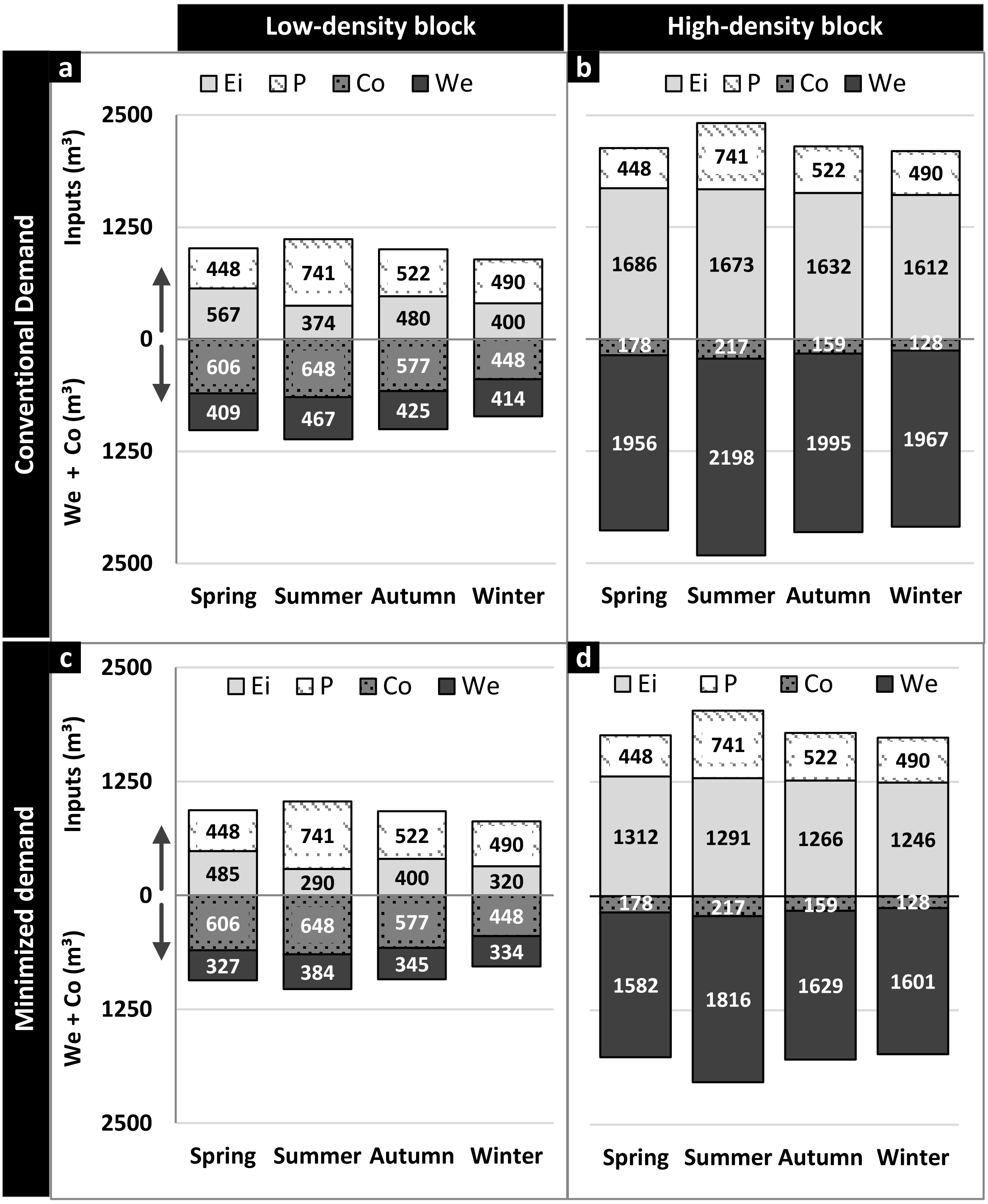


Figure 6 Baseline comparison of the seasonal water balance for the low-density and high-density blocks. 6a-b for conventional demand and 6c-d for minimized demand. External input (Ei), Precipiation (P), Consumption (Co) and Waste exported (We)

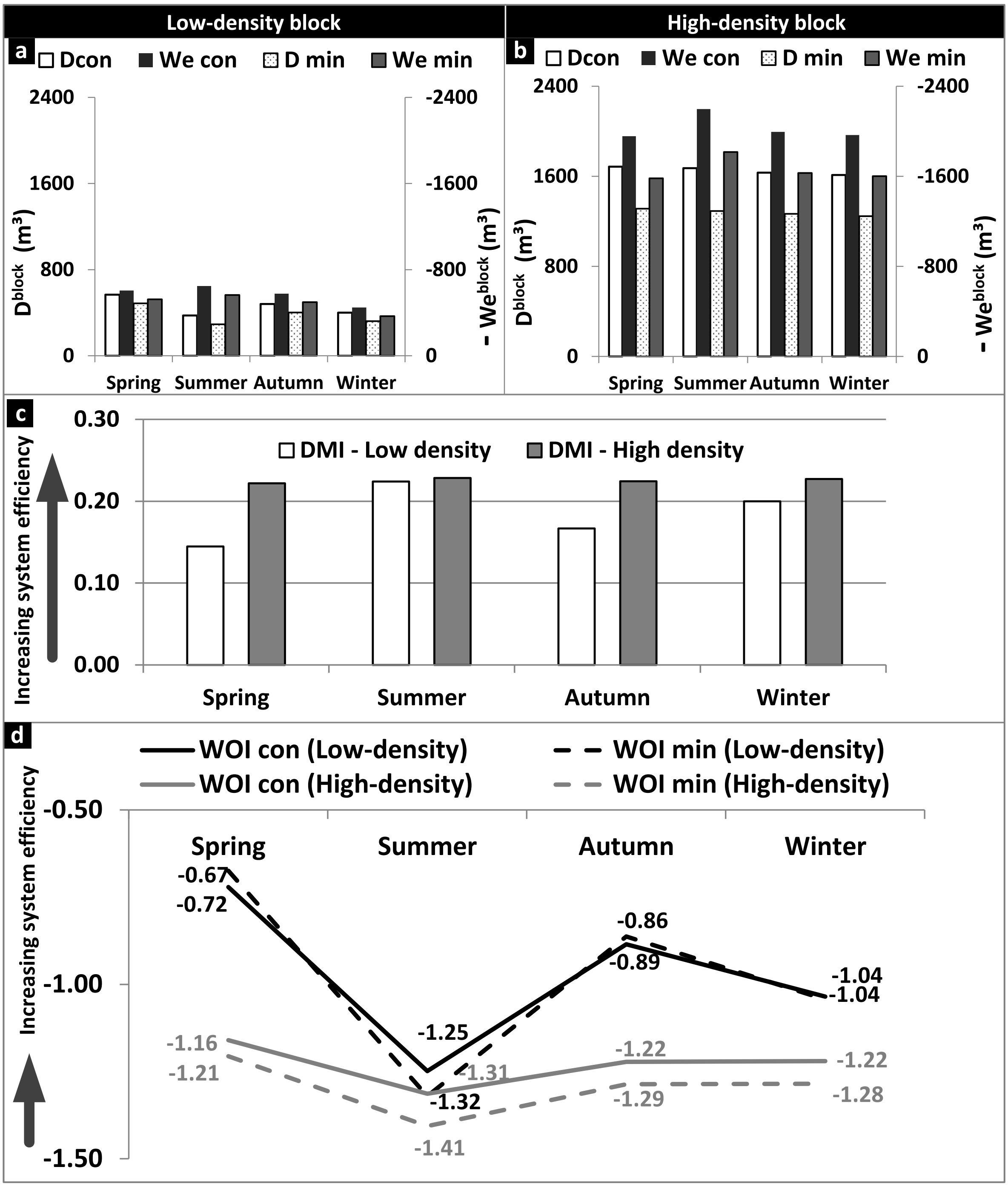


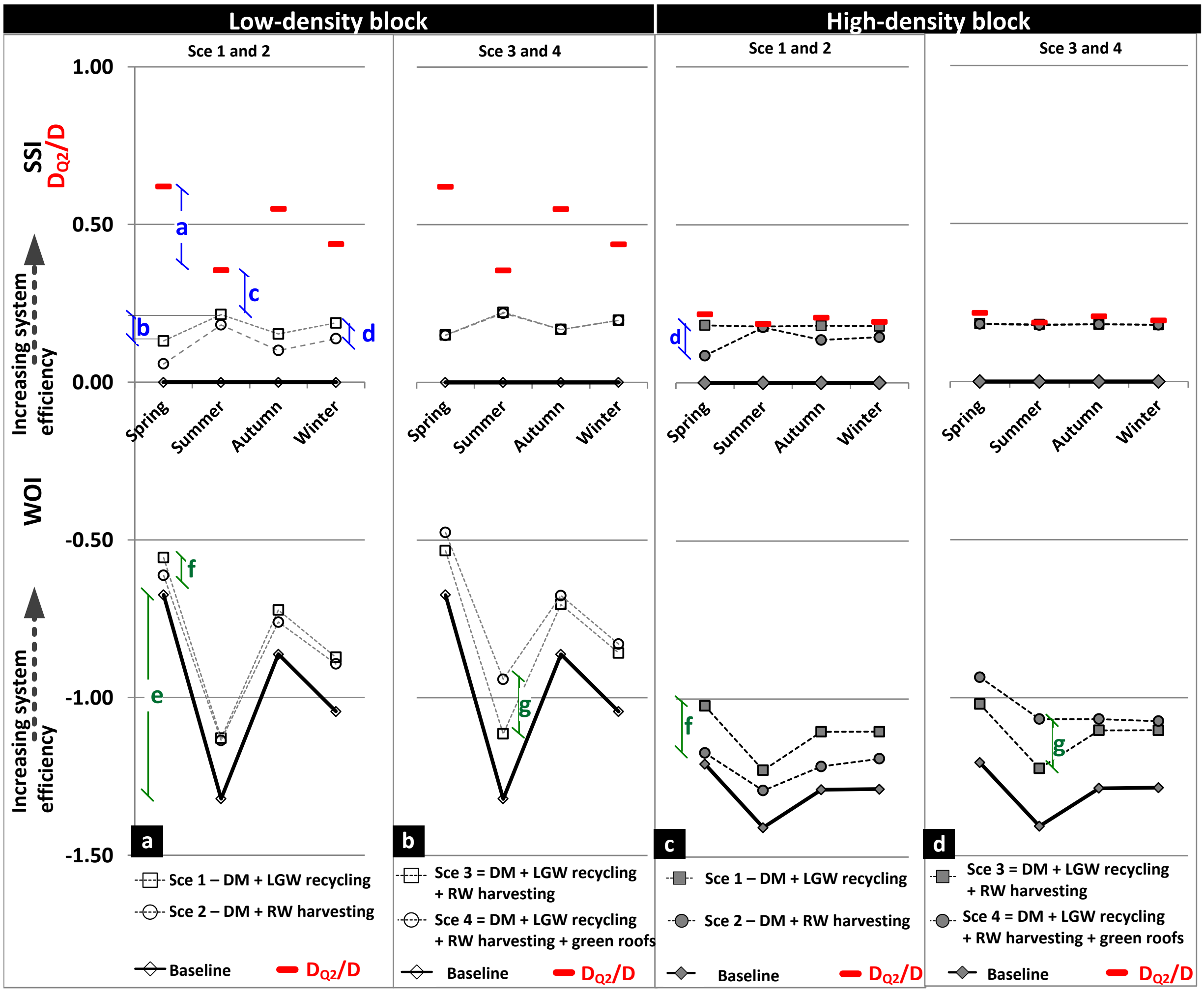
Figure 7 Baseline comparison of the seasonal water balance for the low- and high density blocks. a-b) Changes in demand (D) and waste exported (We) for conventional (con) and minimized (min) demand. c) Changes in the Demand Minimization Index (DMI) for the two blocks and d) Changes in the Waste Output Index (WOI) for the two blocks for conventional (con) and minimized (min) demand

We use the demand minimization index (*DMI*), which considers indoor and outdoor demand, to evaluate the effect of minimizing indoor demand on the water balance of the block. Additionally, we evaluated the waste reduction due to indoor demand minimization by using the waste output index (*WOI*). Fig. 7a-b show the reduction on *D* and *We* for the two blocks. Fig. 7c shows the *DMI* values for the two blocks. For the low-density block, the average *DMI* is 0.18, varying seasonally from 0.14 to 0.22. For the high density block *DMI* is 0.23 and is constant over the year. This shows that for low dense areas with irrigated green areas, it is needed to consider that efficiency of saving measures fluctuates seasonally, according to the changes in the demand.

Fig. 7d shows the seasonal variations of the waste output index (*WOI*) for the two blocks. For a conventional system: $WOI = -1$, which implies that $D = Ei = We$, and that runoff is zero. For $WOI > -1$, part of the demand was used for garden irrigation and thus infiltrated or partly evapo-transpirated. For $WOI < -1$, runoff is being produced as waste export. Although on a yearly basis, $WOI > -1$ for the low-density block, seasonal *WOI* shows that in summer $WOI < -1$. This seasonal increment is due to roof runoff during peak rainfall events. For the high density block, $WOI < -1$ over the year, resulting from the low percentage of permeable areas. During the summer, $WOI = -1.31$, which means that a runoff equivalent of 30% the block demand becomes waste output. In the scenarios considered below, the conventional and minimized demands were included. Fig. 7d also shows the variations in *WOI* if demand minimization is implemented. As *WOI* is related to the demand, with *D* in the denominator, a reduction in *D* will result in more negative (increase the absolute) value of *WOI*. The increments in the *WOI* in Fig. 7d due to demand minimization can thus be interpreted as an increment of the relative importance of natural driven flows, because the ratio $Ro/D_{conv} > Ro/D_{min}$.

6.3.3 Harvesting local resources: recycling and multi-sourcing

For this study, we developed four possible scenarios for improving the sustainable use of urban water resources, and performed dynamic model calculations (Table 2). All the scenarios considered demand minimization. Demand minimization combined with recycling and multi-sourcing was studied. Moreover, changing from conventional to green roofs was also investigated. Scenario (Sce) 1 and 2 compare recycling and multi-sourcing measures for minimized demand. We considered recycling of light grey water (LGW) from shower and harvesting rainwater from roofs to supply toilet flushing and laundry (D_{DQ2}^{ind}) and irrigation demands (D_{DQ2}^{out}). Thus we aim to obtain insight in the contribution of two different measures separately in Sce 1 and 2. Additionally, we studied the combination of measures, demand minimization combined with LGW recycling and rainwater harvesting and with (Sce 3) and without (Sce 4) green roofs. In this way, we can get insight in the maximum of sustainable water resource management at block level, and a possible add on effect by including green roof storage capacity. Fig. 8 shows the seasonal SSI and WOI for the different scenarios and Appendix E provides detailed information on the seasonal water balances for the different scenarios. Below we discuss the effects on water resource dynamics as studied in the different scenarios.



DM: Demand minimization; LGW: Light grey water; RW: Rainwater

Letters [a – b] represent seasonal variability of different factors:

(a) variability of D_{Q2} /D

(b) variability of SSI due to seasonal variations of *Rh* and *D*

(c) unmet D_{Q2} demand as a percentage of *D*

(d) differences of the yield achieved by the different scenarios

(e) variations of WOI due to changes on We and D, WOI=We/D

(f) differences of the yield achieved by the LGW recycling and RW harvesting

(g) changes of the WOI due to green roofs implementation.

Figure 8 Effect of the implementation of the different scenarios for the low-density (a-b) and high-density block (c-d) and main factors that influence seasonal variability of SSI and WOI

Effect of demand minimization combined with recycling LGW (Sce 1) and rainwater harvesting (Sce 2) in the low-density block:

Fig. 8a shows the effect of recycling LGW and rain water harvesting for the low-density block for conventional demand. SSI and WOI show large seasonal variability. This seasonal variability can be explained by different factors affecting the water balance, as identified by the small caps letters [a-g]: (a) indicates the seasonal variability of D_{Q2} /*D*, which represents the maximum value of self-sufficiency that could be achieved, given the restriction of only supplying D_{Q2} with secondary water. This seasonal variability is given by the garden irrigation during the dry seasons. The seasonal variability of SSI is indicated by (b) and is due to seasonal variations of *Rh* and *D*, since SSI=*Rh/D*. For instance, for the low-density block, in Sce 1, *Rh* is more or less constant over the seasons. However, due to the changing *D*, SSI changes as well. The unmet D_{Q2} demand (in percentage of *D*) as indicated by (c) gives an indication of *Ei* used to supply D_{Q2} and reflects the restrictions given by the storage capacity to temporally match the *Rh* and D_{Q2}. Similarly other differences and variations can be observed in Fig. 8, namely (d) indicates the differences of the yield achieved by the different scenarios. For instance, comparing LGW recycling and rainwater harvesting, (d) reflects the differences on the temporal pattern; (e) indicates the seasonal variations of WOI due to changes on *We* and *D*, WOI=*We/D*; (f) indicates the differences of the yield achieved by the LGW recycling and Rainwater harvesting; (g) indicates the seasonal changes of the WOI due to green roofs implementation.

Table 2 Overview of the scenarios studied in this paper

Low-density block = 32 people	**High-density block = 168 people**
Sce 1. Demand Minimization + Recycling of LGW for D_{Q2}	
25% minimization of $\boldsymbol{D^{ind}}$	23% minimization of D^{ind}
R_{pot} = 0.50 * $\boldsymbol{D^{ind}_{minimized}}$	R_{pot} = 0.45 * $D^{ind}_{minimized}$
D_{Q2} = 0.25 * $\boldsymbol{D^{ind}_{minimized}}$ + $\boldsymbol{D^{out}_{DQ2}}$	D_{Q2} = 0.18 * $D^{ind}_{minimized}$ + D^{out}_{DQ2}
Storage: Two tanks of 0.5 m³ each, (31 l/p)	Storage: Two tanks of 2.6 m³ each, (30 l/p)
Treatment unit: 1.3 m³ (40 l/p d)	Treatment unit: 6.7 m³ (40 l/p d)
Sce 2. Demand Minimization + Rain water harvesting for D_{Q2}	
M_{pot} = Ro^{root} = 440 m³/y = 38 l/p d	M_{pot} = Ro^{root} = 1760 m³/y = 28 l/p d
D_{Q2} = 0.25 * $\boldsymbol{D^{ind}_{minimized}}$ + $\boldsymbol{D^{out}_{DQ2}}$	D_{Q2} = 0.18 * $D^{ind}_{minimized}$ + D^{out}_{DQ2}
Storage: One tank 3.7 m³, (140 l/p)	Storage: One tank of 19.3 m³, (140 l/p)
Sce 3. Demand Minimization + Recycling of LGW + Rain water harvesting for D_{Q2}	
M_{pot} = Ro_{roof} = 440 m³/y = 38 l/p d	M_{pot} = Ro_{roof} = 1760 m³/y = 28 l/p d
D_{Q2} = 0.25 * $\boldsymbol{D^{ind}_{minimized}}$ + $\boldsymbol{D^{out}_{DQ2}}$	D_{Q2} = 0.18 * $D^{ind}_{minimized}$ + D^{out}_{DQ2}
Storage: grey water of 0.5 m³; treated grey water and rainwater 2m³ (80 l/p)	Storage: Two tanks of 2.6 m³ each, (30 l/p)
Treatment unit: 1.3 m³, (40 l/p d)	Treatment unit: 6.7 m³ (40 l/p d)
Sce 4. Demand Minimization + Recycling of LGW + Rain water harvesting for D_{Q2} + Green roofs with a storage capacity of 10 mm.	
Idem as in Sce 3.	

LGW: Light Grey Water from shower
S&T: Storage and Treatment; Storage capacity and treatment rates are based on Chapter 4 D_{Q2} = toilet, laundry and D^{out}_{DQ2}
One day of retention hydraulic time in the treatment unit was assumed

For the low-density block, variability of D_{Q2} /*D* (a) is large, due to our assumption, that irrigation occurs within one hour for the whole block. However, no detailed information is available to predict real irrigation pattern in urban green areas. Options to reduce (a) are to increase the storage capacity of the tanks or modify the irrigation pattern.

Comparing seasonal variations of SSI in Fig. 8a, for LGW recycling SSI varies from 0.13 to 0.21 and for rainwater harvesting from 0.06 to 0.18. The unmet demand is large due to temporal variations of garden irrigation and limitations in storage capacity. Similar benefits for WOI are achieved by recycling LGW or harvesting rainwater, where WOI varies from -0.56 to -1.13 for Sce 1 and from -0.61 to -1.14 for Sce 2, see also Appendix E, Table E1. Hence, LGW recycling is more effective than rainwater harvesting because LGW production has a more constant pattern than precipitation. Thus, for a given storage capacity, extreme rainfall events lead to overflows. These overflows can be minimized by increasing storage capacity, which will result in higher SSI.

Effect of combined measures: demand minimization + LGW recycling + rainwater harvesting (Sce 3) and addition of green roofs (Sce 4) in the low-density block:

Fig. 8b shows the effect of combining measures. SSI shows that combining LGW recycling and rainwater harvesting has only a minor effect in SSI and WOI for the low-density block, compared with the results achieved for Sce 1, although the storage capacity of the storage tank was increased by 1.5 m^3 as presented in Table 3. However, if the measures are combined with green roofs, a noticeable reduction in WOI is achieved for the wet season, from WOI of –1.11 to –0.94.

Effect of recycling LGW (Sce 1) and rainwater harvesting (Sce 2) for minimized demand in the high-density block:

Fig. 8c shows the effect of LGW recycling and rainwater harvesting for minimized demand. Again, LGW recycling can supply a large percentage, 90%, of D_{Q2} . Meanwhile, rainwater harvesting can only supply 67% of D_{Q2} , with seasonal variations from 40% to 94% . LGW recycling shows a larger improvement of the WOI. However, WOI < –1, therefore, additional measures are needed to prevent runoff going as waste output.

Effect of combined measures: demand minimization + LGW recycling + rainwater harvesting (Sce 3) and addition of green roofs (Sce 4) in the high-density block:

Fig. 8d shows the effect of combining measures. SSI shows that combining LGW recycling and rainwater harvesting has only a minor effect in SSI and WOI for the low-density block, compared with the results achieved for Sce 3. However, if the measures are combined with green roofs a noticeable reduction in WOI is achieved, e.g. on yearly basis WOI becomes -1.04.

Comparing the low-density with the high density block

Fig. 9 shows an overview of the seasonal variations of the metabolic profiles for the two blocks and for the four scenarios. In the Fig. 9 the bar represents the average year value for each index, and the lines indicate the maximum and minimum seasonal values obtained for the year studied. Comparing the low-density with the high density block, the seasonal variations are larger in the low-density block. Comparing the three indices, the WOI has the larger variations up to 40% in the low-density block and up to 10% in the high-density block. The variations of the SSI for the low-density block are due to irrigation demand, D_{DQ2}^{out}, which is a seasonal demand. Urban blocks with large irrigated areas have a peak demand during dry months. If this demand is averaged over a year, efficiency of a measure can be over-estimated. Meanwhile highly dense areas, with a low percentage of irrigated areas have a more constant demand pattern. Although, combining LGW recycling with rainwater harvesting did not show larger improvements in any of the blocks, for the low-density block a combination of increasing storage capacity and changes in irrigation can improve the SSI and WOI.

For the low-density block, minimizing 25% of the indoor demand results in a reduction between 14% - 22% of the total block water demand. This variation is given due to seasonal variations of the irrigation demand. The maximum *SSI* is in summer, 20% for Sce 1. The best *WOI* is –0.48 (Sce 4 - spring), and the worst *WOI* is –1.14% (Sce 2 - summer). For the high-density block, minimizing 23% of the indoor demand results in reduction of 22% of the total block water demand, without any significant seasonal variation. The maximum *SSI* that can be achieved is also 20% (Sce 1 -spring). For *WOI*, the best value was -0.94 and achieved for Sce 4 in spring, the worst value of –1.29 was found for Sce 2 and in summer. Looking at *Rh*, grey water recycling offers a constant supply over the year meanwhile rainwater has notorious seasonal variations.

This scenario study showed that for both block types, Sce 4 is the best, because fewer resources are entering and leaving the system, see Fig. 9. Looking at the indices, the metabolism of the block can be evaluated as in Fig. 7-9. *SSI* values are constrained by D_{Q2}. In this study, D_{Q2} was defined as the sum of toilet, laundry and garden demand. *SSI* can increase if additional activities are included, for instance, car washing or landscaping. If *WOI* < –1, the waste production of the block is not only limited to the domestic demand, but there is also runoff being exported as waste. This shows the need of complementary measures to improve the overall performance of the block, especially to minimize the waste output. For the studied scenarios, if there is a surplus of harvested water ($R_{act}+M_{act} > D$, $O^{S\&T}>0$), it will be discharged into the sewer system (see Fig. 2). Hence, in practice, there is a need for proper control of the recycling and multi-sourcing components. For instance, if there is a surplus of treated or multi-sourced water, this could be better used to increase the irrigation of green areas. Although, reducing $O^{S\&T}$ to D_{Q2}^{out} will increase the demand, and thus decrease *DMI*. The use of recycled/harvested water also implies that the external input Ei_{Q2}^{out} does not change. Thus, by using recycled water, less waste output is produced. Moreover, irrigation will increase evapotranspiration rates and contributes to cool the area in hot seasons. Therefore, enhancing irrigation of green areas by using recycled/harvested water is a recommended option to improve the water cycle. Proper control of these flows should avoid over-irrigation that could lead to runoff from green areas. Another option to reduce *WOI* is to export recycled/harvested water to other blocks.

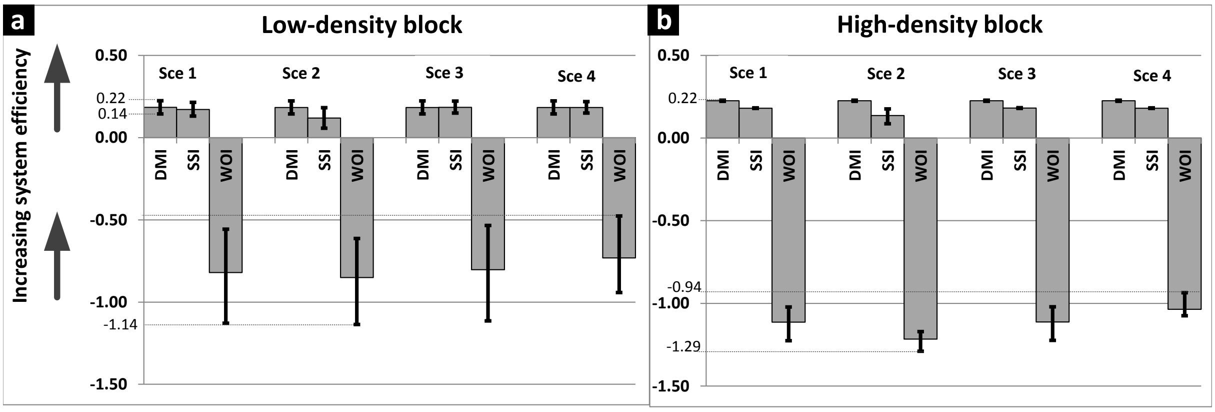


Figure 9 Overview of the seasonal variations of the metabolic profiles for the two blocks. a) Low-density block, b) high-density block. Bars indicate the seasonal average and lines indicates the range of variability for the studied year

The set of indicators, *DMI*, *WOI* and *SSI,* describe the metabolism of each of the scenarios. As introduced in chapter 4, these indices can also be plotted in a metabolic dashboard. Fig. 10 shows the representation of the yearly metabolism for each of the scenarios, by plotting in the horizontal axis the demand, and in the vertical axis the *Rh* in the positive direction and the *We* in the negative direction. The arrows indicate the direction towards more sustainable systems. The dashboard shows that Sce 4 has the best metabolic profile for both blocks, mainly due to reduction on the *We*.

6.3.4 General discussion

Implementing the UHA can lead to significant effects in water resource management efficiencies by minimizing demand, minimizing outputs and multi-sourcing using local and renewable resources at block scale. UHA is an alternative to meet the local water demand concentrated at the city level and to reduce urban water inputs from surrounding catchments in the region.

Due to the interrelation between infiltration-evapotranspiration and irrigation in the green areas, the low-density block has more seasonal variations. This shows the drawbacks of making only an average annual water balance. Moreover, large differences are found by comparing the low and high-density block. This shows the drawback of using average data of urban areas when planning for decentralized systems at block scale. Therefore, measures to optimize the urban water cycle at block scale, should be studied separately for specific urban typologies and evaluated at least seasonally, as in this study.

At building level, mainly technological implementation should be addressed to improve the water balance. At the larger block scale, other options are feasible and needed and three main options are identified: (i) technology implementation, e.g., water saving devices or treatment technologies; (ii) modifications in the building unit envelope, e.g., green roofs; and (iii) changes in the urban surfaces to increase subsurface storage capacity by selecting permeable materials. Thus, measures at building level could be complemented with measures at block level. Temporal multi-scale analysis can help to define the optimal scale for management of certain flows. Thus, combining the measures proposed by the UHA with other type of measures, e.g. real time flow control, will further optimize the water cycle at block scale. As already shown in this chapter, dynamic modeling is needed to understand temporal variations and to support water management of drinking water supply and wastewater treatment. Further, technology implementation requires a supportive policy framework and a trade-off analysis, e.g. to identify rebound effects.

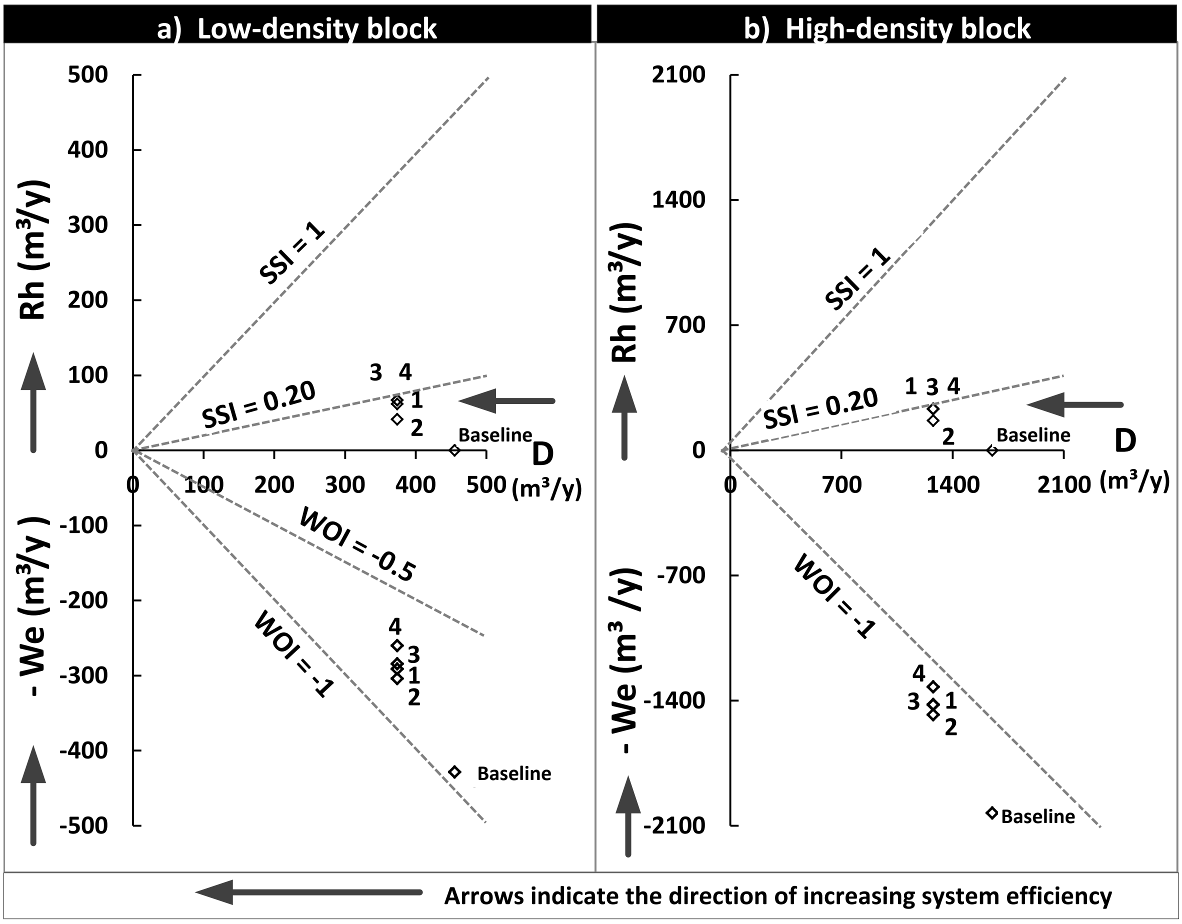


Figure 10 Metabolic dashboard to represent the metabolic profiles for the two blocks, for the baseline and the four scenarios (indicated by numbers and diamonds) on yearly basis. a) Low- and b) High-density block.

In general, a large storage capacity will guarantee that in case of heavy precipitation, the peak runoff can be minimized and delayed in time. Water storage also enhances evapotranspiration and infiltration. Moreover, for dry areas or highly dense urban areas, storage of water combined with regular irrigation, can contribute to an increase in evapotranspiration, thus naturally cooling down the urban setting. To avoid waste of high quality drinking water, irrigation should be supplied by secondary quality water. In this case, although demand D_{Q2}^{out} increases, the other two metabolic indices will show the positive effect in the water cycle at block level, i.e. lower *WOI* and higher *SSI*.

In countries with low precipitation, and hot climates, water scarcity is an issue and management of local resources becomes crucial. Methodologies such as the UHA can support planning of more sustainable urban water systems. Optimization of the urban water cycle implies different measures in different locations according urban typology, climatic conditions and water use. Linkages between urban planning and water management are strong. For instance, the choice of the surface materials will directly affect the evapotranspiration and infiltration. Moreover, the external inputs, which are a function of the demand, are also determined by selection of the building type and the block density. High density by itself does not imply a less sustainable water cycle. By avoiding impermeable surfaces, and implementing different strategies, such as green roofs, recycling and harvesting of rain water, traditional problems of high density areas, e.g. high runoff, can be minimized. Thus, urban water managers and urban planners should work together to optimize urban water flows. Further research is needed to further investigate the water cycle of other urban typologies, e.g. row or duplex houses, and other urban context, e.g. different climatic and topographic conditions.

6.4 Conclusions

Three main options are identified to improve the water cycle at block level: (i) technology implementation; (ii) modifications in the building unit envelope, and (iii) changes in the urban surfaces. Looking at the heterogeneity of blocks within a city, no single solution fits all the blocks. Generalization of urban areas and yearly water flow averages can cause error when planning decentralized water infrastructures. Urban water planning and management has to be adaptive and flexible to cope with the stochastically driven dynamics of the urban water balance. Moreover, urban water planning requires a multi-scale and time-dependent approach to select customized solutions supporting the design of more sustainable urban water metabolisms.

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APPENDIX A – Additional tables with background data

Table A1 Storage capacities according land use.

Land use	**S – storage capacity (mm)**
Soil	150 [b]
Pervious	2.11 [b]
Grass:	1.3 [a]
Impervious:	0.59 [b]
Pavement:	0.48 [a]
Roofs:	0.25 [a]

[a](Grimmond et al., 1986); [b] (Grimmond et al., 1986)

Table A2 Infiltration rate (Mays, 2011)

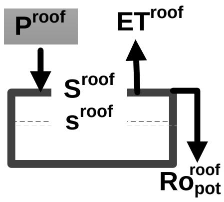
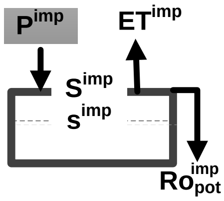
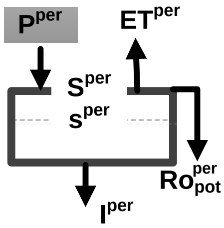
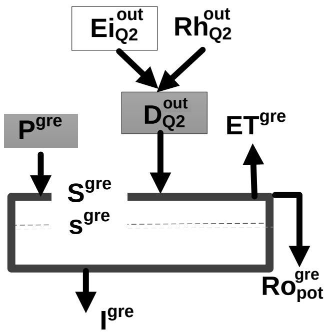
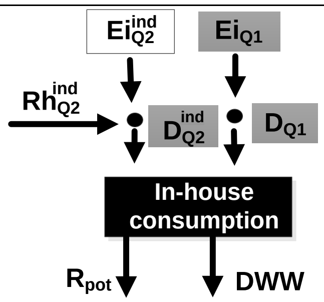
Group	**Description**	Minimum infiltration rate (in/h) [mm/h]
A	Deep sand, deep loess, aggregated silts	0.3-0.45 [7.62 – 11.43]
B	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	0.15-0.3 [3.81-7.62]
C	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0-0.05 [0-1.27]

Table A3 Typical values of runoff coefficients according surface.

Surface type	**Description**	**Runoff coefficient C**
Paved	High quality paved roads with gullies < 100 m apart	1.00[a]
Paved	High quality paved roads with gullies > 100 m apart	0.90 [a]
Paved	Medium quality paved roads	0.85 [a]
Paved	Poor quality paved roads	0.80 [a]
	Asphalt and concrete pavement	0.70-0.95 [b]
	residential	0.3-0.7 [b]
Roofs		0.75-0.95 [b]
Permeable	High to medium density housing	0.55-0.45 [a]
Permeable	Low density housing or industrial areas	0.35 [a]
Permeable	Open areas	0.00-0.25 [a]
Lawns		0.05-0.35 [b]

[a] (Loucks et al., 2005), [b] (Butler and Davies, 2000)

APPENDIX B – Dynamic modeling of components

Balances for surfaces and roofs		***Roof balance in mm*** $ET_t^{roof} = PE_t$ $s_t^{roof} = s_{t-1}^{roof} + P_t - ET_t^{roof}; Ro_t^{roof} = 0$ $if\ s_t^{roof} > S^{roof} \Rightarrow Ro_t^{roof} = s_t^{roof} - S^{roof} \Rightarrow s_t^{roof} = S^{roof}$ $if\ s_t^{roof} < 0 \Rightarrow ET_t^{roof} = s_{t-1}^{roof} + P_t \Rightarrow s_t^{roof} = 0$
		***Impermeable areas balance in mm*** $ET_t^{imp} = PE_t$ $s_t^{imp} = s_t^{imp} + P_t - ET_t^{imp}; Ro_t^{imp} = 0$ $if\ s_t^{imp} > S^{imp} \Rightarrow Ro_t^{imp} = s_t^{imp} - S^{imp} \Rightarrow s_t^{imp} = S^{imp}$ $if\ s_t^{imp} < 0 \Rightarrow ET_t^{imp} = s_{t-1}^{imp} + P_t \Rightarrow s_t^{imp} = 0$
		***Permeable areas balance in mm*** $ET_t^{per} = PE_t\ ;\ I_t^{per} = k_{soil}$ $s_t^{per} = s_{t-1}^{per} + P_t - ET_t^{per} - I_t^{per}; Ro_t^{per} = 0$ $if\ s_t^{per} > S^{per} \Rightarrow Ro_t^{per} = s_t^{per} - S^{per} \Rightarrow s_t^{per} = S^{per}$ $if\ s_t^{per} < 0 \Rightarrow I_t^{per} = s_{t-1}^{per} + P_t - ET_t^{per} \Rightarrow s_t^{per} = 0$ $if\ I_t^{per} < 0 \Rightarrow ET_t^{per} = s_{t-1}^{per} + P_t \Rightarrow I_t^{per} = 0$
		***Green areas balance in mm*** $ET_t^{gre} = PE_t\ ;\ I_t^{gre} = k_{soil}\ ;\ D_{Q2,t}^{out} = 0$ If # dry hours>156, then: $D_{Q2,t}^{out} = 0.8 * S^{gre} - s_{t-1}^{gre}$ $s_t^{gre} = s_{t-1}^{gre} + P_t + D_{Q2}^{out} - ET_t^{gre} - I_t^{gre}; Ro_t^{gre} = 0$ $if\ s_t^{gre} > S^{gre} \Rightarrow Ro_t^{gre} = s_t^{gre} - S^{gre} \Rightarrow s_t^{gre} = S^{gre}$ $if\ s_t^{gre} < 0 \Rightarrow I_t^{gre} = s_{t-1}^{gre} + P_t + D_{Q2,t}^{out} - ET_t^{gre} \Rightarrow s_t^{gre} = 0$ $if\ I_t^{gre} < 0 \Rightarrow ET_t^{gre} = s_{t-1}^{gre} + P_t + D_{Q2,t}^{out} \Rightarrow I_t^{gre} = 0$
In house		***In house balance - (Volume) – No storage*** $Ei_{Q1,t} + Ei_{Q2,t}^{ind} + M_{act,t} + R_{act,t-RT} - D_{Q2,t}^{out} = R_{pot,t} + DWW_t$ $D_t^{ind} = D_{Q1,t} + D_{Q2,t}^{ind}$ $D_t^{ind} = Ei_{Q1,t} + Ei_{Q2,t}^{ind} + M_{act,t} + R_{act,t-RT} - D_{Q2,t}^{out}$

*Treatment and storage unit as described in chapter 5

Eq. (1) can be defined for each of the storage units as follows:

$$\frac{ds_{S\&T}}{dt} = R_{pot} + M_{pot} - (R_{act} + M_{act}) - O^{S\&T} \qquad (B1)$$

$$\frac{ds^i}{dt} = P^i + Ei_{Q2}^{out} + Rh_{Q2}^{out} - ET_{act}^i - I^i - Ro^i \qquad (B2)$$

$$\frac{ds^{roof}}{dt} = P^{roof} - ET_{act}^{roof} - Ro_{pot}^{roof} \qquad (B3)$$

Therefore, Eq. (1) applied to the storages in the block becomes $\frac{ds}{dt} = \frac{ds_{S\&T}}{dt} + \sum \frac{ds^i}{dt} + \frac{ds^{roof}}{dt}$. Consequently,

$$\frac{dS}{dt} = R_{pot} + M_{pot} - (R_{act} + M_{act}) - O^{S\&T} + \Sigma P^i + Ei_{Q2}^{out} + Rh_{Q2}^{out} - \Sigma ET^i - \Sigma I^i - \Sigma Ro^i + P^{roof} - ET_{act}^{roof} - Ro_{pot}^{roof} \qquad (B4)$$

Organizing the terms in inputs, outputs and consumption,

$$\frac{dS}{dt} = [P^{roof} + \Sigma P^i + Ei_{Q2}^{out} + Rh_{Q2}^{out} + R_{pot} + M_{pot}] - \left[R_{act} + M_{act} + O^{S\&T} + \Sigma Ro^i + Ro_{pot}^{roof}\right] - [ET_{act}^{roof} + \Sigma ET_{act}^i + \Sigma I^i] \qquad (B5)$$

Recall that $R_{pot}+M_{pot}=R_{act}+M_{act}+O^{S\&T}$, thus Eq. (6) can be re-written as:

$$\frac{dS}{dt} = [P^{roof} + \Sigma P^i + Ei_{Q2}^{out} + Rh_{Q2}^{out}] - \left[\Sigma Ro^i + Ro_{pot}^{roof}\right] - [ET_{act}^{roof} + \Sigma ET_{act}^i + \Sigma I^i] \qquad (B6)$$

Notice from Fig. 2, that there is no storage in the building unit. Neglecting the losses *DWW* is given by

$$DWW = Ei_{Q1} + Ei_{Q2}^{ind} \qquad (B7)$$

APPENDIX C – Detailed information of the seasonal simulation with and without irrigation for green areas in the low-density block

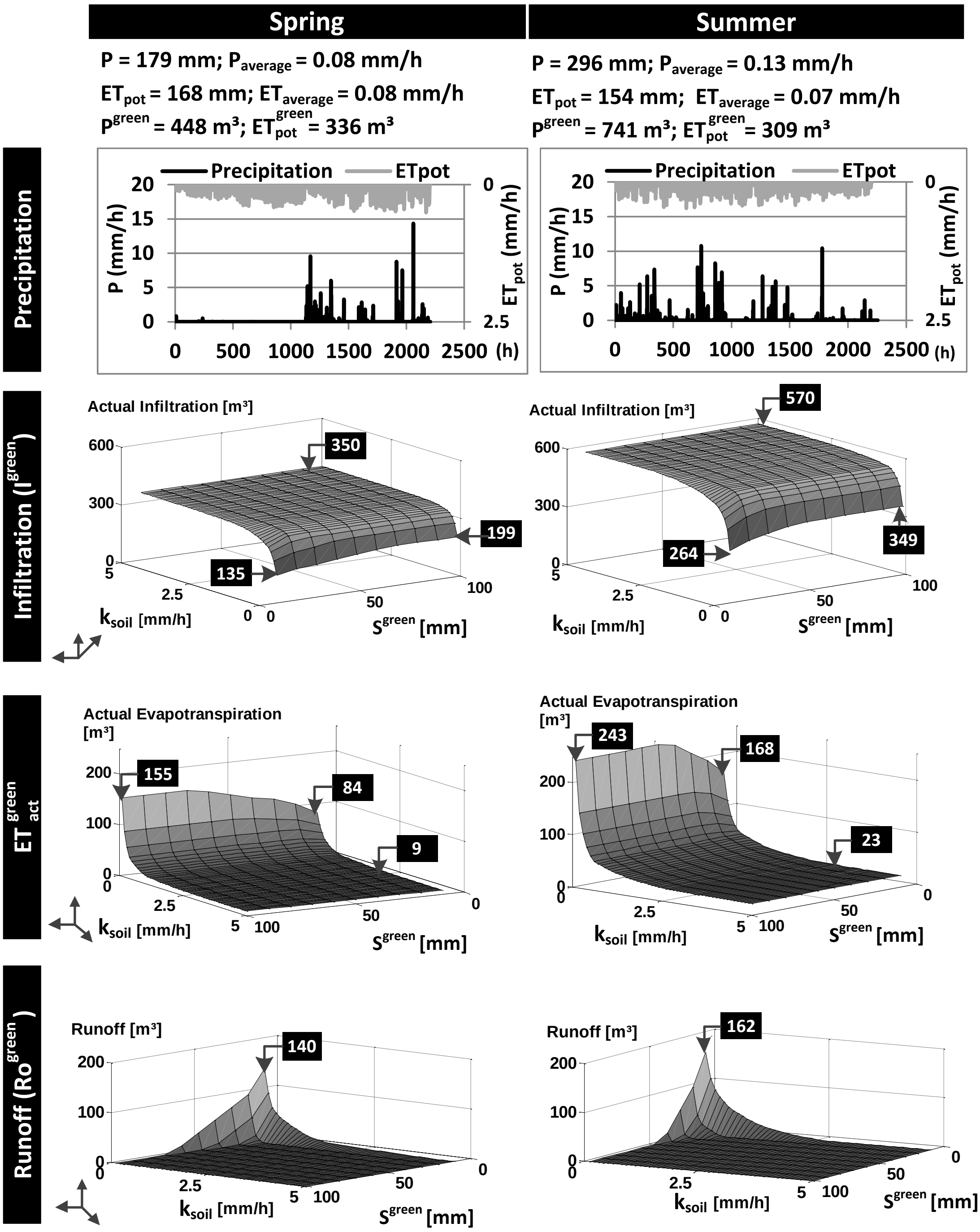


Figure C1. Seasonal variations for the green areas of the low-density block. simulation for the green areas (2000m²) of the low density block to evaluate the sensitivity of the water balance to k_{soil} = 0.1 – 5 mm/h and, S^{green} = 10 – 100 mm without irrigation

APPENDIX C – (Continuation)

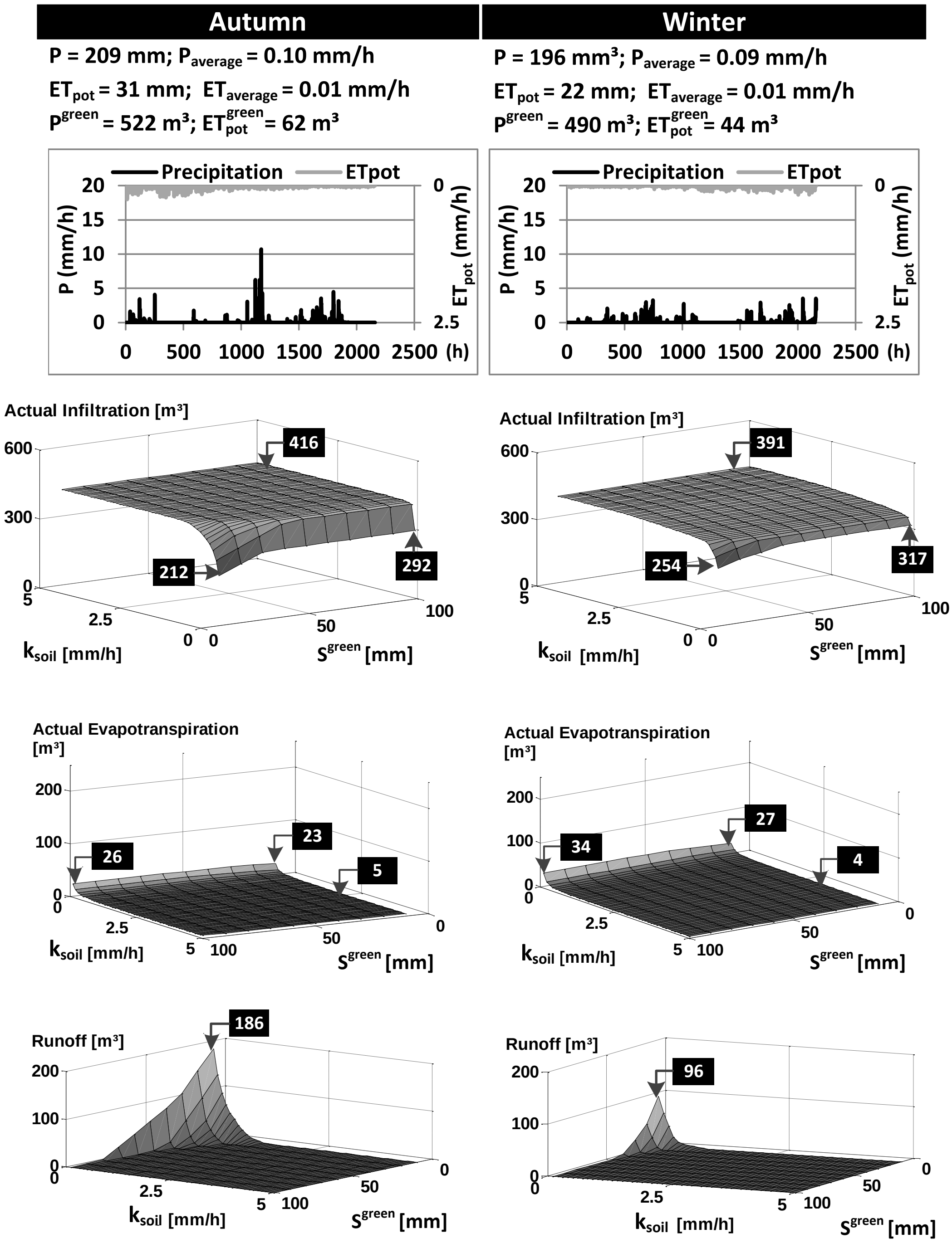


Figure C1. (Continuation)

APPENDIX C – (Continuation)

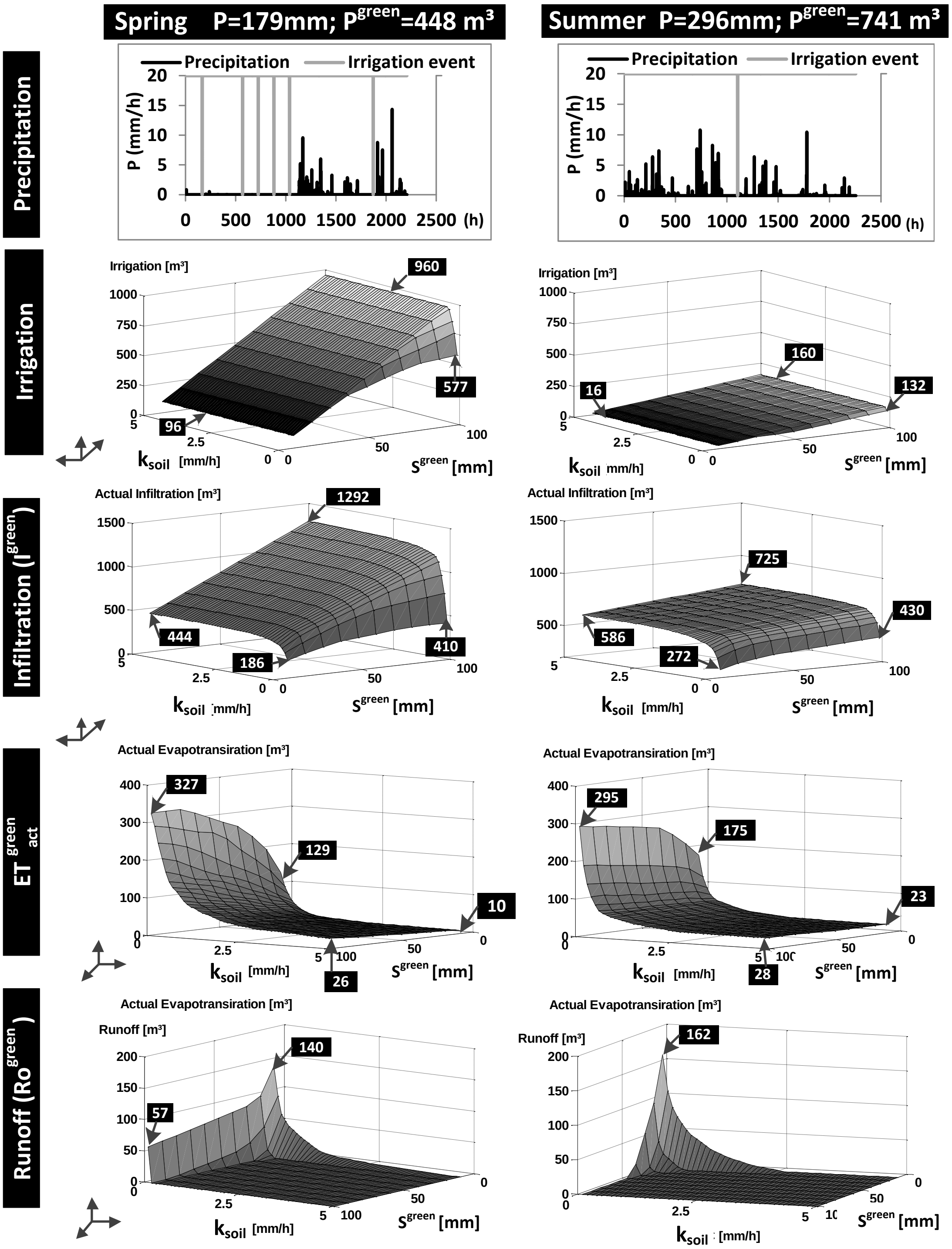


Figure C2. Seasonal variations for the green areas of the low-density block. simulation for the green areas (2000m²) of the low density block to evaluate the sensitivity of the water balance to k_{soil} = 0.1 – 5 mm/h and, S^{green} = 10 – 100 mm with irrigation, assuming irrigation after 156 dry hours filling 80% of S^{green}

APPENDIX C – (Continuation)

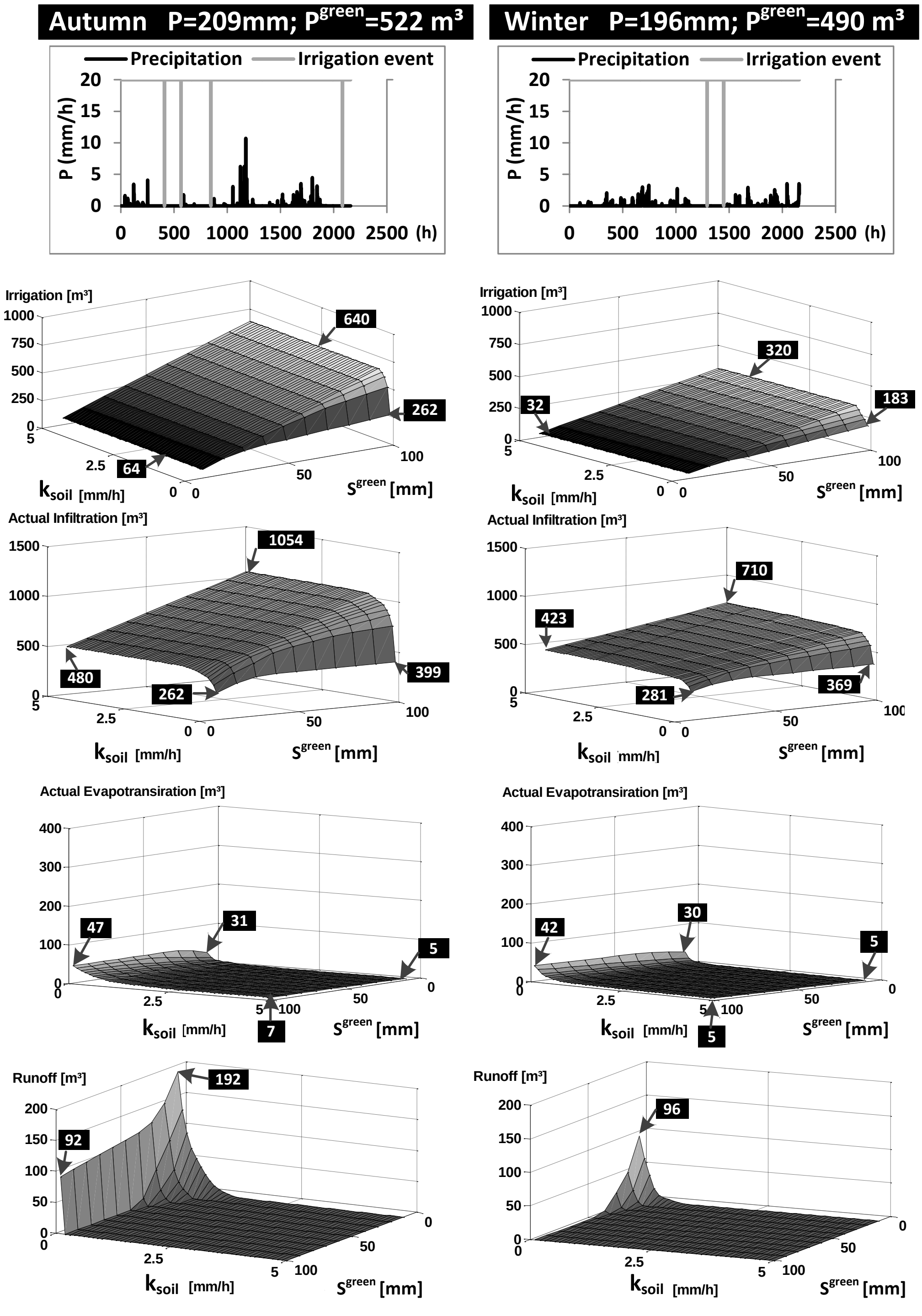


Figure C2. (Continuation)

APPENDIX D – Detailed information of indoor demand for conventional and minimized demand

Table D.1 Dutch daily indoor water demand per person in liters according to the household size (SIMDEUM) year 2007 and potential minimization of the largest demands.

	Two-people household High-density block				Four-people household Low-density block			
	Conventional		**Minimized**		**Conventional**		**Minimized**	
Activity	**Demand (l/p d)**	**%**	**Demand (l/p d)**	**%**	**Demand (l/p d)**	**%**	**Demand (l/p d)**	**%**
Shower	42	40	37[a]	50	45	41	37[a]	45
Toilet flushing	23	22	5[b]	7	20	18	4[b]	5
Washing machine	14	13	13[c]	18	14	13	11[c]	13
Bath	2	2	2	3	3	3	3	4
Sink	4	4	4	6	4	4	4	5
Dish washing	17	16	17	23	9	8	9	11
Drinking water	3	3	3	4	2	2	2	2
Other				0	13	12	13	16
Total	**105**	**100**	**81**	**100**	**110**	**100**	**83**	**100**

[a] Shower with a demand of 6 l per minute.
[b] Vacuum toilets with a demand of 0.8 l per flush.
[c] Washing machine with a demand of 9 l kg^{-1} and 4 kg per cycle.

APPENDIX E – Detailed information of seasonal simulation of the effect of the UHA measures for the two blocks

Table E1 Seasonal simulation to evaluate the effect of the UHA strategies for the baseline and per scenario

Low density block	Baseline					Sce 1					Sce 2					Sce 3					Sce 4				
	Sp	Su	Au	Wi	Y	Sp	Su	Au	Wi	Y	Sp	Su	Au	Wi	Y	Sp	Su	Au	Wi	Y	Sp	Su	Au	Wi	Y
D	567	374	480	400	1821	485	290	400	320	1495	485	290	400	320	1495	485	290	400	320	1495	485	290	400	320	1495
D_{Q2}	354	157	272	192	975	301	103	220	140	764	301	103	220	140	764	301	103	220	140	764	301	103	220	140	764
Rh	0	0	0	0	0	63	62	61	60	247	28	53	40	44	165	73	65	67	63	267	72	64	67	63	266
Ei	567	374	480	400	1821	422	228	339	260	1248	457	237	360	276	1330	412	225	333	257	1228	413	226	333	257	1229
We	409	467	425	414	1766	270	327	289	279	1226	297	330	304	286	1271	259	324	282	275	1196	231	273	270	266	1091
DMI	0	0	0	0	0	0.14	0.22	0.17	0.2	0.18	0.14	0.22	0.17	0.2	0.18	0.14	0.22	0.17	0.2	0.18	0.14	0.22	0.17	0.2	0.18
-WOI	0.72	1.25	0.88	1.03	0.97	0.56	1.13	0.72	0.87	0.82	0.61	1.14	0.76	0.89	0.85	0.53	1.11	0.7	0.86	0.8	0.48	0.94	0.68	0.83	0.73
SSI	0	0	0	0	0	0.13	0.21	0.15	0.19	0.17	0.06	0.18	0.1	0.14	0.12	0.15	0.22	0.17	0.2	0.18	0.15	0.22	0.17	0.2	0.18

High –density block	Baseline					Sce 1					Sce 2					Sce 3					Sce 4				
	Sp	Su	Au	Wi	Y	Sp	Su	Au	Wi	Y	Sp	Su	Au	Wi	Y	Sp	Su	Au	Wi	Y	Sp	Su	Au	Wi	Y
D	1686	1673	1632	1612	6604	1312	1291	1266	1246	5115	1312	1291	1266	1246	5115	1312	1291	1266	1246	5115	1312	1291	1266	1246	5115
D_{Q2}	385	343	358	338	1425	285	241	261	241	1027	285	241	261	241	1027	285	241	261	241	1027	285	241	261	241	1027
We	1956	2198	1995	1967	8116	1341	1582	1397	1375	5694	1536	1664	1536	1481	6218	1339	1580	1397	1375	5690	1227	1378	1352	1338	5295
Rh	0	0	0	0	0	239	231	229	224	922	113	226	172	180	692	240	233	229	224	926	239	231	229	224	922
Ei	1686	1673	1632	1612	6604	1073	1060	1037	1022	4193	1199	1065	1094	1066	4423	1072	1058	1037	1022	4189	1073	1060	1037	1022	4193
DMI	0	0	0	0	0	0.22	0.23	0.22	0.23	0.23	0.22	0.23	0.22	0.23	0.23	0.22	0.23	0.22	0.23	0.23	0.22	0.23	0.22	0.23	0.23
-WOI	1.16	1.31	1.22	1.22	1.23	1.02	1.23	1.1	1.1	1.11	1.17	1.29	1.21	1.19	1.22	1.02	1.22	1.1	1.1	1.11	0.94	1.07	1.07	1.07	1.04
SSI	0	0	0	0	0	0.18	0.18	0.18	0.18	0.18	0.09	0.18	0.14	0.14	0.14	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18

**D, D_{Q2}, We, Rh and Ei in [m³/season]*

DMI, WOI and SSI [ ]

Sp:spring; Su:summer; Au:Autum; Wi:winter; Y: year

APPENDIX E – (Continuation)

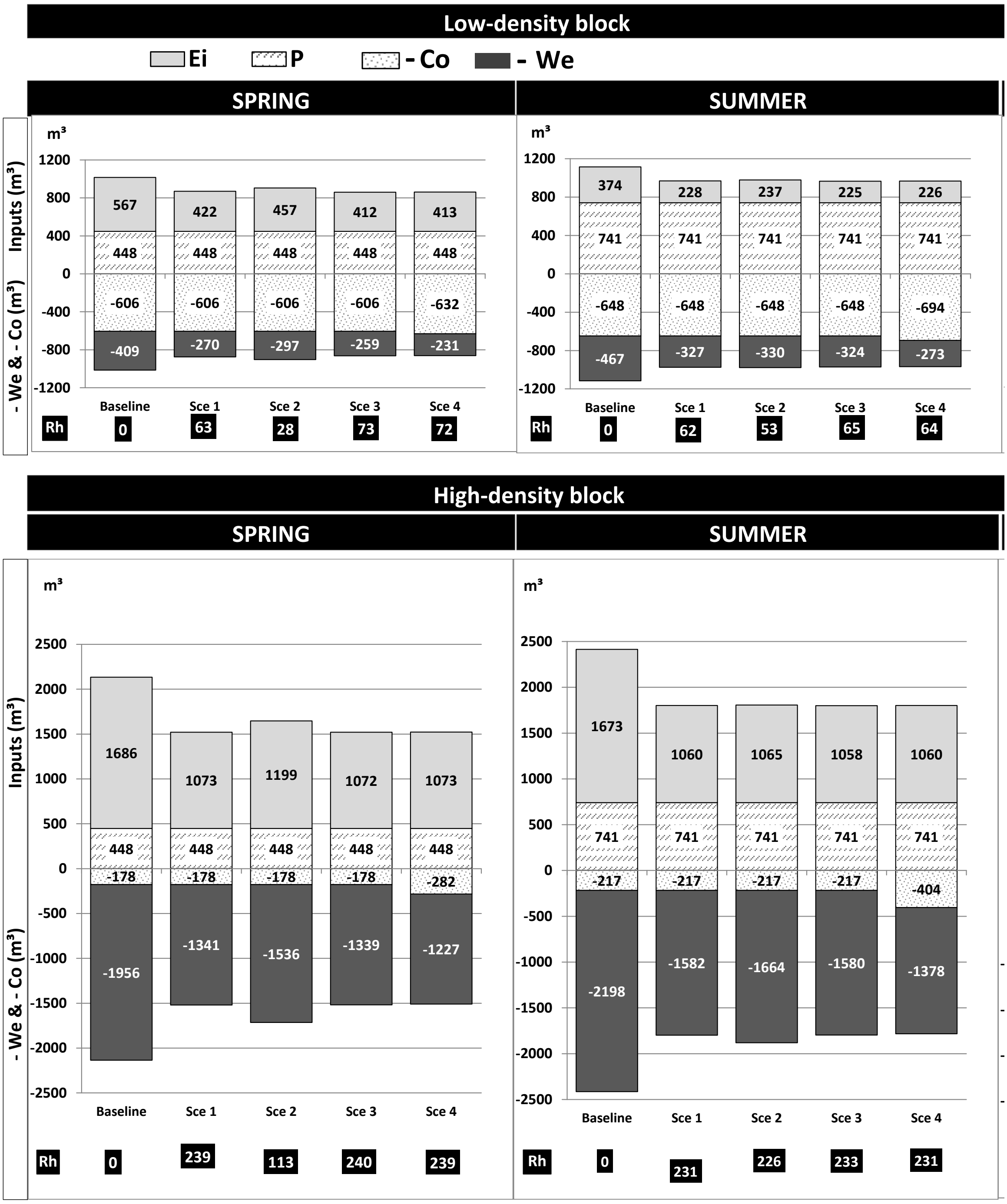
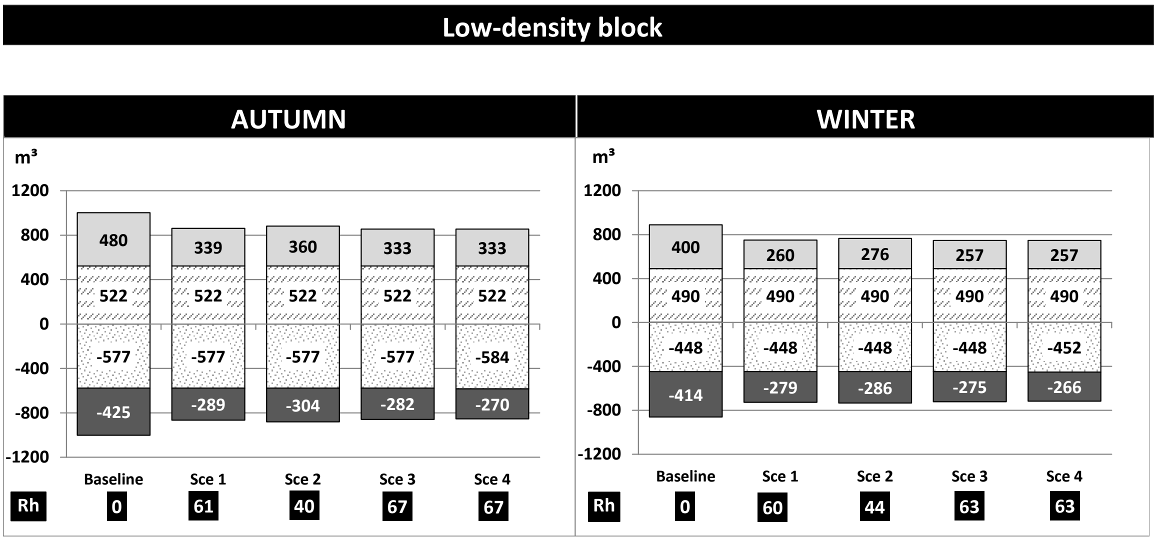
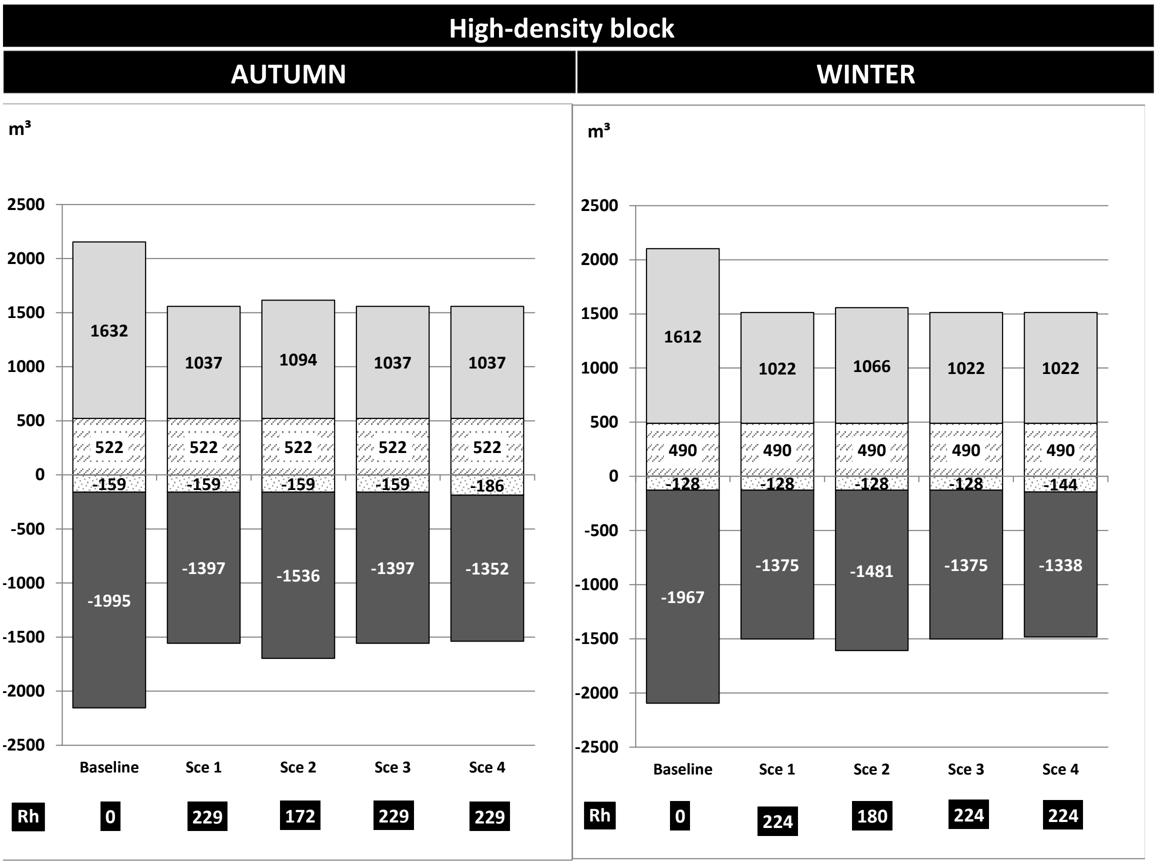


Figure E1 Water balances per season to evaluate the effect of the UHA strategies

APPENDIX E – (Continuation)





Chapter 7

Evaluating the potential of improving the water metabolism at city scale

Abstract

In developed countries, centralized infrastructure is the conventional approach to provide potable water to consumers and to transport wastewater and storm water runoff away from urban areas. Over the last decade, increasing attention has been given to decentralized infrastructures towards improving the urban water balance. However, traditional planning and design approaches are not appropriate for the selection of decentralized systems. This chapter studies the potential of improving urban water balance at city scale by means of decentralized and centralized infrastructure. The city of Wageningen in the Netherlands was studied. Yearly water balances were investigated for each of the neighborhoods. Neighborhoods were classified according the impact level on the water balance. Interactions between spatial scales and the dependence of the system on temporal scales were evaluated to gain insight in the effect of different measures on the urban water balance. Results showed large potentials to optimize the urban water balance by combining decentralized and centralized infrastructure. The decentralized measures included: demand minimization, light grey water recycling, rainwater harvesting, green roofs. The tested centralized measure was rainwater infiltration. Results showed that demand can be minimized by 14% and the city is able to supply 100% of the non-potable water for laundry, toilet and irrigation. Moreover, runoff can be completely minimized. And the waste output can be reduced to 69% of the demand. Furthermore, infiltration and evapotranspiration are enhanced increasing the quality of the urban environment, with respect to water retention and flattening peak temperatures in summer.

This chapter is in preparation as:

Agudelo-Vera, C.M.; Keesman, K.J., Mels, A.R.; Rijnaarts. H.H.M. Evaluating the potential of improving residential water balance at city scale.

7 Harvesting urban resources towards more resilient cities

7.1 *Introduction*

Cities are complex entities. Each urban area is unique in form and functioning due to factors as population density, topography, geology, etc. A city is composed of many heterogeneous "patches" with, for instance, different surfaces, land uses and densities of infrastructures with green, blue and built elements. Traditional approaches for the design of centralized urban infrastructure are top-down approaches. Herein, cities are treated as homogeneous entities, in which consumption of resources such as energy, water and materials and waste production are based on average urban characteristics, such as, average population density and/or household size. Our research shows that generalization of urban areas using yearly averages cannot meet tailored approaches to improve sustainable resource management (Chapter 6). Simulations showed that a dynamic time dependent resource approach at smaller spatial scales is needed especially when optimizing resource efficiency of cities. Previous chapters have shown that building and block type influence the urban water use and waste water production. Moreover, systems dynamics need to be taken into account to properly assess the implementation of a measure, as it is determined by the interactions between spatial scales (e.g. saving devices at building unit influence the supply of centralized drinking water) and the dependence of the system on temporal scales (e.g. day-night or seasonal patterns). The spatial interactions and temporal dependencies provide valuable insight in urban flows and their time and seasonal fluctuations and allow us to evaluate strengths and weaknesses of centralized or decentralized measures for improving resource efficiency.

The Urban Harvest Approach (UHA), as described in Chapter 4, aims to provide guidelines for optimizing resource management in cities. UHA encompasses a qualitative, dynamic multi-scale analysis of inputs and outputs to select the most appropriate scale for interventions that decrease the demand of external resources and the export of waste by supporting urban planning and design. The UHA allows coordination of scales for technology selection and allows coupling of different urban units and blocks. Coupling should not be confused with aggregation. When looking at cities at multiple spatial and temporal scales, productive and "resource-hotspot" areas can be identified. This information is useful for management, planning and design of urban water at city scale. This research studied resource reduction strategies, at different, increasing scales; decentralized at household and building unit scale was studied in Chapter 5, block scale was studied in Chapter 6, followed by decentralized and centralized approaches at city scale in this chapter.

The objective of this chapter is twofold, firstly to test the UHA at city scale and secondly to gain insight into the influence of urban heterogeneity on the water balance in residential areas. In this chapter, we studied the city of Wageningen in the Netherlands. Yearly water balances for the entire city and for each of its nine neighborhoods were investigated based on hourly time steps for different scenarios. The study included a quantitative assessment of different scenarios to improve the residential water balance at city scale, following the hierarchy of measures proposed within the UHA and with focus on changes in the land cover and interactions between neighborhoods and scales.

7.2 The urban water balance

Fig. 1 shows a schematic representation of the urban water system at city level. A general volume balance for a dynamic system with actual amount of water stored (s) reads as:

ds/dt = Inputs – Outputs - Consumption *(1)*

The term *ds/dt* is the change in storage per unit of time, in our case the water volume. We distinguish between five different types of water storage at city scale: surface depression storage (s^i), roof storage (s^{roof}), storage in tank/treatment units ($s^{S\&T}$), storage in the separated storm sewer (s^{SS}) system and storage in the combined sewer (s^{CS}). Decentralized systems ($s^{S\&T}$) can be implemented at single block level or shared by two or more blocks. Although, water is also stored in the subsurface, this storage is considered outside of the system boundary, because usually it is managed at regional level. Thus, *ds/dt* is the change in the sum of volumes of water stored in the different subsystems in a small time interval and divided by the time interval.

At city level in conventional urban systems, there are two main inputs of water: precipitation (*P*) and external inputs (*Ei*) – provided by the drinking water network. There is one waste output, wastewater (*WW). WW* is collected and transported to wastewater treatment plants. There are two main alternative inputs at city scale, namely, recycled wastewater (R_{pot}) and harvested rain water (M_{pot}) from roofs. Runoff from the land surfaces is not harvested for further (re-)use due to quality requirements of re-used water. As described in Chapter 5, we consider two types of residential demand: potable (D_{Q1}) and non-potable (D_{Q2}). D_{Q2} is divided into indoor (D_{Q2}^{ind}) and outdoor (D_{Q2}^{out}). Fig. 1 shows that D_{Q1} is supplied by Ei_{Q1}, thus $Ei_{Q1} = D_{Q1}$ and that $D_{Q2} = D_{Q2}^{ind} + D_{Q2}^{out}$. *Rh* are the resources harvested in the block, that can be used for actual recycling (R_{act}) and actual multi-sourcing (M_{act}). For an isolated block, if $Rh>D$, this will result in overflows. However, if two or more decentralized systems are coupled, exchange of flows is feasible. Thus, if $Rh > D$, then export of secondary resources is feasible ($Er_{Q2}>0$), and in this case, Er_{Q2} is a positive output. In case $Rh \leq D_{Q2}$, import of secondary resources is feasible (Ir_{Q2}). Thus, $D_{Q2} = Ei_{Q2} + Rh + Ir_{Q2} - Er_{Q2}$, with $Ei_{Q2} = Ei_{Q2}^{ind} + Ei_{Q2}^{out}$, and subsequently Ei_{Q2} can be expressed as:

$$Ei_{Q2} = D_{Q2} - Rh - Ir_{Q2} + Er_{Q2} \quad (2)$$

At city level, three main flows are consumed by ecosystem or natural processes: actual evapotranspiration (ET_{act}), infiltration (I) and natural recharge (N_{rec}). ET has a cooling effect in urban areas, I recharges the soil profile and N_{rec} recharges superficial water bodies, hence, $Co=ET + I + N_{rec}$. In this study, we use the Penman-Monteith method (FAO, 1988) to calculate the reference evapotranspiration. And we assumed the reference evapotranspiration as potential evapotranspiration (ET_{pot}). Infiltration is assumed to be constant over the hourly time step. Infiltration at a given time step is a function of the stored water in the permeable surfaces, and with a maximum rate equal to the soil hydraulic conductivity ($I \leq k_{soil}$, both in mm/hr). For more details see Chapter 6.

In this chapter, we focus on water resource management in the built environment. Therefore, we only consider harvesting of rain water from roofs, while non-harvested water is discharged to the sewer. Runoff from the land surfaces is not harvested for further (re-)use due to quality requirements. Runoff is often described using the runoff coefficient (RC). RC is defined as the proportion of rainfall that contributes to runoff from the surface, $RC=Ro/P$ (Butler and Davies, 2000). If there is a separated storm sewer (SS), the runoff (Ro^{SS}) will be collected and discharged into superficial water. If there is overflow from the separated sewer system (O^{SS}), O^{SS} will be discharged into the combined sewer (CS). The runoff of the areas connected to the combined sewer (Ro^{CS}) is collected together with the domestic wastewater (DWW), waste water from industries and business ($WW_{i\&b}$) and eventually overflow from decentralized $S\&T$ units ($O^{S\&T}$). In extreme rainfall events, if there is overflow from the combined sewer system (O^{CS}), O^{CS} will be discharged into surface water. Eq. (1) can be defined for each of the storage units based on Fig. 1. Appendix A shows the balances for each unit and the deduction the city water balance:

$$\frac{ds}{dt} = P^{city} - ET_{act}^{city} - \Sigma I^{i} + Ei_{Q2} + Ir_{Q2} - Er_{Q2} - N_{rec} + WW_{i\&b} - WW + D_{Q1} \quad (3)$$

7.2.1 The UHA at city level

As described in Chapter 4, the Urban Harvest Approach (UHA) consists of three steps: (i) input minimization by implementation of more resource efficient technology; (ii) output minimization by cascading and recycling of flows[18]; and (iii) multi-sourcing of the remaining demand by harvesting local-renewable resources. One of the objectives of the UHA is to reduce external input Ei_{Q2}. Notice from Eq. (2) that $Ei_{Q2,i}$ can be minimized by reducing non-potable water demand D_{Q2} and maximizing Rh and Ir_{Q2} or reducing Er_{Q2}. Additionally within the UHA, waste export should be reduced. The waste exported (We) of the system is equal to WW. From the balance of the domestic sewer (see Fig. 1), the following equality can be derived:

$$WW = DWW + O^{S\&T} + Ro^{CS} + O^{SS} + WW_{i\&b} - O^{CS} \quad (4)$$

[18] Cascading refers to direct reuse of waste flows, meanwhile recycling includes quality upgrading of the flow before reuse. In this paper, to secure quality standards, we will only consider recycling.

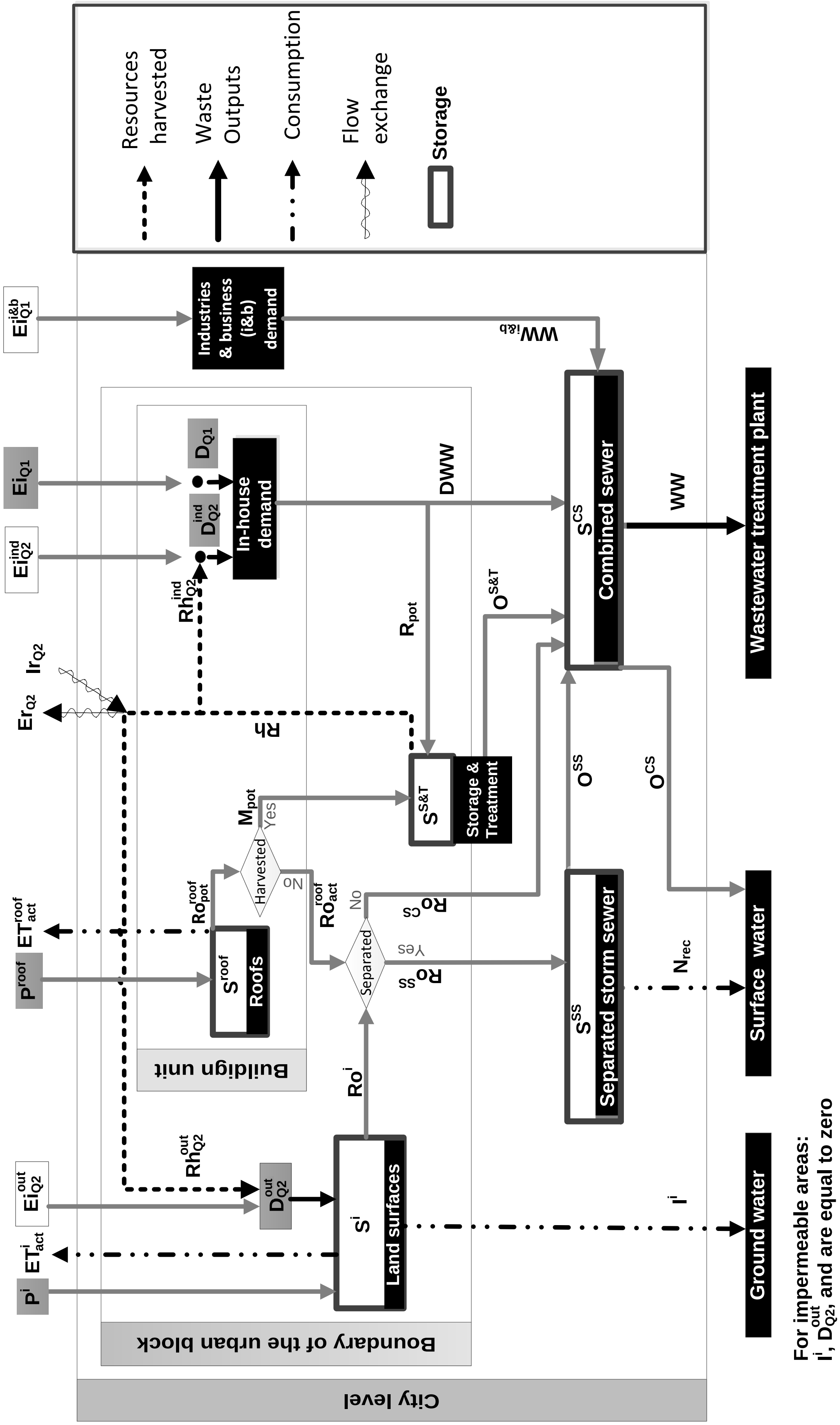


Figure 1 Schematic representation of the urban water system at city level

Hence, to effectively reduce *We*, a combination of measures is needed. These measures include the implementation of water saving devices at the domestic and industrial waste water level (DWW and $WW_{i\&b}$), the choice of optimal storage capacity ($O_{S\&T}$), the selection of permeable materials with larger storage capacities (O^{SS} and O^{CS}) and the disconnection of impermeable surfaces from the domestic sewer system (Ro^{CS} and O^{SS}).

To relate the different variables of the water balance and to evaluate the different measures, the so-called "metabolic profile" is calculated. The metabolic profile is described in terms of the demand ($D=D_{Q1}+D_{Q2}$), the waste exported (*We*), the resources harvested (*Rh*) and the exported resources (Er_{Q2}). The metabolic profile is defined by four indices, i.e. Demand Minimization Index (*DMI*), Waste Output Index (*WOI*), Self-Sufficiency Index (*SSI*), and Resource Export Index (*REI*), as defined in Chapter 4.

$$DMI = \frac{Conventional\ demand\ (D_{con}) - Demand\ (D)}{Conventional\ demand\ (D_{con})} = \frac{D_{con}-D}{D_{con}} \quad (5)$$

Where, D_{con} represents the demand when conventional technologies are implemented, while D is the actual demand.

$$WOI = -\frac{Waste\ exported\ (We)}{Demand\ (D)} = -\frac{WW}{D} = -\frac{DWW+O^{S\&T}+Ro^{CS}+O^{SS}+WW_{i\&b}-O^{CS}}{D} \quad (6)$$

$$SSI = \frac{Resource\ harvested\ for\ local\ supply\ (Rh)}{Demand\ (D)} = \frac{R_{act}+M_{act}-Er_{Q2}}{D} \quad (7)$$

$$REI = \frac{Exported\ resources}{Demand\ (D)} = \frac{Er_{Q2}}{D} \quad (8)$$

7.2.2 Urban characteristics and the urban water balance

In literature, impervious surface coverage is used as a key environmental indicator (Arnold Jr and Gibbons, 1996; Pauleit and Duhme, 2000). The impermeable coverage percentage can be related to the impact level on the water balance in urban areas, as discussed in Chapter 6. We developed a diagram to identify the impact level on the water balance in urban areas based on the land coverage, see Fig. 2. Three impact levels were defined: low, moderate and high. Low, moderate and high are correlated to green, pervious and impervious predominant land cover, respectively. Moreover, impermeability, density and building type can be related by using the transect concept (Duany and Talen, 2002), as shown in the horizontal axis in Fig. 2.

For evaluating the potential harvesting of water in our approach, it is important to consider the total impervious area and the disconnected impervious area (DIA). For the purpose of water balancing in this chapter, DIA includes only those impervious areas that drain into a separated storm sewer. Therefore, an effective runoff coefficient (RC_e) is defined as the proportion of rainfall that is discharged into the combined sewer and becoming waste output. Additional parameters that strongly influence the urban water balance are the soil type and soil compaction degree. Construction activities increase soil compaction and change the soil profile. Thus, more intense development results in surfaces with lower storage capacities and lower hydraulic conductivity (Brabec et al., 2002).

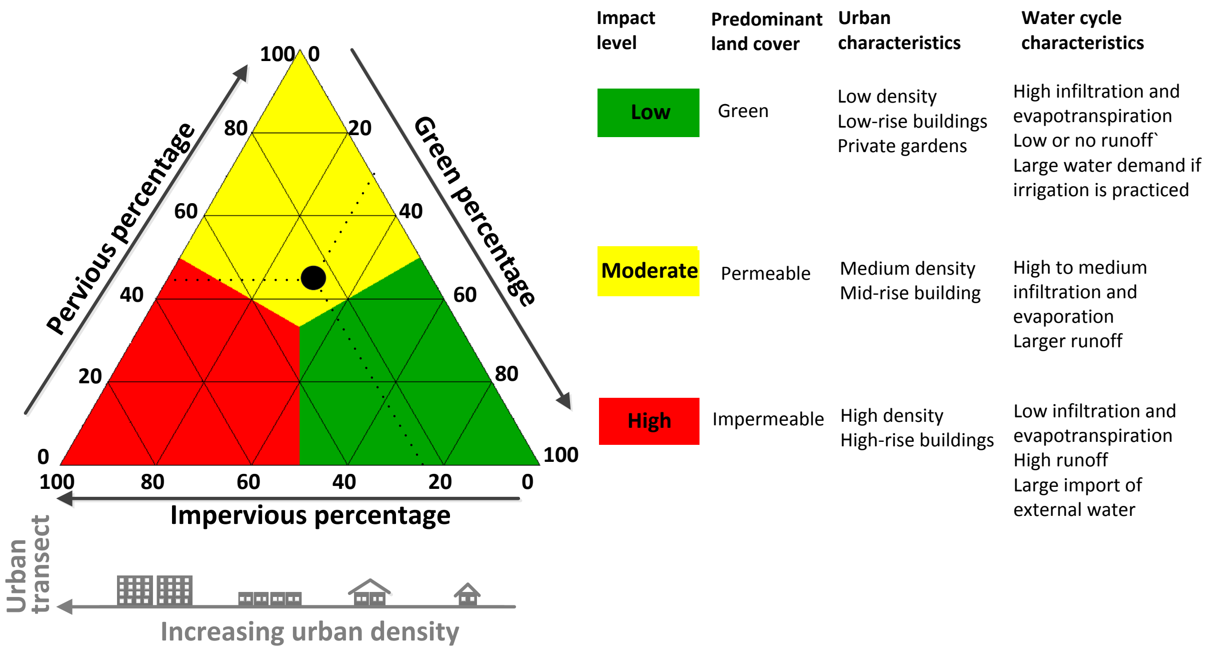


Figure 2 Impact level on the water balance according to land cover.

7.2.3 Case study

In this chapter, the water system of Wageningen, a city in the Netherlands was chosen as a case. Following the UHA, first, we prepared a baseline assessment for each of the neighborhoods of the city. The results are obtained for 2007, as for this year most of the required data were available. The hourly indoor water demand of each of the neighborhoods was simulated using the software SIMDEUM[19] (Blokker et al., 2010). Hourly meteorological data from the meteorological station in Wageningen[20], the Netherlands, were used to determine precipitation and reference evapotranspiration using the Penman-Monteith equation (FAO, 1988). As a first step, a calibration of k_{soil} and S^{green} and the irrigation pattern at city level was performed. Yearly water balances for the city and for each of the nine neighborhoods were modeled. After that, the UHA was implemented by simulating three scenarios in each of the neighborhoods and the results were evaluated. Scenarios included demand minimization combined with light grey water (LGW) recycling, green roofs implementation and rainwater harvesting from roofs. Finally, the potential interaction among neighborhoods was investigated by evaluating the potential of resource exchange within the city. Moreover, linkages between centralized versus decentralized infrastructure were analyzed.

[19] SIMDEUM software was developed by the water cycle institute (KWR), it simulates daily patterns for different household types in The Netherlands.
[20] http://www.met.wau.nl/haarwegdata/

7.3 Results and discussion

This section evaluates some decentralized and centralized options to improve the urban water balance, focusing on residential demand. In literature, increasing attention is given to the dichotomy centralization – decentralization in urban water systems (Libralato et al., 2012; Makropoulos and Butler, 2010). In practice, one approach cannot exclude the other and vice versa. There are several options available for water infrastructure at city level. Makropoulos and Butler (2010) provide a summary of the available options. Each type is substantially related to the characteristics and volumes of wastewater to be treated, as well as to the possibility of flow separation at source (Libralato et al., 2012). Table 1 provides information of the location of the city and relevant characteristics of each of the neighborhoods.

7.3.1 Model calibration

In cities, monitoring data on volumes and quality of the water flows is usually limited. Moreover, in most cases the monitored flows are sampled with a different frequency. For our case study, the following information was available: yearly external water input (*Ei*) provided by the Drinking Water Company, hourly precipitation data (*P*) and daily inflow to the wastewater treatment plant (*WW*). First, a theoretical water balance was prepared, with the known a priori information. N_{rec} was calculated assuming that 30% of impermeable surfaces are disconnected from the domestic sewer system. Consequently, the sum of evapotranspiration and infiltration (*ET+I*) was deduced from the difference of the other flows, see Fig. 3.

In this case, both *ET* and *I* are unknown in the water balance. One equation with more than one unknowns can have an infinite number of solutions because different combinations of values can give a similar result. Consequently, more information is needed. For our case study, additional assumptions were necessary. Values for potential evapotranspiration were assumed based on reference evapotranspiration calculated by using the Penman-Monteith equations. The model was calibrated using an hourly water balance as described in the previous chapter. Using SIMDEUM software, a yearly indoor demand pattern with hourly time step was generated. The different variables were calibrated using the daily wastewater flow monitored in the Wageningen wastewater treatment plant located in Renkum. The calibrated model is shown in Fig. 3. The assumptions mentioned in Fig. 3 are used for further analysis. A water balance sensitivity analysis towards changes in the precipitation and changes in k_{soil} and S^{green} is shown in appendix B.

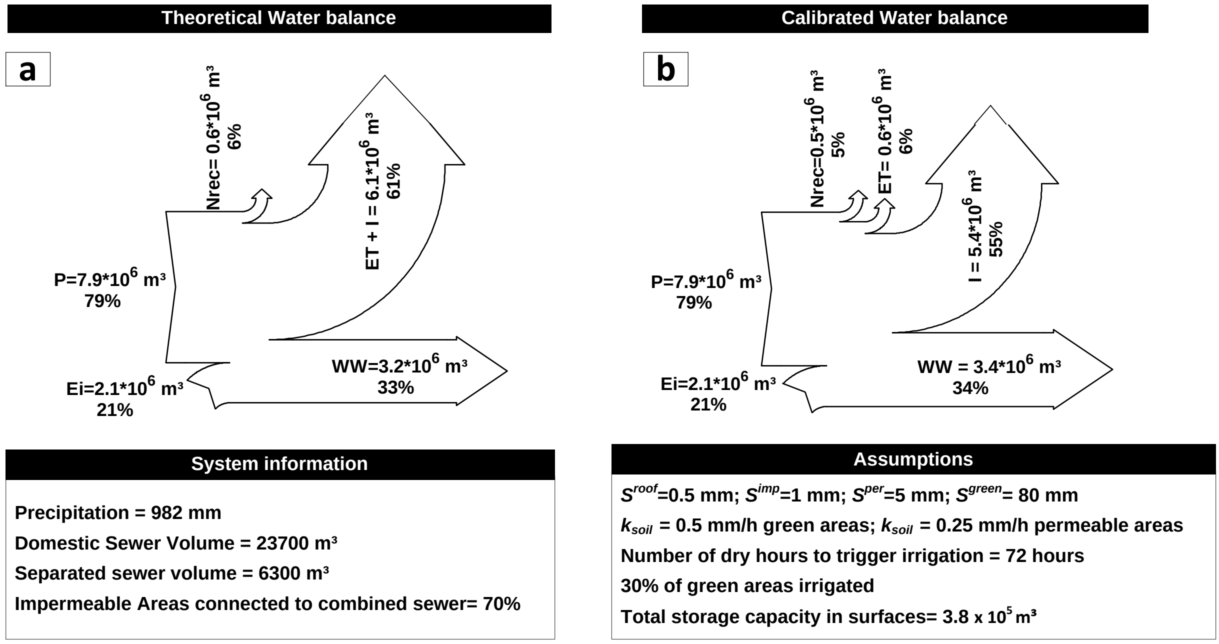


Figure 3 Theoretical (a) and calibrated (b) model representing the annual water balance for the city of Wageningen in 2007.

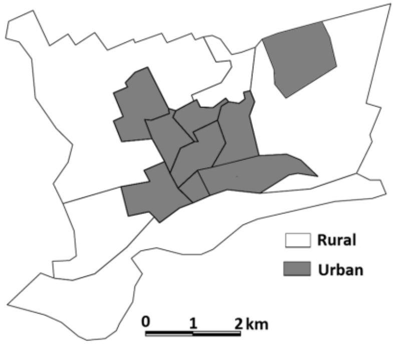
In urban drainage models, there are many sources of uncertainty that interact non-linearly in the modeling process (Deletic et al., 2011). Differences between the theoretical and the calibrated water balance can be explained by three main factors: uncertainties in the flows (volumes), neglected flows and assumptions in the model. Uncertainties in the data are, for example, lack of accuracy of urban evapotranspiration data. Another uncertainty is the lack of knowledge about the irrigation patterns of green areas, as well as the daily demand patterns of industries and business. Neglected flows are, for instance, the presence of leakages in the distribution or in the sewer system and infiltration of groundwater in the sewer. Errors related to assumptions in the model are, for instance, simplified infiltration processes, the assumption of a constant gravity flow in the sewer[21] and neglecting topographical factors. Moreover, at city level, we assume that the hydraulic conductivity k_{soil} and S^{green} are homogenous.

[21] In reality, water is pumped in certain points of the sewer network.

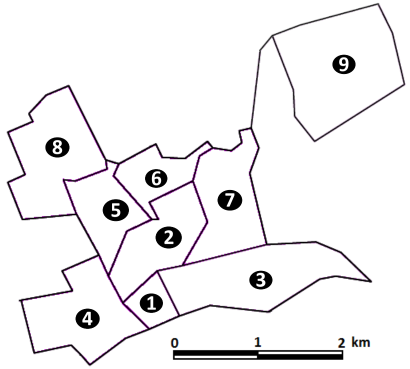
Table 1 Location and detailed information of the studied neighborhoods

The Netherlands

Gelderland Province



Wageningen



Id	Neighborhood	Inhabitants	Area (ha)	Impervious Roof %	Impervious surfaces %	Pervious %	Green %	Number of hh	hh size	Pop. density (p/ha)
1	Oude Stad Binnenstad	1880	23	31	23	29	17	1490	1.3	81.7
2	Wageningen-Noord	5660	81	19	15	48	18	3000	1.9	69.9
3	Wageningen-Oost	2920	130	12	14	15	59	1480	1.9	22.5
4	Wageningen-West	3980	100	15	12	22	51	2710	1.4	39.8
5	Wageningen-Noordwest	4250	64	16	12	22	50	2500	1.7	66.4
6	Tarthorst-Roghorst-Haverlanden	4850	46	15	17	34	34	3130	1.5	105.4
7	Wageningen-Noordoost	4420	93	13	12	11	64	2440	1.8	47.5
8	Uitbreidingsplan-Noordwest	4640	107	8	12	8	72	1610	2.9	43.4
9	Wageningen Hoog	1180	158	5	7	0	88	530	2.2	7.5
	Total Urban area	33780	802	12	13	17	58	18890	1.8	42.2

Source: 2008, CBS, Gemeente op maat

7.3.2 Decentralized measures to improve the urban water balance

Each neighborhood was classified according the impact level of land cover on the water balance, see Fig. 4a-b. Looking at the city of Wageningen as a whole, the water balance has a low impact level. However, at neighborhood scale, some “hot-spots” can be identified. Hot-spots are defined as areas with large resources demand and large waste production. Areas with a high level of impact, e.g. neighborhood 1, are identified as hot-spots, because they are related to large runoff and high densities. Fig. 4c shows the water balance baseline per neighborhood. As expected, the baseline assessment showed noticeable differences in the water balance related to the characteristics of the neighborhoods. The differences are mainly due to variations in the land cover, neighborhood size and density. To facilitate comparison, the water balance per neighborhood was recalculated per hectare, (Fig. 4d) and per person, (Fig. 4e). The water balance per hectare shows that neighborhood 6 is also a hot-spot. Neighborhood 6 has the largest amount of inputs and outputs per hectare (16100 m^3-year/ha), almost 30% larger than the average value for the city (12500 m^3-year/ha). Recalculating the water balance per person shows large differences in the demand per person. Especially neighborhood 9 has a high demand, i.e. the double of the average for the city due to irrigation of green areas, while available precipitation per person is approximately 10 times the demand. These variations of the water balance within the city suggest that for improving the urban water balance, customized solutions should be selected based on neighborhood characteristics.

To further investigate the effect of the urban heterogeneities on the water balance, we focused on three neighborhoods. The selected neighborhoods were 1, 2 and 9; each one with a different impact level. Fig. 5 shows the land cover of the three selected neighborhoods. Three scenarios were defined based on results from Chapter 6: LGW recycling, green roofs and rainwater harvesting, all combined with demand minimization, see Table 2. We investigated the influence of the neighborhood characteristics on the efficiency of the scenarios. Fig. 6 shows the results for the three selected neighborhoods per hectare. The positive vertical axis represents the inputs, (P and Ei). The negative vertical axis represents the exported waste outputs (We) and the consumption (Co). We is the sum of WW and O^{CS}. And Co is the sum of I and N_{rec}. Appendix C shows the results recalculated per person.

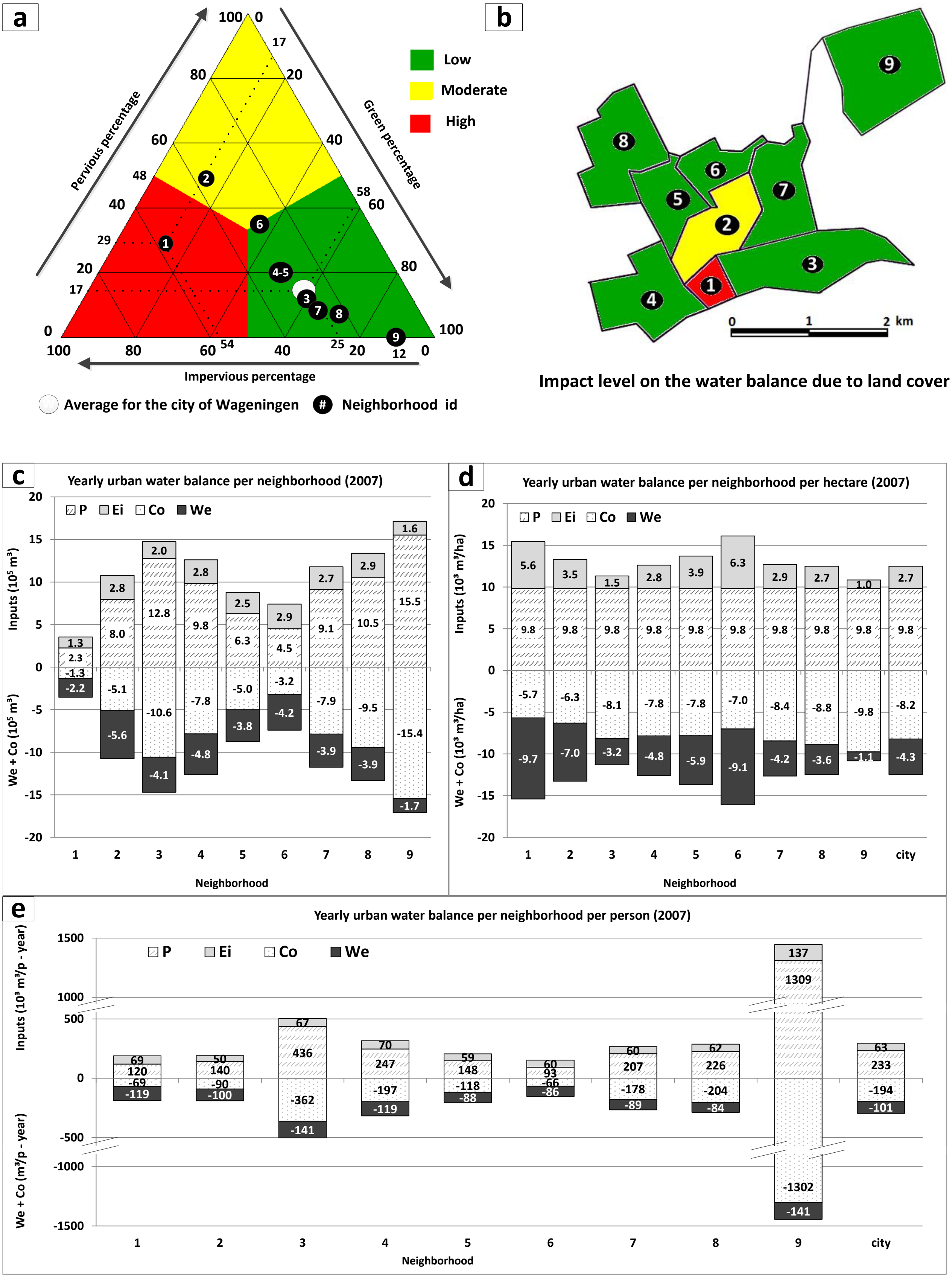


Figure 4 (a-b) Classification of each of the neighborhoods according to the level of impact on the water balance. c) Baseline water balance for each of the neighborhoods. d) Normalization per hectare. e) Normalization per person. Precipitation (P), External input (Ei), Consumption (Co) and Waste exported (We)

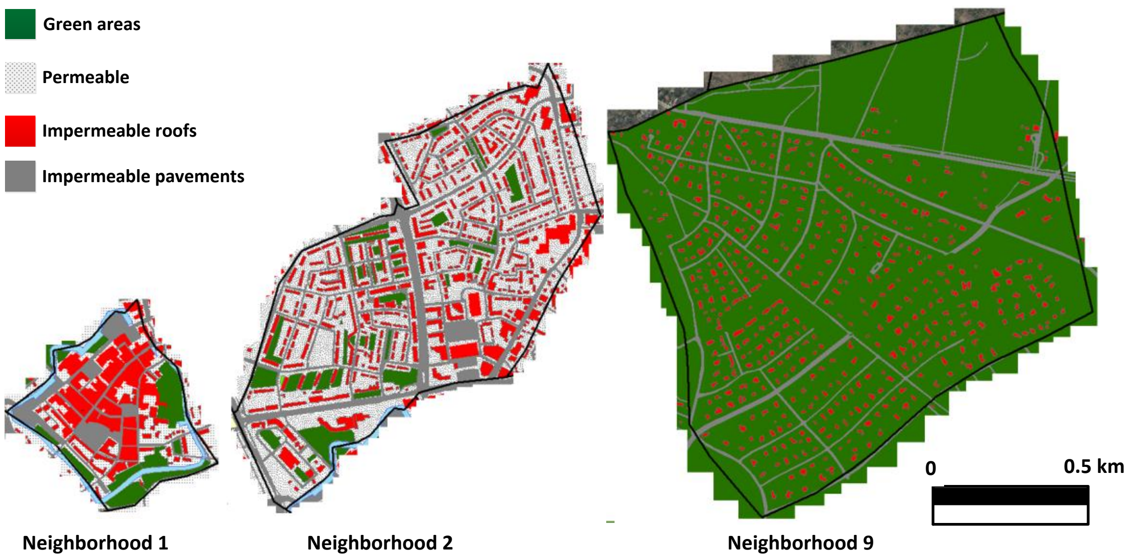


Figure 5 Land cover of the three selected neighborhoods

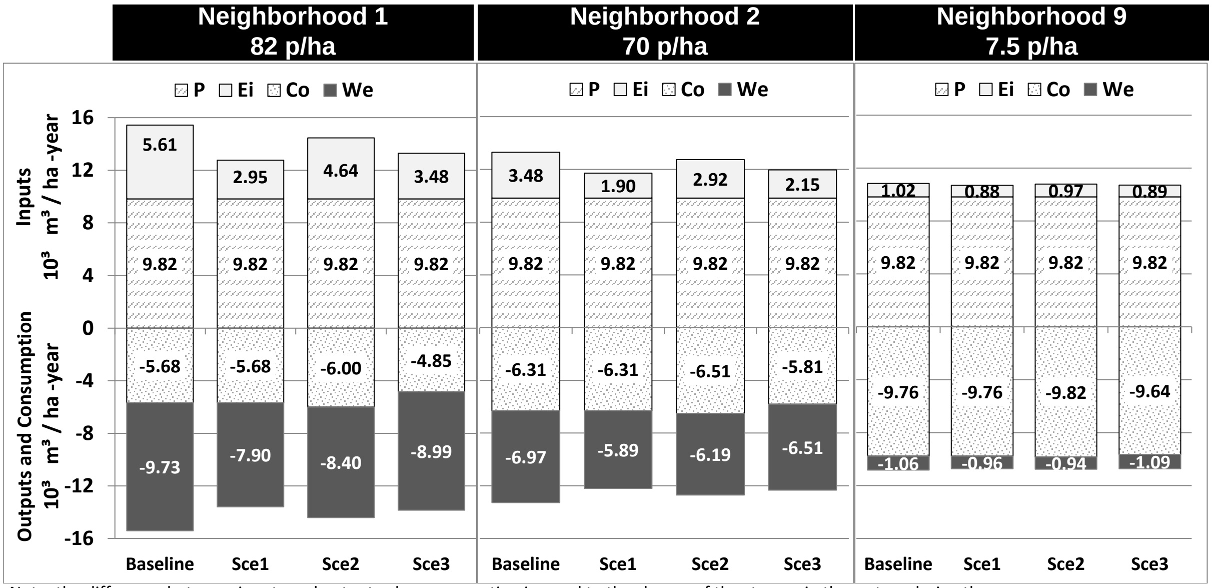
Table 2 Overview of the scenarios studied in this chapter

Sce 1. Demand Minimization + Recycling of LGW for D_{DQ2}
20% minimization of D^{ind} and recycling of LGW for toilet, laundry and D^{out}_{DQ2}
$R_{pot} = 0.45 * D^{ind}_{minimized}$; $D_{Q2} = 0.2 * D^{ind}_{minimized} + D^{out}_{DQ2}$
Storage: grey water of 5 l per person; treated grey water 20 l per person
Treatment unit: 40 l per person – (assumed 1 day hydraulic retention time)
Sce 2. Demand Minimization + Green roofs
20% minimization of D^{ind} + Green roofs with a storage capacity of 10 mm.
Sce 3. Demand Minimization + Rain water harvesting for D_{DQ2}
20% minimization of D^{ind} and Multi-sourcing rain water for toilet, laundry and D^{out}_{DQ2}
$D_{Q2} = 0.2 * D^{ind}_{minimized} + D^{out}_{DQ2}$. One storage tank: 140 l per person

LGW: Light Grey Water from shower and bath; storage capacity and treatment rates are based on Chapter 6.

The results showed that different measures have different efficiency in each of the neighborhoods. For neighborhood 1, which is a hot-spot, the different scenarios showed evident reductions in external input (*Ei*) and waste exported (*We*). Meanwhile for neighborhood 9, there is less room for improvement, due to the already low impact level. The results of the dynamic model scenario calculations are discussed below using the results of Fig. 6.

For demand minimization and LGW recycling (Sce 1), there was a reduction in *Ei* of 48%, 46% and 5%, for the neighborhoods 1, 2 and 9, respectively. Meanwhile, *We* was decreased by 19%, 16% and 9% for the neighborhoods 1, 2 and 9, respectively. The results showed that efficiency gains of recycling are larger at higher densities. This is due to the fact that in highly dense areas the water balance is dominated by human-driven flows.



Note: the difference between inputs and outputs plus consumption is equal to the change of the storage in the system during the year

Sce 1. Demand minimization + LGW recycling | **Sce 2. Demand minimization + Green roofs** | **Sce 3. Demand minimization + Rainwater harvesting**

	Neighborhood 1				Neighborhood 2				Neighborhood 9			
10³ m³ / ha	**Baseline**	**Sce1**	**Sce2**	**Sce3**	**Baseline**	**Sce1**	**Sce2**	**Sce3**	**Baseline**	**Sce1**	**Sce2**	**Sce3**
$D + D^{i\&b}$	5.61	4.64	4.64	4.64	3.48	2.92	2.92	2.92	1.02	0.97	0.97	0.97
D^{ind}	4.87	3.89	3.89	3.89	2.82	2.26	2.26	2.26	0.26	0.21	0.21	0.21
D^{out}_{Q2}	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.71	0.71	0.71	0.71
D_{Q2}	1.11	0.92	0.92	0.92	0.71	0.59	0.59	0.59	0.76	0.75	0.75	0.75
Rh	0.00	0.84	0.00	0.58	0.00	0.51	0.00	0.39	0.00	0.05	0.00	0.04
Runoff												
RC [-]	0.58	0.58	0.53	0.30	0.46	0.46	0.43	0.29	0.11	0.11	0.10	0.06
RC_e [-]	0.43	0.43	0.40	0.24	0.37	0.37	0.35	0.25	0.08	0.08	0.07	0.04
Metabolic profile [-]												
DMI	0.00	0.17	0.17	0.17	0.00	0.16	0.16	0.16	0.00	0.05	0.05	0.05
WOI	-1.73	-1.70	-1.81	-1.94	-2.00	-2.02	-2.12	-2.23	-1.03	-0.98	-0.97	-1.12
SSI	0.00	0.18	0.00	0.13	0.00	0.18	0.00	0.13	0.00	0.05	0.00	0.04
REI_{pot}	0.00	0.19	0.00	0.47	0.00	0.17	0.00	0.44	0.00	0.05	0.00	0.44

Figure 6 Effect of different scenarios for three neighborhoods, values per hectare for the year 2007. All the scenarios consider demand minimization

For demand minimization and green roofs implementation (Sce 2), there was a reduction in *Ei* of 18%, 17% and 5%, for the neighborhoods 1, 2 and 9, respectively. Meanwhile, *We* was decreased by 13%, 11% and 10% for the neighborhoods 1, 2 and 9, respectively. For this scenario the reduction of *Ei* is due to demand minimization. Meanwhile, the reduction on *We* is due to the increment in the storage capacity of the roofs, which, minimizes the runoff and enhances evapotranspiration. These results also indicate that the contribution of demand minimization to a better balance increases with increasing density. Meanwhile, green roofs reduced approximately the waste outflow of the neighborhoods by 10%.

For demand minimization and rainwater harvesting (Sce 3), there was a reduction in *Ei* of 38%, 16% and 5%, for the neighborhoods 1, 2 and 9, respectively. Meanwhile, *We* was decreased by 8%, 7% and 3% for the neighborhoods 1, 2 and 9, respectively. This shows that although there is a significant amount of rainwater available, only a percentage can be harvested and used to supply D_{Q2}. Restrictions to harvest rainwater are given by the roof area, by the temporal variations (peaks) of the rainfall, by the temporal variations of the D_{Q2} and by the restrictions given by the storage capacity ($S^{S\&T}$).

Fig. 6 show a difference of one order of magnitude of resources harvested (*Rh*) per hectare for neighborhoods 1 and 9. This indicates that high dense areas can become producers and exporters of secondary resources while low dense areas can become importers. The results also show that there are significant overflows from the storage units ($O^{S\&T}$) in Sce 1 and 3. Overflows are resources surpluses. These overflows are important factors to further optimize the system. The surpluses could be harvested and exported as secondary resources (*Er*), resulting in *We* minimization. In Fig. 6, the potential resource export index (REI_{pot}) indicates the amount of resources available to be exported.

Comparing the three scenarios, we observed that the efficiency of measures is determined by the characteristics of the neighborhoods, i.e. population (or housing) density and land coverage. Fig. 7 shows the variability of each of the scenarios, the bars show the average value for the city per hectare, and the lines show the variations found in the three studied neighborhoods. These results are for a specific year, 2007. Therefore, inter-annual variability of precipitation is not considered.

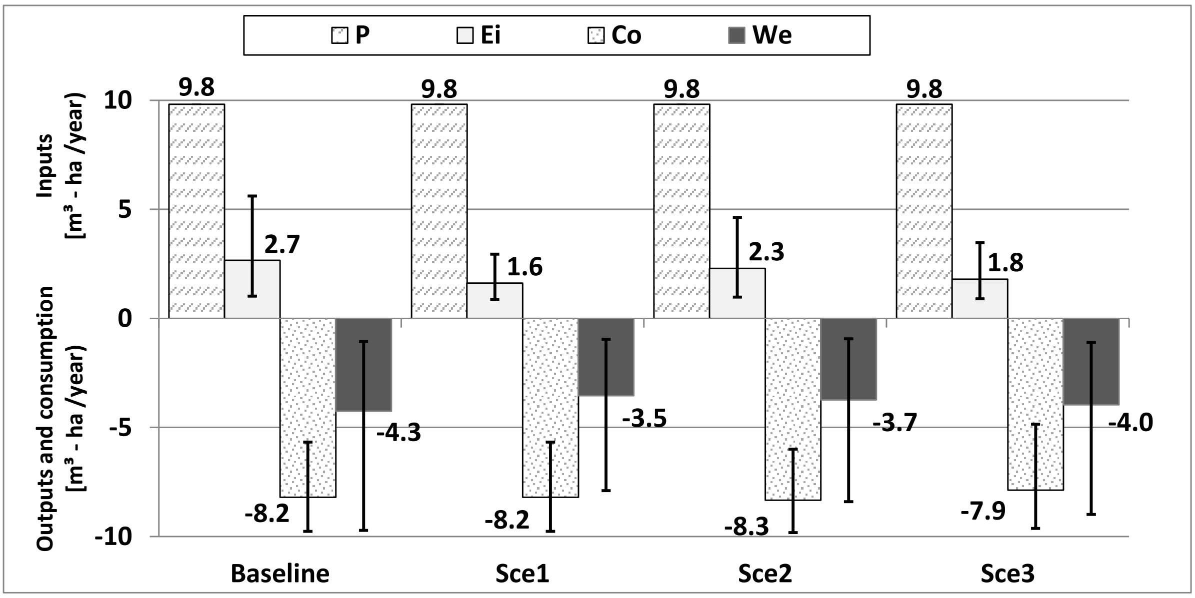


Figure 7 Average values per hectare for the city of Wageningen (bars) and the range of variation of the studied neighborhoods for the baseline and the three scenarios for the year 2007

Fig. 8 shows the metabolic indices for the three neighborhoods and for the three scenarios without (a-c) and with (d-f) export of resources. From Fig. 8 (a-b), scenario one is the best option for the neighborhoods 1 and 2 because it has the highest *SSI* and the highest *WOI*. This confirms that recycling is a crucial measure towards improving urban water metabolism. Fig. 8c shows small differences in the metabolism of neighborhood 9. If resources are exported, *REI* > 0, there is an improvement in the *WOI*. Fig. 8 (d-f) shows that if export of resources is possible, additional improvements in the metabolic profile are achieved. Moreover, we can see that highly dense areas, neighborhood 1 and 2, can export treated LGW (Sce 1) or harvested rainwater (Sce 3). Meanwhile for the Neighborhood 9 only harvested rainwater is valuable to be exported, LGW recycling (Sce 1) only represents 5% of the neighborhood demand.

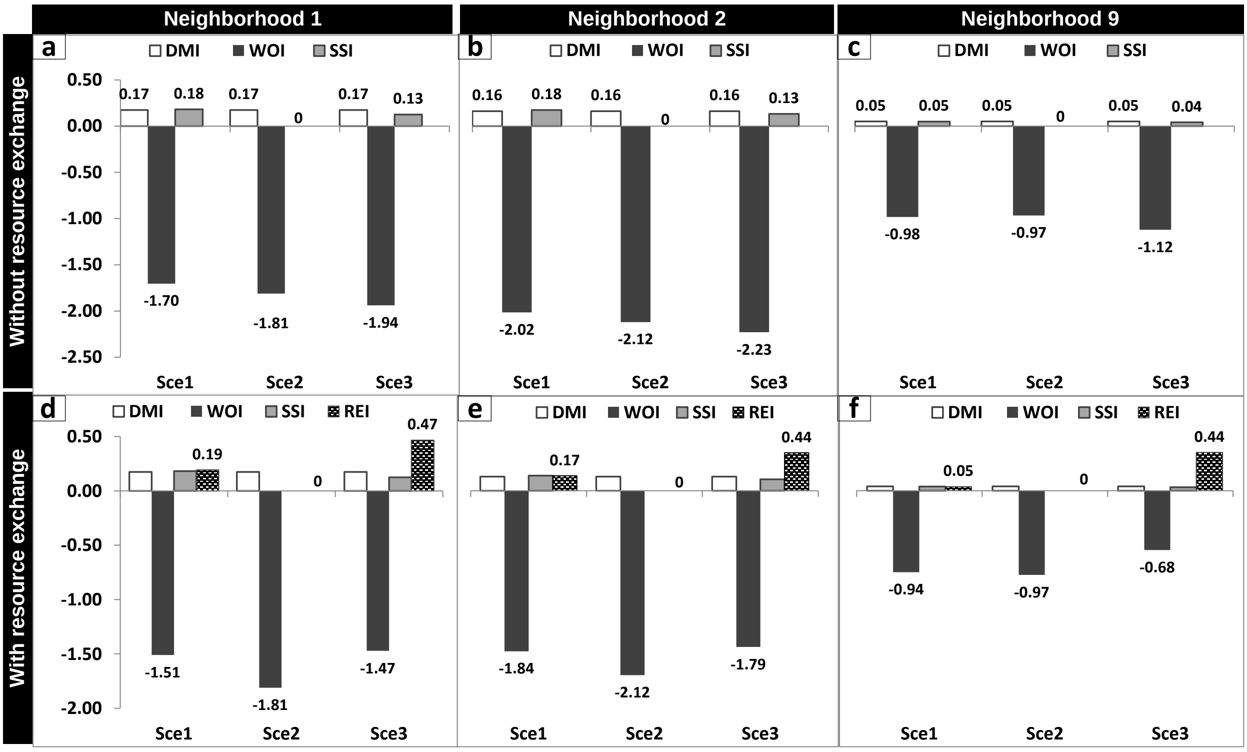


Figure 8 Effect of different scenarios for three neighborhoods and for the city, values per hectare for the year 2007. All the scenarios consider demand minimization

A large percentage of the waste output of cities is runoff. Runoff coefficient (*RC*) is often related to land use function or to the impermeable percentages degree of the surface. Although for the baseline and Sce 1, the average *RC* for the city is 0.28, *RC* varies from 0.11 to 0.58 within the city. Runoff has four pathways, *i*) being harvested, *ii*) being retained or infiltrated, *iii*) going to the combined sewer system, or *iv*) going to a separated sewer system. Studies have shown that runoff from urban areas is one of the major causes of water quality degradation in surface waters (Hatt et al., 2004). Many Dutch cities have already adopted runoff minimization as a measure to improve surface water quality and reduce sewer overflows. Runoff minimization is achieved by harvesting, retaining or infiltrating rainwater, as in scenarios two and three, in which *RC* is reduced. Fig. 9 shows the daily wastewater production for the baseline and for the three scenarios. Although visible benefits are achieved during dry periods, the measures are not enough to fully cancel the high peak flows during heavy rainfall. To reduce these peak flows, infrastructure at a larger scale is needed. Special attention should be given to the disconnected impermeable areas, because typically a part of the runoff from these areas is collected in the combined sewer, effective runoff coefficient (RC_e). In the city of Wageningen, 70% of the impermeable areas are connected to the combined sewer system. In order to minimize RC_e, changes in the percentage of connected impermeable areas are needed. Connection of impermeable areas to the sewer is often managed at city level. Hence, measures at block level should be complemented with measures at city scale.

7.3.3 Centralized measures to improve the urban water balance

In developed countries, centralized infrastructure is the conventional approach to provide potable water to consumers and to transport wastewater and storm water runoff away from urban areas. For areas where water resources are scarce, centralized infrastructure can be used to improve self-sufficiency, e.g. via large scale wastewater reclamation for non-potable use, or seawater desalination for potable use (drinkable standard). However, wastewater reclamation needs a multi-stage treatment and desalinated water use is generally limited to coastal and brackish groundwater containing areas, and it has – at this moment – high energy costs and produces residual brine (Makropoulos and Butler, 2010). Some more energy efficient and zero liquid discharge desalinization technologies are being developed (Rijnaarts et al., 2011). Nevertheless, we argue that decentralized LGW recycling and re-use will yield more benefits, because in addition to increasing the self-sufficiency, it reduces the waste output.

Waste output minimization at city level can be achieved by recycling waste streams (as discussed in previous chapters), by increasing consumption coupled to natural outlets (*I*, *ET* or N_{rec}) and by exporting secondary resources (*Er*). For example, increase of *I*, *ET* and N_{rec} can be achieved by increasing surface storage (e.g. increasing green and permeable areas percentage) or disconnecting the impermeable areas from the domestic sewer. Disconnecting the impermeable areas implies either a large separated sewer system or retention and infiltration infrastructures. If urban runoff is collected in the combined sewer system, dilution of the domestic water and large peaks will decrease treatment efficiency at the wastewater treatment plant. If untreated runoff is discharged into surface water, it releases unwanted pollutants into the environment. Therefore, retention and infiltration are preferred over increasing sewer capacity. This preference is also reflected in the recent developments on sustainable urban drainage systems (SUDS).

The storage capacity needed to reduce runoff was investigated for the city of Wageningen. To simulate a wet year, the precipitation of 2007 was increased by a factor of 1.1. Different storage capacities were assumed by varying the percentage of the total area allocated for retention and infiltration from 1% to 10% and varying the storage depth[22] from 1 mm to 250 mm. Results shown in Fig. 10 demonstrate that there are several options to minimize runoff in a wet year, for instance by allocating 4% of the area for infiltration in case the storage depth is 200 mm or 8% of the area with a storage depth of 100 mm. In both cases runoff approaches a value zero, as indicated in Fig. 10.

Exporting secondary resources (*Er*) can refer to export between neighborhoods or from the city to peri-urban areas. In the case study, there is a mismatch between demand of secondary resources and production of secondary resources, because production of LGW is larger than D_{Q2}. Resource exchange is a win-win situation because the exporter minimizes its waste and the importer minimizes its external input of potable water.

Thus, to optimize the urban water balance a combination of decentralized and centralized measures is required. Fig. 11 shows the optimization of the water balance for the city of Wageningen for the year 2007. Results showed potential of providing 100% of D_{Q2}, which represents 34% of the total demand. Additionally, there is a resource surplus, which can be exported to peri-urban areas. By implementing green roofs and harvesting rainwater, runoff is reduced from 2710 m³/ha to 910 m³/ha. Therefore, centralized infiltration facilities are feasible to manage the remaining runoff.

7.3.4 General discussion

From the point of view of resource management, a decentralized infrastructure allows to implement customized measures for different parts of the city, which can enable exchange of flows between neighborhoods. For instance, a high density area can become an exporter of secondary resources; meanwhile a low density area can become an importer of secondary resources. Moreover, resources surpluses can foster development of new functions within the urban area, e.g. urban agriculture, without exerting additional pressures on the water balance.

Another option to further improve the urban water balance is to close the water balance of water consuming private sector activities, e.g. laundries or car wash facilities, by implementing decentralized measures. Decentralized recycling technologies for laundry services have been successfully tested. Results showed that by using a membrane bioreactor and reverse osmosis treatment, up to 90% of the water demand of the laundry service was recycled on-site (Hoinkis and Panten, 2008). Another option at city scale is rainwater utilization using precipitation runoffs from traffic surfaces. Nolde, (2007) has shown the feasibility of treatment of rainwater runoff for use in

[22] Storage depth refers to the effective storage depth, therefore the total depth of the infiltration area will be given by the porosity of the soil and it will be larger than the storage depth.

irrigation or toilet flushing using a substrate filter (aerobic biological treatment) and UV disinfection.

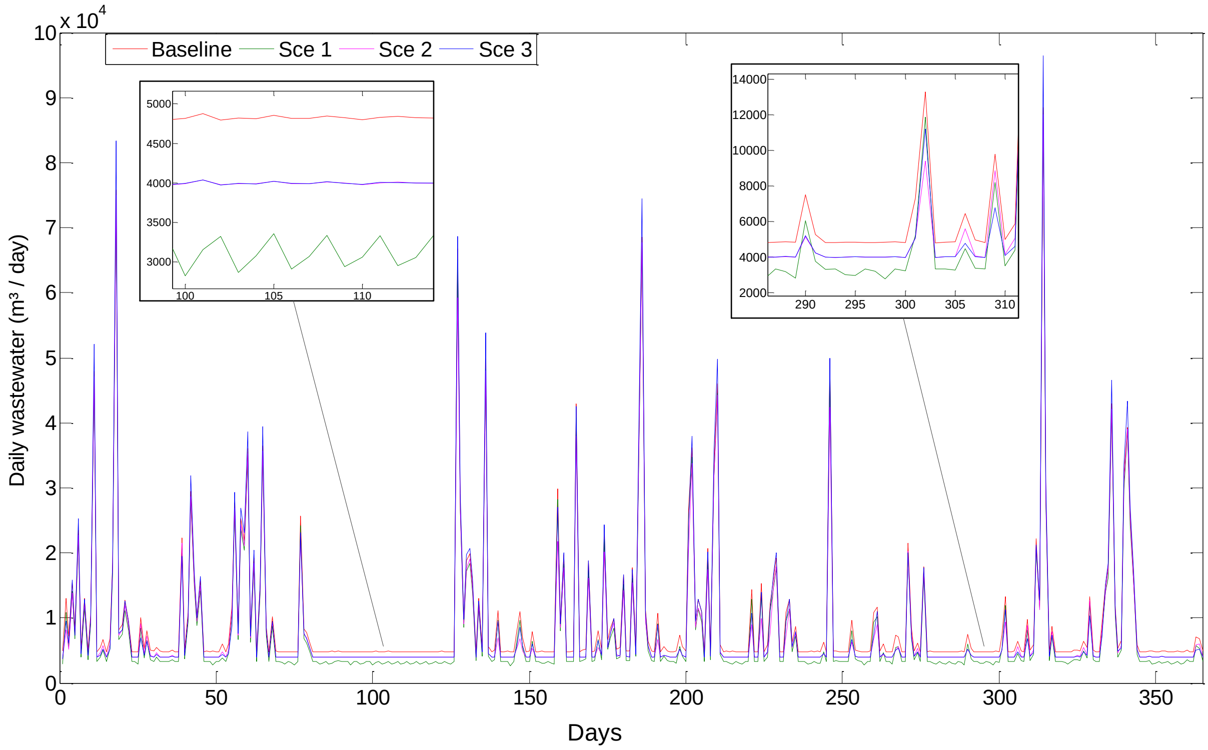


Figure 9 Daily wastewater production for the city of Wageningen year 2007 (baseline) and for three selected scenarios

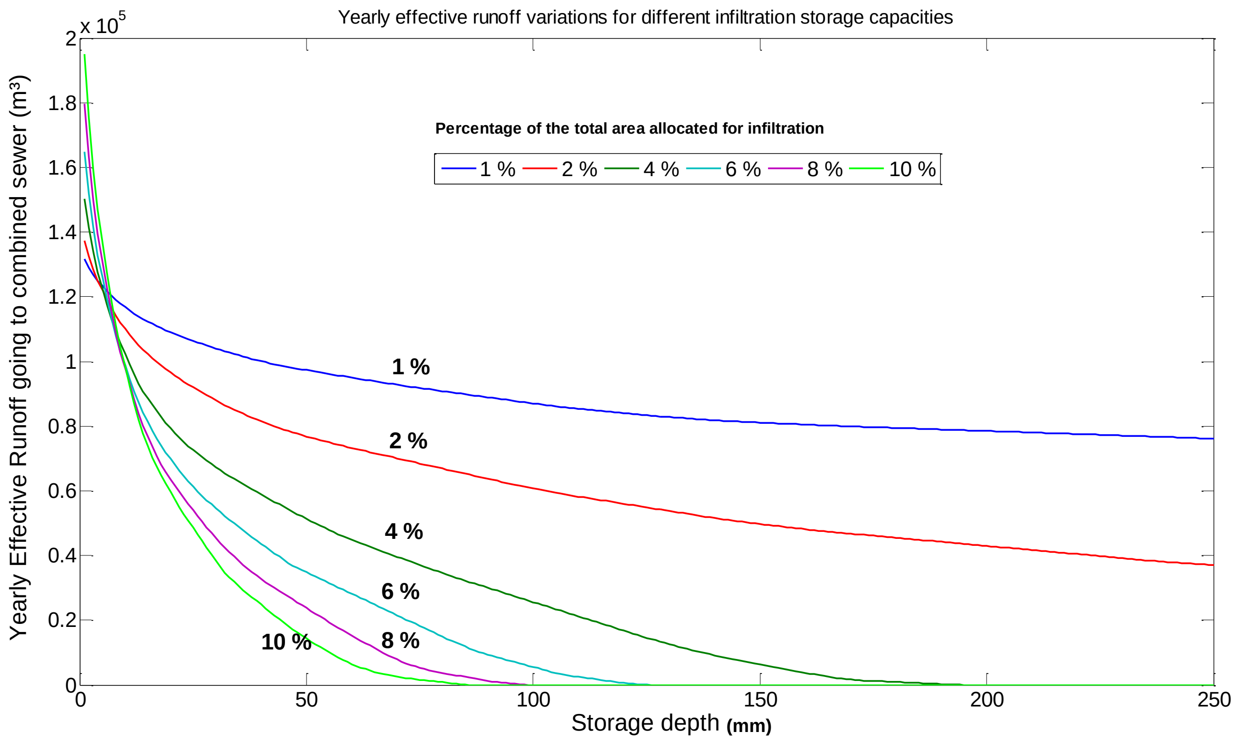


Figure 10 Storage capacity versus effective runoff at city scale

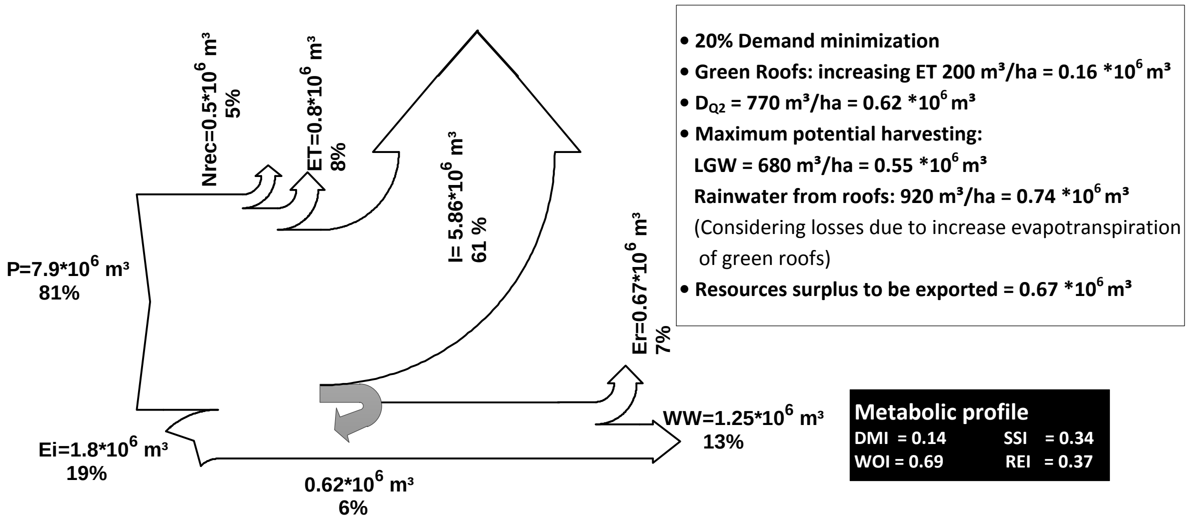


Figure 11 Towards an optimized water balance for the city of Wageningen, year 2007

Since cities are dynamic complex systems, it is important to consider the effect of decentralized infrastructure in the overall metabolism of the city in order to avoid negative side effects. Multi-scale analysis helps to identify whether problems are being shifted to another part of the system. For instance, when rainwater harvesting is implemented, peak flows may result in overflow in the treatment and storage unit ($O_2^{S\&T}$). Such an overflow would become a waste output. This negative side effect can be reduced by implementing active control devices in the system. By active control, the rainwater collection during extreme rainfall events can be disconnected. Therefore the excess water will be collected by the separated sewer system or by the retention and infiltration infrastructure. Fig. 12 shows the proposed arrangement for managing urban runoff.

The results show that significant efficiency improvements in the urban water balance are possible by implementing a combination of decentralized measures. Complete optimization of the water balance (SSI=1 and WOI=0) is technologically feasible, e.g. production of potable water by advanced membrane filtration or indirect wastewater reuse: infiltration of treated wastewater for later abstraction (and treatment) for potable use. However, implementing these measures implies additional energy consumption at decentralized scale, for treatment and pumping. This will require additional energy studies to identify optimal scales for treatment and transport. These studies should consider the energy consumption in the different steps, from the production of potable water to the disposal of the outputs.

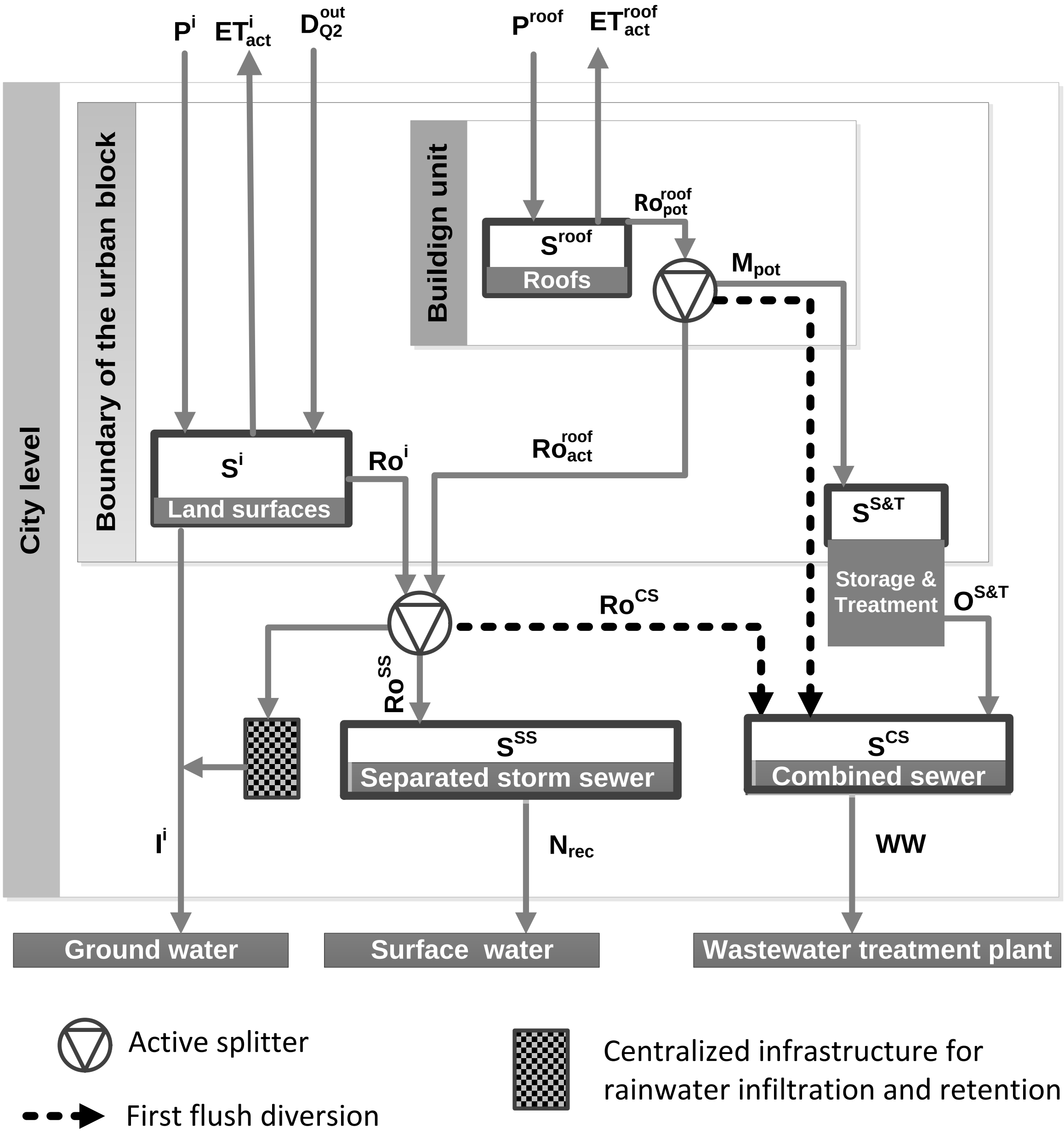


Figure 12 Proposed arrangement for managing urban runoff

Fig. 13 shows the changes in the indices at city scale for selected measures. These results show that a combination of centralized and decentralized infrastructure can improve the urban water management. Urban water systems are often discussed at two levels: decentralized scale (i.e. building and neighborhood level) or centralized scale. Single scale analysis neglects the connections between scales. For instance, decentralized recycling of light grey water in wastewater minimizes the morning and evening peaks, and reduces the dilution of domestic wastewater. Meanwhile a centralized infiltration infrastructure minimizes seasonal peaks caused by rainfall, thus diminishing the volume required for the sewer system and reducing the dilution of the wastewater in the combined sewer system. Wastewater reclamation is the most effective measure to minimize input and output;

however it has a larger energy demand than decentralized treatment of LGW or rainwater collection. LGW recycling and rainwater harvesting have a low energy demand and have positive effects on WOI, SSI and REI. However, for a system optimization they should be combined with rain water retention or infiltration.

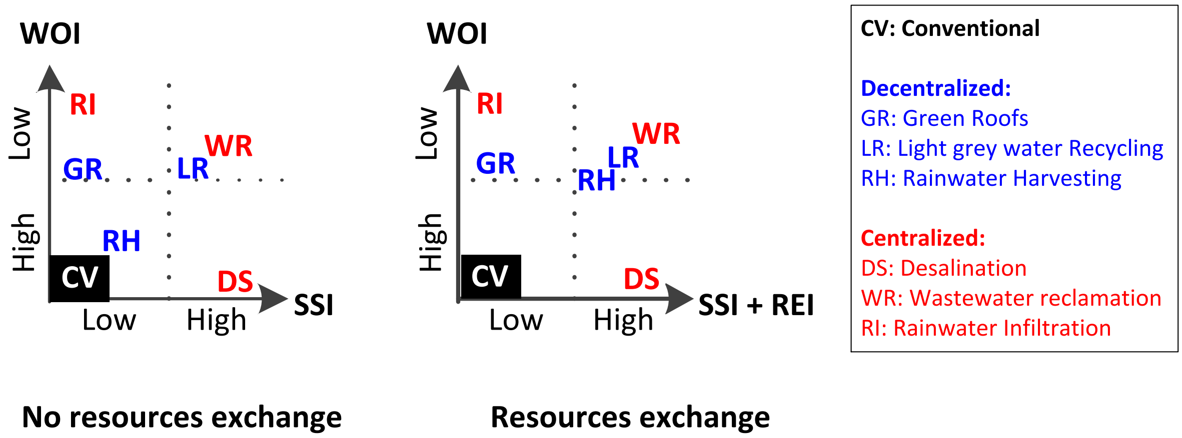


Figure 13 Changes in indices at city scale due to selected measures

7.4 Conclusion

Cities offer a broad range of possibilities to improve the current water resource management. Our research shows that by taking a multi-scale approach and taking into account the heterogeneities of the different areas (neighborhoods or blocks), tailor made approaches result in higher efficiency gains than by taking a city scale approach only, based on average neighborhood characteristics. It also increases the portfolio of measures to improve urban water metabolism in cities. Moreover, hot-spots in which high efficiency gains are possible can be identified to be addressed first. However, not only internal characteristics of the city are important, the external environment will also partly determine the options. Optimizing the urban water balance requires multiple criteria analysis at different scales in which goals and scenarios should be defined per case.

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Appendix A – Balances for each of the units in the urban system

The change in the storage in the city is given by Eq. (1). Eq. (1) can be defined for each of the storage units based on Fig. 2 as follows:

For the roofs: $\frac{ds^{roof}}{dt} = P^{roof} - ET_{act}^{roof} - Ro_{pot}^{roof}$ *(A1)*

For the surfaces: $\frac{ds^{i}}{dt} = \Sigma P^{i} + Ei_{Q2}^{out} + Rh_{Q2}^{out} - \Sigma ET_{act}^{i} - \Sigma I^{i} - \Sigma Ro^{i}$ *(A2)*

For the decentralized storage and treatment: $\frac{ds^{S\&T}}{dt} = M_{pot} + R_{pot} - Rh - O^{S\&T}$ *(A3)*

For the separated storm sewer: $\frac{ds^{SS}}{dt} = Ro^{SS} - N_{rec} - O^{SS} + O^{CS}$ *(A4)*

For the domestic or combined sewer:

$\frac{ds^{DS}}{dt} = DWW + O^{S\&T} + Ro^{CS} + O^{SS} + WW_{i\&b} - WW - O^{CS}$ *(A5)*

In the building unit there is no storage, thus ds/dt = 0, thus

$0 = D_{Q2}^{ind} + D_{Q1} - R_{pot} - DWW$ *(A6)*

Assuming no storage in the industries and business, thus ds/dt = 0, thus

$0 = Ei_{Q1}^{i\&b} - WW_{i\&b}$ *(A7)*

Consequently, after taking into account all these flows, Eq. (1) becomes

$\frac{ds}{dt} = P^{roof} - ET_{act}^{roof} - Ro_{pot}^{roof} + \Sigma P^{i} + Ei_{Q2}^{out} + Rh_{Q2}^{out} - \Sigma ET_{act}^{i} - \Sigma I^{i} - \Sigma Ro^{i} +$
$M_{pot} + R_{pot} - Rh - O^{S\&T} + Ro^{SS} - N_{rec} - O^{SS} + O^{CS} + DWW + O^{S\&T} + Ro^{CS} +$
$O^{SS} + WW_{i\&b} - WW - O^{DS} + D_{Q2}^{ind} + D_{Q1} - R_{pot} - DWW$ *(A8)*

Simplifying Eq (A7) and considering that $P^{city} = P^{roof} + \Sigma P^{i}$; $ET_{act}^{city} = ET_{act}^{roof} + \Sigma ET_{act}^{i}$; $Ro_{pot}^{roof} = M_{pot} + Ro_{act}^{roof}$; $Ro^{SS} + Ro^{CS} = Ro^{i} + Ro_{act}^{roof}$; $Rh = D_{Q2} - Ei_{Q2} - Ir_{Q2} + Er_{Q2}$; $D_{Q2}^{out} = Ei_{Q2}^{out} + Rh_{Q2}^{out}$; $D_{Q2} = D_{Q2}^{ind} + D_{Q2}^{out}$; Eq. (A8) becomes:

$\frac{ds}{dt} = P^{city} - ET_{act}^{city} - \Sigma I^{i} + Ei_{Q2} + Ir_{Q2} - Er_{Q2} - N_{rec} + WW_{i\&b} - WW + D_{Q1}$ (A9)

Appendix B – Sensitivity analysis

We performed a series of simulation to evaluate the sensitivity of the water balance to variations of different variables. First, we evaluated the sensitivity to changes in the precipitation, over the last 25 years a wet year was 1998 with a precipitation of 1050mm and a dry year was 1996 with a precipitation of 573. The precipitation of 2007 was multiplied by a factor of 1.1 to simulate a wet year and by a factor of 0.58 to simulate a dry year. Fig. 1B shows the results. The flows that are more sensitive are infiltration (*I*) and wastewater (*WW*).

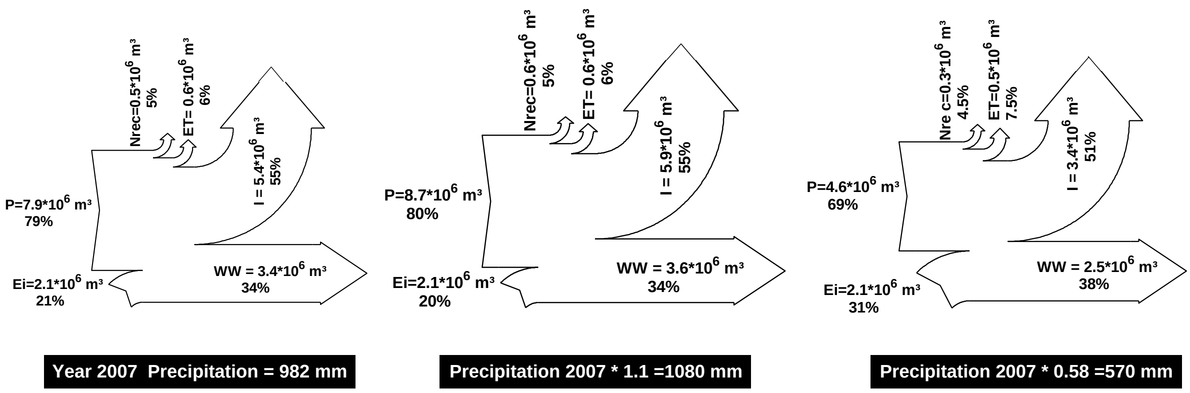


Figure 1B Sensitivity analysis to changes in the precipitation

Second, we evaluated the sensitivity to changes in k_{soil} and S^{green} values for the year 2007. Fig. 2B shows the results. The flows that are more sensitive are Evapotranspiration (*ET*) infiltration (*I*) and wastewater (*WW*). This results show the need to measure soil properties in order to properly asses the water balance.

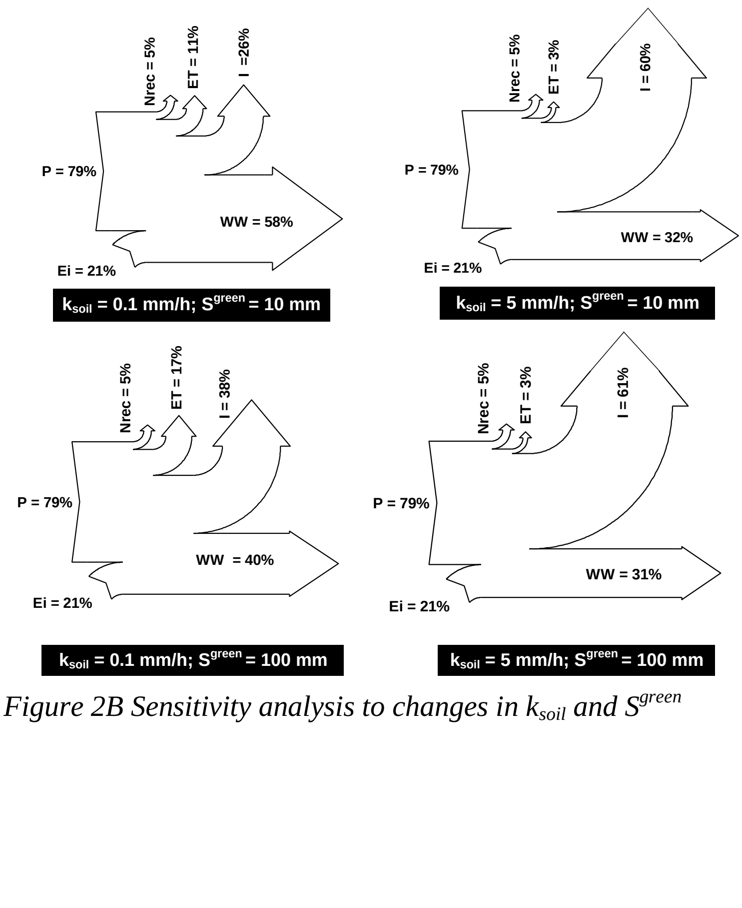
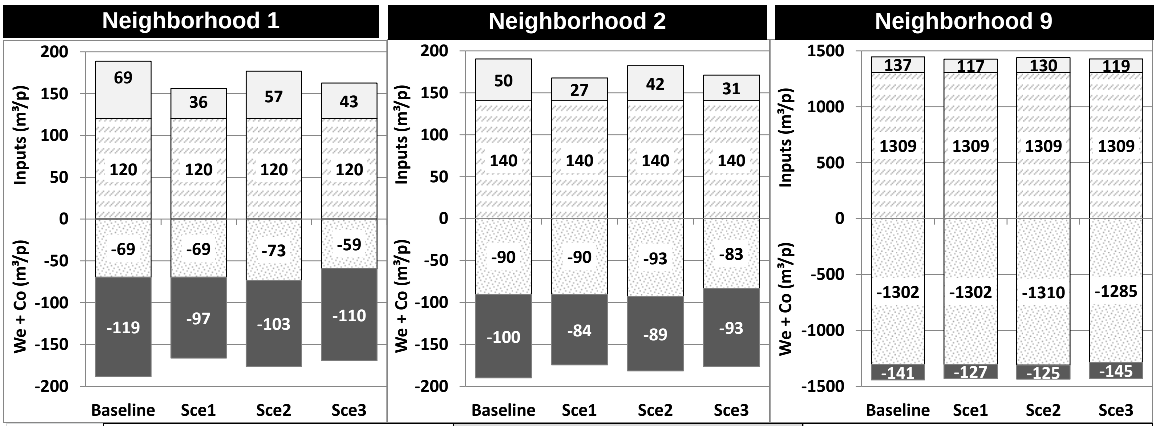


Figure 2B Sensitivity analysis to changes in k_{soil} and S^{green}

Appendix C – Scenario results normalized per person



	Neighborhood 1				Neighborhood 2				Neighborhood 9			
m³ / p	Baseline	Sce1	Sce2	Sce3	Baseline	Sce1	Sce2	Sce3	Baseline	Sce1	Sce2	Sce3
$D + D^{i\&b}$	68.7	56.8	56.8	56.8	49.9	41.8	41.8	41.8	136.6	129.7	129.7	129.7
D^{ind}	59.5	47.6	47.6	47.6	40.4	32.3	32.3	32.3	34.4	27.5	27.5	27.5
D^{out}_{Q2}	1.7	1.7	1.7	1.7	2.0	2.0	2.0	2.0	94.8	94.8	94.8	94.8
D_{Q2}	13.6	11.2	11.2	11.2	10.1	8.5	8.5	8.5	101.7	100.3	100.3	100.3
Rh	0.0	10.3	0.0	7.1	0.0	7.3	0.0	5.5	0.0	6.4	0.0	5.3

Chapter 8

Sustainable resource metabolism in cities of tomorrow: synthesis, concluding remarks and outlook

This chapter is in preparation as:
Agudelo-Vera, C.M.; Keesman, K.J., Mels, A.R.; Rijnaarts. H.H.M. Sustainable resource metabolism in cities of tomorrow.

8 Harvesting urban resources towards more resilient cities

8.1 *Introduction*

In our era, human activity is the main driver of global environmental change (Rockström et al., 2009). We have reached this stage as a result of a number of simultaneous exponential increases, as increasing population, resource and land use, emissions of climate-altering gases and economic activity (Gleick, 2010a). Consequently, we are causing planetary-scale disruptions of the ecosystems that sustain life (Rockström et al., 2009). In return, these ecosystem disruptions impose unprecedented stresses on our ecosystems, political systems, and economies (Gleick, 2010a).

8.1.1 Urbanization and urban metabolism

Urbanization and rising living standards are at the core of these global changes. Since the existence of the first settlements, management of resources like water, energy and materials has been fostered by innovation and technological developments. Changes in resource management have driven population growth and urbanization, as described in **Chapter 2**. Most current cities are highly dependent on external supply of water, energy, nutrients and other materials. In general, the larger and wealthier a city, the larger the area from which resources are drawn (McGranahan and Satterthwaite, 2003). With increasing technological development, the local and current impacts of urban resource consumption have shifted to larger spatial scales, to other time scales (e.g. by overexploiting a given resource) and to other flows (e.g. biofuel production requiring nutrients and water). As a result, the scale of resource use and waste generation, resulting from the urban metabolism[23], has major implications for broad ecological sustainability at short and long term (McGranahan and Satterthwaite, 2003).

8.1.2 Urban resource planning and management

Resource consumption and waste production are linked to urban spatial characteristics, such as urban functions, densities and building typology. The foundations for these urban characteristics are to a large extent defined by urban planners. Consequently, urban planners indirectly influence the urban metabolism of the future. Vice versa, urban planning can contribute to improve local resources management towards cities with a smaller resource footprint. For this, planners need formal information and tools to understand cities and regions as environmental systems that are part of regional and global resource networks (Campbell, 1996, Kennedy et al., 2011).

Ideally, urban resource planning and management would employ methodologies and tools that facilitate systematic assessment of planning options at various temporal and spatial scales with the aim to minimize resource import and waste export. Unfortunately, there is

[23] "Urban metabolism is defined as the sum of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The changing metabolism of cities. Journal of Industrial Ecology 11(2) 43-59.

a lack of understanding and attention on how urban resource management is influenced by spatial (from local to regional) and temporal (from daily to yearly patterns) variations. Moreover, there are neither multi-scale methods nor indicators to measure the efficiency of changes in the urban metabolism.

Recent urban metabolism studies have highlighted the large amount of flows going in and out of urban systems (Kennedy et al., 2011). Although urban metabolism studies give a complete picture of the urban flows in a given urban area at a certain point in time, usually the temporal and spatial scales are coarse. Coarse scales are appropriate for traditional centralized urban infrastructures, which are often end-of-pipe solutions. However emerging decentralized options require a more detailed understanding of the urban processes. Urban systems are composed of several sub-units, e.g. houses or industries. Each of these sub-units has a specific urban metabolism, in terms of quantity, quality and temporal pattern of resources use, see Fig. 1. Moreover, these sub-units are aggregated at different spatial scales, block, neighborhoods, or cities. Our hypothesis is that urban systems and their direct peri-urban surroundings can – to a large extent – become self-sufficient in resources and can reduce their waste production by improving local resource management at the smallest scale possible.

In this thesis, we developed and investigated a novel approach, the so-called urban harvest approach (UHA), as an assessment and planning tool for changing inefficient linear urban resource use and waste production into a sustainable urban metabolism. Herein, a city is regarded to have multiple potentials in the form of untapped primary and secondary (already used) resources that can be utilized, as shown in **Chapter 3**. The objective of this research was to test our hypothesis on one urban resource – water – by applying the UHA at various spatial scales to determine the optimal scale(s) of water resource management, taking into account time dependent water flow dynamics by applying a dynamic modeling approach and using detailed urban water flow data (Fig. 1).

8.2 The Urban Harvest Approach (UHA)

The Urban Harvest Approach (UHA) starts with a baseline assessment, followed by the implementation of three strategies. The first strategy is to minimize the demand. The second strategy is to reduce outputs by recovery, cascading and recycling. The third strategy is to multi-source the remaining demand by using renewable and local sources. As indicated in paragraph 8.1.2, the reduction in resource use starts at the smallest scale possible, followed by a stepwise scaling up from building to city scale. This approach considers cities as the sum of its subsystems and takes into account that there are several multi-scale interactions. Fig. 2 shows some multi-scale interactions of the urban water cycle as well as some source-sink connections. We argue that coupling of scales is needed to identify key multi-scale interactions and to identify the optimal scale(s) of management of different urban flows, as water, energy and materials.

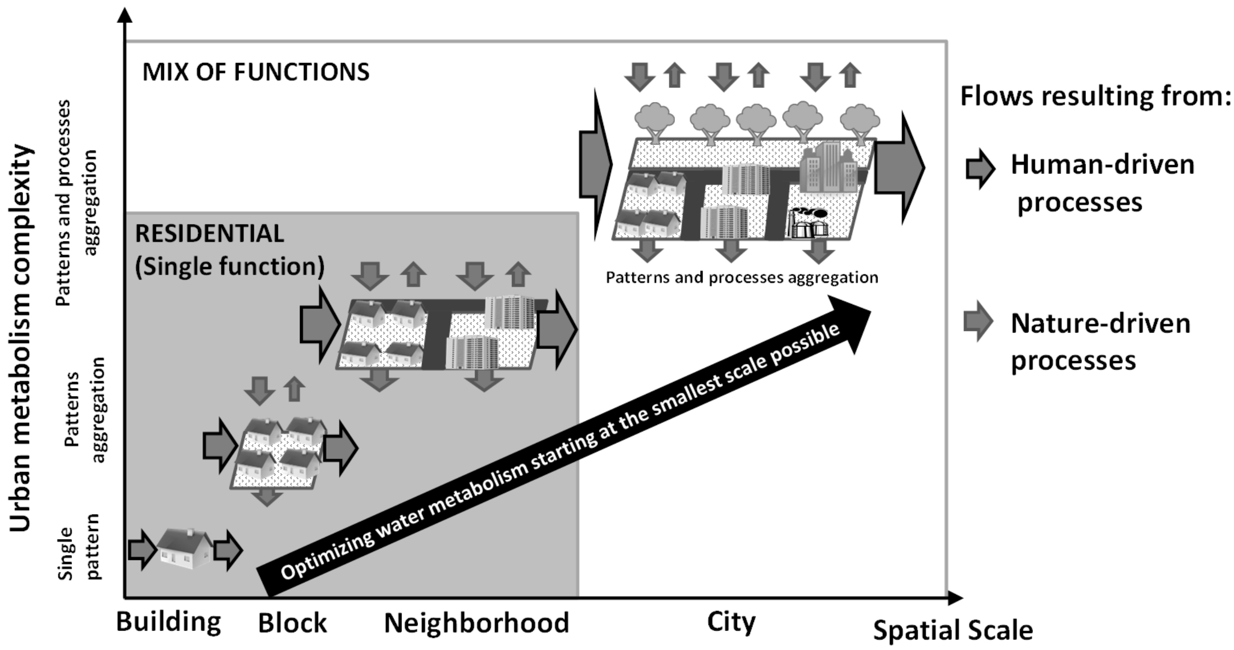


Figure 1 Hypothesis: reduced urban resource consumption requires optimizing urban metabolism, taking dynamic natural and human driven water flow processes into account, starting at the lowest scale possible (building) and a subsequent stepwise scaling up to block, neighbourhood and city level.

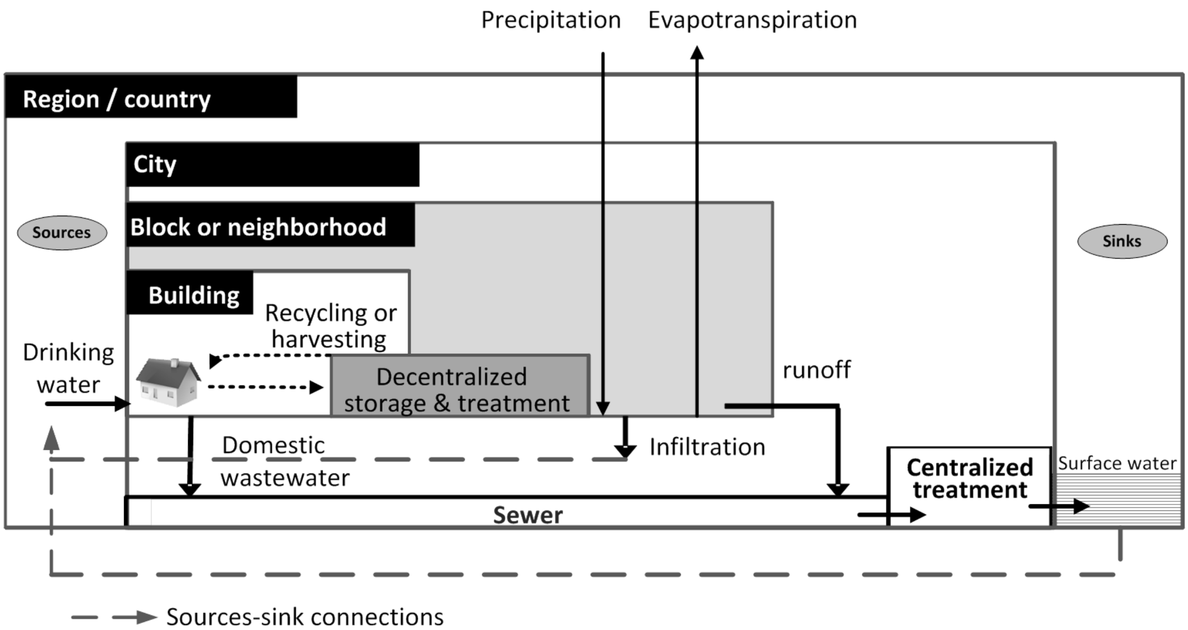


Figure 2 Examples of multi-scale interactions in the urban water cycle

Chapter 4 describes the UHA in detail. This chapter shows that the UHA allows coordination of scales for technology selection and allows coupling of different building units and blocks. Moreover, by analyzing the urban metabolism at multiple spatial and temporal scales productive and "resource-hotspots" areas can be identified. We proposed four indicators to describe and compare the urban metabolism of a given resource at any scale, namely: Demand Minimization Index (*DMI*), Waste Output Index (*WOI*), Self-Sufficiency Index (*SSI*) and Resource Export Index (*REI*).

8.2.1 The Urban Harvest Approach (UHA) applied to urban water cycles

In the 19th and 20th century, in developed countries the "engineering" approach towards urban water management was leading. The predominant focus of water supply planners and managers has been on identifying and meeting growing human demands for water. Large scale centralized infrastructures are used to move water in both space and time to meet current and projected demands (Gleick, 2010b). Current trends, increasing population, climate change and local or seasonal limited water resources pose new challenges. Many cities worldwide face challenges of water shortages and rapidly depleting ground water and reservoir resources while facing challenges of increasing volumes of wastewater at the same time. New approaches are needed to improve urban water management to meet human and environmental demands for water (Gleick, 2010b).

Climate change will, in many cities, result in more flooding risks. Moreover, in many coastal regions, the risk of flooding is aggravated by sea level rise and/or land subsidence. Land subsidence is stimulated by groundwater extractions that are often required to avoid water shortages. Even in the Netherlands, a country rich in water, high urbanization and high living standards increasingly pose pressure on available deep ground water resources. Improving the water cycle aimed at lower dependency of these natural sources will reduce the effects of climate change and lead to a higher resilience, e.g. with respect to droughts (van de Ven et al., 2011).

8.3 UHA applied to residential urban water in the Netherlands

Over the last decades, there has been an ongoing discussion over centralization versus decentralization of urban water systems (Libralato et al., 2012; Makropoulos and Butler, 2010). Authors that favor decentralization argue that there are an increasing number of approaches to improve the efficiency in use and management of urban water flows at building and block level, including low- to high-technological options (see Makropoulos and Butler, 2010).

In line with our hypothesis, we argue that "decentralized" systems play a central role in new paradigms towards more sustainable urban water management. Planning decentralized systems, however, requires thorough understanding of the influence and interaction of urban characteristics like, e.g., building type or land cover. Moreover, system dynamics need to be taken into account as a result of the interactions between spatial scales (e.g. saving devices at building unit influence the dynamic supply of centralized drinking water) and the dependence of the system on temporal scales (e.g. day-night or seasonal patterns, and the related need for implementation of storage tanks).

These spatial interactions and temporal dependence provide necessary insights in the urban water flows dynamics behavior to assess the applicability and contribution to sustainable water use of a given approach or set of technological measures such as grey water recovery, treatment and re-use.

In **Chapters 5-7**, we evaluated the residential water cycle for the Netherlands and the potentials for improvement. We considered multiple spatial scales, from building to city scale. Different scenarios to improve the residential water cycle were studied by dynamic modeling, following the hierarchy of measures and scale proposed in the UHA.

In the Netherlands, the residential water demand is approximately 127 liters per capita (Foekema and van Thiel, 2008), of which 40% is used for showering, 30% is used for toilet flushing and 12% is used for washing clothes in the laundry machine. As a first strategy in UHA, demand minimization by implementation of water saving technologies (at the building level) were studied, including water saving toilets, head-showers and laundry machines. The second strategy in UHA, output minimization, was studied at the building level by optimization of the recycling of wastewater from shower for non-potable activities, including toilet flushing, laundry machine and garden watering demands. This so called Light Grey Water (LGW), has a low concentration of pollutants, and it has a relative constant temporal pattern. Moreover, LGW treatment is feasible at decentralized (i.e. building and block) scale. Multi-sourcing, as the third strategy in UHA, was studied via harvesting rain water from building roofs to supply for non-potable demand. Fig. 3 shows the spatial and temporal scales and the main characteristics relevant for urban water management that were studied in this thesis.

8.3.1 Urban Water cycle at building unit scale

In **chapter 5**, we investigated indoor water metabolism at building level for two building types, a freestanding house (one four-people household) and a mid-rise apartment flat (28 two-person households). It is known that the type of building relates to the total residential water demand (House-Peters et al., 2010). The reason is that building types are related to occupancy and type of appliances. For instance, families with children more often live in free standing houses and have a bathtub compared to families without children. Meanwhile couples without children more often live in apartment flats. In apartment flats, it is more likely to have a shower than a bathtub, due to space limitations. With respect to use dynamics, daily residential water demand is characterized by a morning and evening peak. Moreover, these peaks are influenced by the number of households in the building unit.

Our reviews showed that implementing water saving devices at building level, focusing on the activities with larger water demand, may reduce up to 35% of the conventional

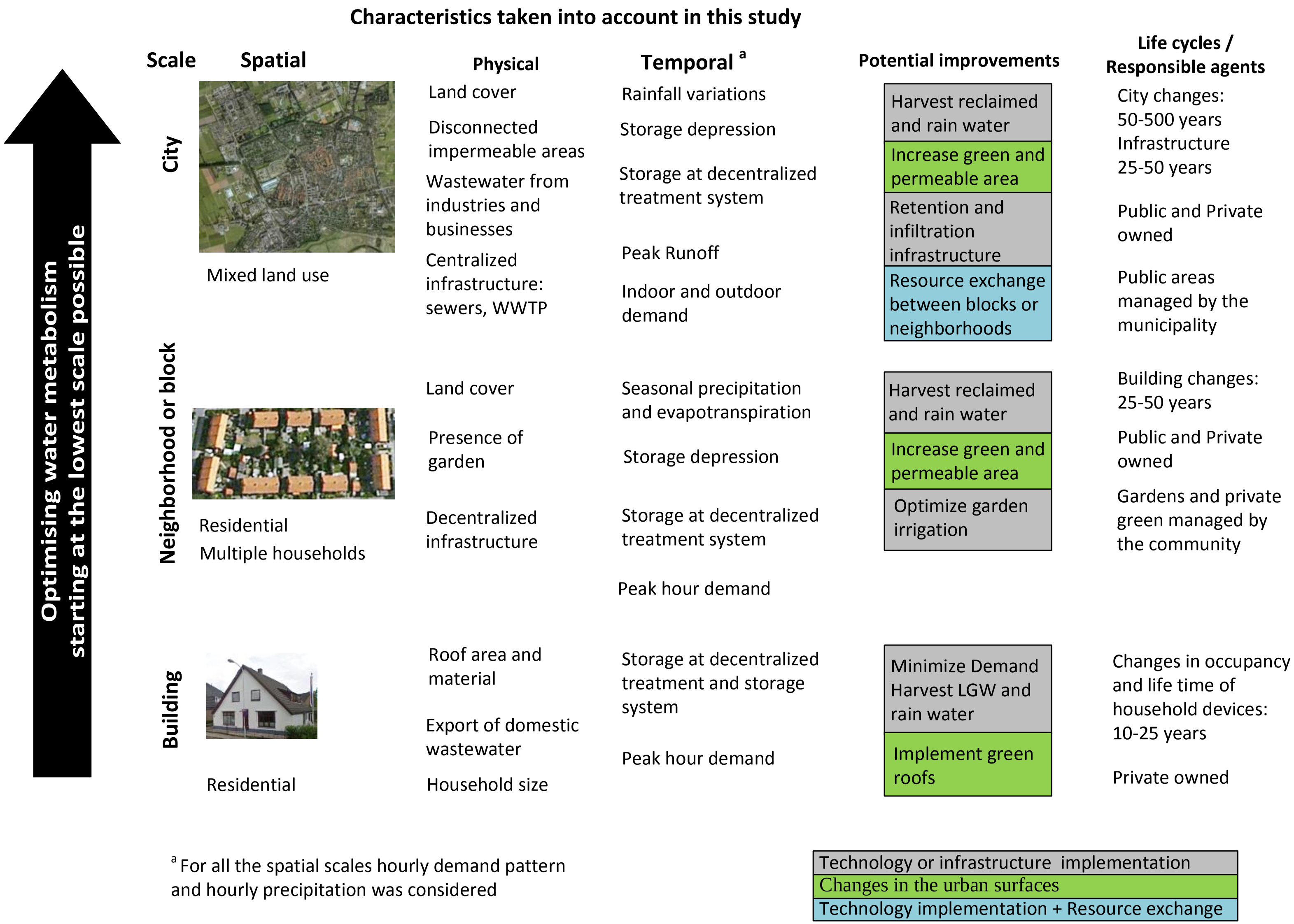


Figure 3 Description of the scale, spatial characteristics and their influence in the urban water cycle investigated in this thesis. (Images source: Google Maps

demand. If demand is minimized, 100% of toilet and laundry demands could be catered by LGW recycling. If minimization is not implemented, a combination of LGW recycling and rainwater harvesting is needed to supply 100% of the conventional toilet and laundry demands. Although 100% is achieved in both cases (with and without minimization) noticeable differences are found in the storage capacity requirements, which can be a limitation in high dense urban areas. Considering the required space per inhabitant (including treatment and storage), efficiency is larger for building units with multiple households than for building units with a single household.

Overall, our results showed that requirements for external water resources can be reduced by 45 - 50% by optimizing water metabolism at the building level. At the same time, optimization is hampered by suboptimal dynamics of LGW production and demand for non-potable water, requiring relatively large storage volumes at the building level with single household.

8.3.2 Urban Water cycle at block scale

In Chapter 6, two different city blocks were analyzed for climate and water use conditions in the Netherlands; a low-density city block composed of freestanding houses with gardens and a high-density block composed of mid-rise apartment flats without gardens. At block level, outdoor demand was investigated. As outdoor demand we considered garden watering. Garden watering has a high seasonal variability and is correlated with high residential water demand. Moreover, the presence of a garden is highly related to urban characteristics such as, building type or density (Duany and Talen, 2002). Seasonal water balances were investigated for different scenarios. Modeling results showed that at block level, surface coverage and soil characteristics (for water infiltration), roof area (for rainwater harvest potential) and housing density (for water needs per km2) are key indicators for estimating the potential to reduce the dependence on external water resources and to reduce the export of waste. Import of drinking water represented up to 40% and 80% of the total input, in the low- and high-density block, respectively. Special attention was given to the variations of the runoff coefficient. The results showed large seasonal fluctuations in the runoff coefficient, from 18 to 55% for the low-density block. Meanwhile for the high-density block, this coefficient was relatively constant over the year, approx. 80%. Considering minimization of shower, laundry and toilet demands, 16% self-sufficiency can be achieved by recycling LGW. The main changes are found in the waste production ratio (waste/demand), see Fig. 4. Looking at the heterogeneity of blocks within a city and the temporal variations on garden watering and precipitation pattern, no single solution fits all the blocks and some benefits are only seasonal. Consequently, generalization of urban areas and yearly averages can cause error when evaluating the efficiency of measures.

8.3.3 Urban Water cycle at city scale

In **Chapter 7**, the total urban water cycle was investigated for the city of Wageningen, The Netherlands. At city level, we compared the water cycle "*of"* the city with the water cycle "*in*" the city. Urban areas are complex dynamic systems. Each one is unique due to the combination of physical and socio-economic factors. In this approach, a city is composed of heterogeneous "patches" with different building typology, land cover, density, etc. Traditional approaches, for the design of centralized urban infrastructure are top-down approaches. Herein, cities are treated as homogeneous entities, which generally causes introduction of errors in water flows when evaluating the efficiency of measures, as shown in section 8.3.2. To study the water balance of the city of Wageningen, we used a combination of strategies at different scales. Firstly demand minimization at building scale, and then recycling, green roofs and rainwater harvesting at neighborhood level. The city of Wageningen has nine neighborhoods. Each of the neighborhoods is composed of several heterogeneous blocks. Our results showed a large variability of water metabolism which are related to neighborhood characteristics, namely population density, land cover, surface storage and soil permeability. Although, Wageningen is a small city, with low densities and a large percentage of green areas, hot-spots were identified by studying the water metabolism of each of the neighborhoods. This implies that cities require a portfolio of measures to improve urban water metabolism according to the neighborhood or block characteristics. Moreover, resource hotspots can and should be identified to be addressed in early stages of renewed planning and design by using approaches, such as, the UHA. The results show that imported potable water could be reduced by 15%, wastewater production could be reduced by 50%, and 100% of the non-potable demand could be supplied by locally harvested resources. There was a surplus of harvested resources. This surplus can be made available for export to peri-urban areas as for instance for use in agriculture.

Since improving the urban water cycle is a multi-objective problem[24], one strategy cannot exclude another and vice versa. Moreover, the results show that a combination of centralized and decentralized approaches is needed to improve urban water management. We identified three key measures to reduce external water demand and waste export: (i) technology implementation, e.g., water saving devices or decentralized wastewater treatment technologies; (ii) changes in the urban surfaces to increase storage capacity, infiltration or evaporation by selecting permeable materials, e.g., green roofs or permeable pavements; and (iii) resource exchange between blocks, neighborhoods or export to peri-urban areas. Table 1 summarizes the results of this thesis and indicates the hierarchy of the different measures and the spatial scale feasible to improve urban water metabolism.

[24] Minimizing import of resources, minimizing export of waste and optimizing harvest of local resources at each scale.

The results showed the added value of multi-scale analysis of urban water systems. Single scale analysis neglects the connections between scales. For instance, recycling of light grey water at building or block level minimizes the morning and evening peaks, and reduces the dilution of the domestic wastewater. Meanwhile a centralized infiltration infrastructure at city level minimizes seasonal peaks due to rainfall, minimizes the volume required for the sewer system, and reduces the dilution of the wastewater in the combined sewer system. Fig. 5 shows a schematic representation of the peak reduction effect of the different measures.

Our research also showed that studies on urban metabolism at increasing spatial scales provides valuable insights in measures that are customized for different parts of the city, which can enable exchange resource flows. For instance, a highly dense area may become an exporter of secondary resources to an area with a low density. A city can also export resources to other cities or to the peri-urban areas. Therefore, not only internal characteristics of the city are important, the external environment will also partly determine the options. Moreover, resources surplus can foster development of new functions within the urban area, e.g. urban agriculture, without exerting additional pressures in the water balance. Summarizing, optimizing the water metabolism of a city requires multi-scale analysis.

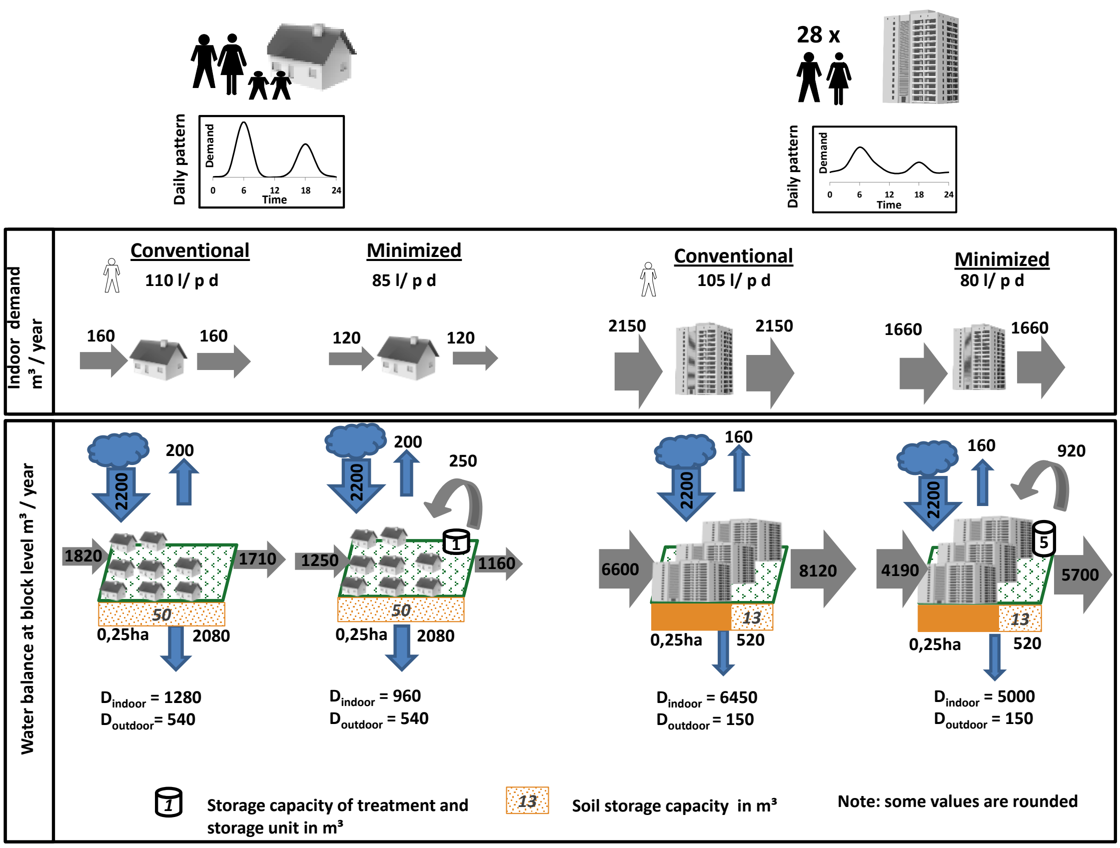


Figure 4 Comparison of the urban water cycle of two urban blocks for conventional and minimized demand in the Netherlands; low density – left figure, high density - right figure.

Water use patterns are not evenly distributed over space and time, and thus are affected not only by socio-economic, climatic and physical property variables, but also by the geographical location of the region and its interactions with other adjacent regions (House-Peters et al., 2010). High urban densities often are related to a highly disturbed water cycle with large runoff coefficients and concentrated resource demand and waste production. Thus areas with high densities can become easily "hot-spots". However, in dense areas several measures can be taken to address runoff, such as, green roofs, rainwater harvesting, retention and infiltration infrastructures.

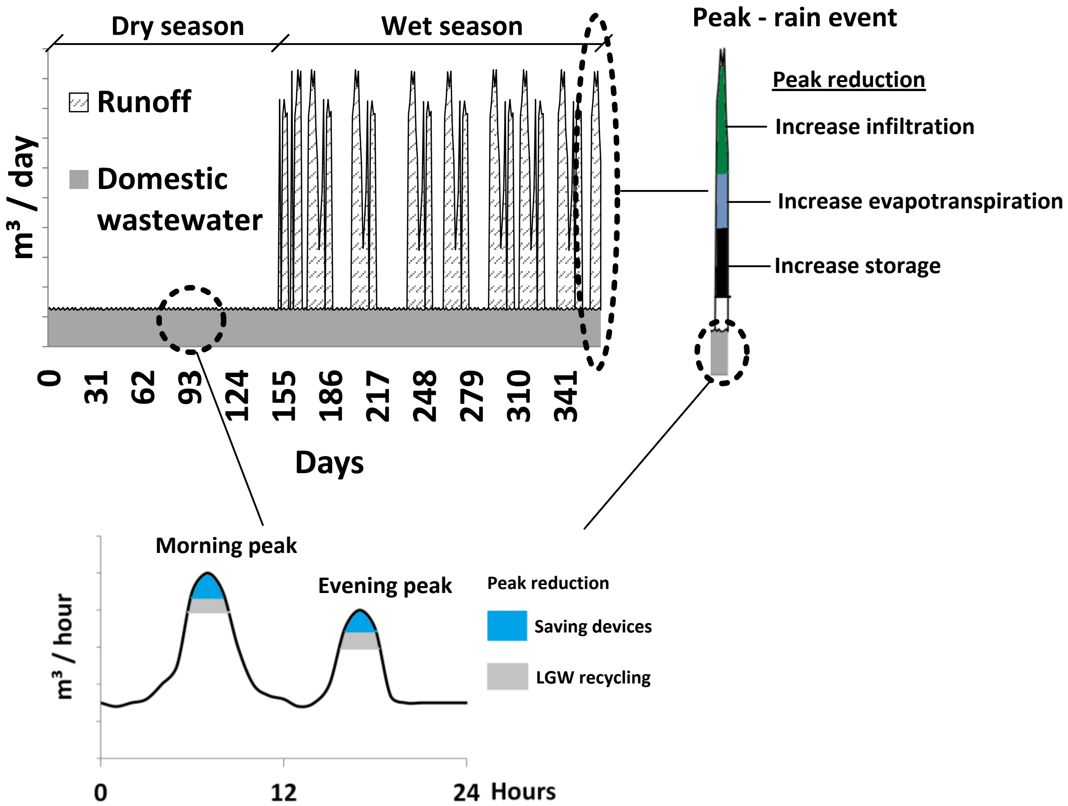


Figure 5. Schematic representation of the wastewater production in a city and the peak reduction due to different measures.

8.4 Concluding remarks

In this thesis, we investigated the hypothesis that urban systems and their direct peri-urban surroundings can become – to a large extent – self-sufficient and reduce their waste production by improving local resource management in a multi-scale approach and starting at the smallest scale possible. We developed the urban harvest approach (UHA), as an assessment and planning tool to change inefficient linear urban resource use and waste production into a more efficient urban metabolism, using less external resources and reducing waste production. The described approach relates urban characteristics to resource harvesting potentials, aiming to foster a re-thinking of our current urban systems by a multi–scale and time dependent dynamic analysis. We tested this approach for urban residential water flows in the Netherlands.

Table 1 Overview of results – Hierarchy of measures, preferred spatial scale for implementation and effects of the metabolic

Hierarchy of Measures		Spatial Scale								Indicator improved
		Building		Block		Neighborhood			city	
		Free-standing 	Mid-rise flat 	Low density 	High density 	**Low Impacted:** low density and high permeability	**Moderate Impacted**	**Highly impacted:** High density and low permeability		
1	Saving Technology	√	√							*DMI*
2	LGW recycling		√	√	√	√	√	√		*SSI / WOI*
3	Green roofs	√	√							*WOI*
4	Change to permeable surfaces			√	√		√	√	√[b]	*WOI*
5	Rainwater harvest from roofs	√[a]	√[a]	√	√					*SSI*
6	Export of treated LGW		√	√	√	√				*WOI / ERI*
7	Export of rainwater		√	√	√	√				*WOI / ERI*
8	Import of secondary resources			√	√	√	√		√	*SSI / WOI*[c]
9	Decoupling storm water system								√	*WOI*
10	Reclamation / desalination								√	*SSI*

[a] Only if LGW recycling is not feasible. [b] Sustainable urban drainages. [c] At city level

8.4.1 *Applicability of the UHA*

The approach showed to be feasible because it provides a single approach to evaluate the urban flows at different spatial and temporal scales. Moreover the metabolic profile indices provided detailed information for evaluation and comparison of inputs, outputs, storage and consumption within urban areas. The multi-scale approach helps to identify interactions between scales and between human- and nature-driven processes, e.g. increasing garden watering can increase infiltration and evapotranspiration affecting the ground water recharge or the micro-climate. The main limitations are the need of detailed data about resource demand patterns and the complexity of some urban processes that are still difficult to quantify and model, e.g. urban evapotranspiration.

8.4.2 *Strategies to manage urban water metabolism in the city of tomorrow*

The results indicate that cities have a large potential to improve current resource management. A key issue to improve resource efficiency is understanding where, when, and why we use a certain resource (Gleick, 2010b). For example, the resource water is used for different activities. Most of these activities can be catered with less water. Demand minimization is foremost the best first step in a strategy towards a more sustainable urban metabolism. In addition, the quality surplus in conventional water metabolism can be addressed, by transforming the use of high quality potable water for activities that do not require that quality, into use of water with a lower quality of water for such activities. The second strategy is to minimize the output by cascading, recycling and multi-sourcing. By doing this, demand and supply qualities are matched and quality surpluses are minimized. The third proposed strategy is multi-sourcing by harvesting local renewable resources. As discussed in this thesis, cities should be seen as producers of secondary resources.

The cases studied for the Netherlands showed that cities can minimize the domestic water demand by 20-30%. They are able to provide up to 100% of the non-potable water by implementing decentralized treatment of light grey water (LGW). The optimal scale of management for LGW varies from building unit to neighborhood scale, depending on the building type, LGW production and non-potable water demand. Rainwater harvesting is less recommended to achieve self-sustainability than LGW because of its seasonal and inter-annual variability. Due to the high percentage of impermeable areas in cities, rainwater runoff becomes a waste output. In our approach, not only self-sufficiency is pursued, but also output minimization. The results showed that runoff minimization requires a multi-scale approach, including changes from the building unit, e.g. green roofs or rainwater harvesting, to the city level, e.g. building retention and infiltration infrastructures.

The multi-scale approach is also indicative for the time scales in which urban metabolism can be altered. Measures at household/building level can be taken at short term. Household appliances have a life time of 5-10 years. At the block and city level, not only the interdependence of flows is much more complex, but also the number of stakeholders involved becomes much larger. In addition, the life time of urban assets (pipes, roads, houses) is much longer (typically 30 – 100 years). This implies that changes at these levels require much more time compared to building unit level. Increasing the efficiency of urban (water) metabolism requires an adaptive approach. We argue that a combination of short term and long term measures is required towards transitioning the urban system. Short term measures support the transitioning processes at long term because of the visibility of results. At the same time a long term vision and strategy is required for the larger scales. Within the transitioning strategy, it is important to take into account that changes at one scale may influence the efficiency of measures at other scales. For instance, if recycling facilities are designed for conventional demand, while in a later stage water saving measures are implemented, the efficiency of the recycling unit is likely to become compromised. Moreover, with accelerated changes in urban systems and their surroundings, adaptive management is needed to periodically revise and adapt strategies according emergent pressures, to make sure that the vision and goals of the city are achieved.

More drastic re-arrangements could also be proposed to improve self-sufficiency, for instance, the implementation of decentralized systems to provide potable water (Peter-Varbanets et al., 2009). Therefore, small decentralized plants to provide drinking water could be combined with a centralized network that delivers water of a non-potable quality.

Our results showed that different water streams can and have to be managed at different spatial scales and that a combination of centralized and decentralized measures is needed to minimize urban impacts at short and long term. Cities offer a broad range of possibilities to improve current water resource management. However, the heterogeneities of the different areas, neighborhoods or blocks, should be considered to achieve optimal design and management. Technology implementation and infrastructure development require a supportive policy framework and a trade-off analysis to identify rebound effects. Moreover, it has to be adaptive and flexible to cope with the stochastically driven disturbances and non-linear dynamics of the urban water balance. Appropriate time and space scales are crucial to understand the changes in the urban water cycle and also to identify the influence of the different variables on the overall performance of the system. Efficiency of the measures is linked to local context and urban typology. Therefore, urban planning can contribute to facilitate harvesting of local resources towards sustainable cities of tomorrow.

8.5 Outlook

Relevance of (urban) resource management has increased recently. The European Union has selected resource efficiency as one of the seven flagship initiatives for its 2020 strategy. It aims to bring major economic opportunities, improve productivity, drive down costs, and boost competitiveness – while also supporting a low-carbon economy and sustainable growth. In a similar spirit, the OECD and the UNEP promote resource efficiency in their campaign for "green growth" and a "green economy"[25]. Additionally, European projects such as Revisions[26], or SUME[27] and Tabula[28] investigate resource management within urban areas.

8.5.1 Data and modeling gaps

There may be a perception that the urban water budget is well quantified because urban water systems are highly engineered and managed (Pataki et al., 2011). However, especially for the smaller scales this is not the case, as important flows of water tend to be poorly monitored or even unmonitored. Accurate and reliable data on water use are vital for evaluating the efficiency of current use, establishing efficiency targets, and evaluating performance towards meeting those targets (Gleick, 2010b). In urban areas, in particular, two main parameters need to be better monitored: soil compaction and urban evapotranspiration.

In our work we found that soil compaction is an important parameter needed to assess urban water storage on the surface and infiltration rates. The sensitivity analysis showed that variations in soil characteristics influence infiltration, evapotranspiration and runoff flows. Recent studies in USA and China have shown a large variability of soil compaction in urban sites. Soil compaction is determined by land use, land cover, and age of the development. Linking the UHA to hydrology studies using ground water or runoff models can provide more insight for urban design.

Water-Energy nexus is another issue, in-door and out-door. Indoor water-energy nexuses are given by thermal properties and chemical composition of the flows. Therefore, a more detailed inclusion of the water quality in the modeling is required. A complete evaluation of the measures should include energy and material balances to investigate options for recovery of heat or nutrients and to avoid negative side effects. Outdoor water-energy nexuses are given mainly by urban evapotranspiration. Urban Evapotranspiration is a function of multiple system parameters that are often not quantified or known for cities. Although methodologies based on energy fluxes have been developed, they require a large amount of data. Simplified methodologies are needed for cases were data is limited.

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[25] http://ec.europa.eu/resource-efficient-europe/.
[26] http://www.regionalvisions.ac.uk/ReVISIONS/Options.aspx
[27] http://www.sume.at/
[28] http://www.building-typology.eu/existent-concepts/typologies-examples.html

8.5.2 UHA as a supporting tool in urban planning

UHA is meant as a tool to support planning processes. UHA could be used by urban planners and decision makers to study the urban flows and provide smart, customized solutions for existing and new urban areas. The approach allows for comparisons between centralized and decentralized measures, helps for a first screening of measures and of hot-spots of resource demand and waste production. Urban design with a holistic approach does not guarantee zero trade-offs among flows, but it allows to identify, to choose and to plan in advance the negative indirect effects in and outside the system.

8.5.3 Implications for urban managers and planners

There is a large degree of heterogeneity in urban water governance, similarly as in the biophysical properties of cities that influence the urban water balance. Decision making, ownership, design and management of urban infrastructure range from individual home owners to private institutions and public agencies. It is very challenging to understand the human factor in the water management system, because water supply, wastewater, storm water and landscape design are generally handled by separate entities (Pataki et al., 2011). A wide variety of tools for making changes are possible, including new technology, economic approaches, regulatory requirements, and education. It would be helpful to establish incentives for improving water efficiency and reducing wasteful use of water at all levels, using a range of financial, regulatory, and educational tools (Gleick, 2010b).

Sustainable urban water management is hindered by the lack of coordination among national, regional, local, and non-governmental entities (Gleick, 2010b). Usually, national governments have a crucial role in developing guidelines and supporting innovation (McGranahan and Satterthwaite, 2003). Local authorities can translate such guidelines into regulations, norms and codes for planning and regulating the built environment. For example, in the city of Antwerp, Belgium, implementation of green roofs is compulsory for new buildings.

Hence, better communication is needed among the different institutions in charge of the urban water infrastructure. There is a need for platforms where data can be shared and for unification on how data is recorded. When analyzing the complete water system, the "real" benefits or trade-offs are identified. This would lead to more systematic analysis of the impact of water management strategies.

8.5.4 Increase public awareness

In this research, human behavioural changes were not considered. To avoid rebound effects, we are aware that one of the big challenges is to increase public awareness and understanding of sustainable consumption patterns by citizens. One important issue in developed countries is promoting the necessary delinking of high standards of living –

quality of life – from high levels of resource use and waste generation (McGranahan and Satterthwaite, 2003). If citizens are aware of their environmental impact and the benefits of implementing new promising technologies, the transition towards more sustainable urban systems can be speeded up.

The value of secondary resources like reused water is mainly appreciated in countries facing severe water scarcity, e.g., Israel, Australia and Jordan. Other countries face other kind of pressures, such as, pollution and salinization of aquifers, resulting in increased costs to produce drinking water. Cost increases have shown to be important triggers of change towards more sustainable resource systems. Although in dual reticulation systems, the risk of cross-connections may exist, efforts should be focused on increasing awareness of the benefits of these systems and on building trust by training and informing users and technicians about the functioning of the systems.

8.5.5 Need for interdisciplinary linkages

Increasingly prosperous urban areas almost inevitably draw more heavily on non-renewable resources and create more waste. For instance, a larger world population will result in a larger food demand requiring higher crop yield, and higher water footprints, in order to feed the increasing population (Hellegers et. al, 2008). Additionally, depletion of the phosphorus resources, increasing urbanization and larger food demand in cities, have become hot issues that should be given special attention. Traditional urban infrastructure for water supply, waste and wastewater discharge and treatment, and energy networks is planned and managed separately, and designed for different time scales. The problems facing human society are interconnected. However, these interconnections are still poorly understood (Huppes and Ishikawa, 2011). Single-discipline and single-scale analysis are insufficient to provide sustainable options, because unplanned trade-offs can appear when optimizing a single flow.

The UHA allows (*i*) evaluating each of the urban flows (water, energy, nutrients, etc.), (*ii*) identifying connections between them, e.g., potential heat recovery from wastewater, and (*iii*) moving from micro- to macro-level, and from building unit to city scale. Within the UHA, waste flows are not only key indicators of systems efficiency, but they may also provide insights into potential linkages between flows for a more efficient urban metabolism. Recovery of nutrients from wastewater is a promising strategy. Moreover, new technologies allow harvesting of the thermal energy present in the water flows. Verstraete and Vlaeminck (2011) proposed a zero-wastewater approach, in which the potential resources in used water are quantified. Economic benefits of harvesting resources from wastewater are almost €1 per cubic meter of wastewater.

8.5.6 Integrating local models with global and regional climate models

Frequency and intensity of extreme events are expected to increase with climate change (IPCC, 2007). Therefore, climate change impacts should be integrated into all federal and state water decisions, planning, and management (Gleick, 2010b). However, climate models still remain coarse in space and in time resolution. Most regional model simulations are available at daily time scales and from 25 to 50 km (Willems et al., 2012). Moreover, global models often use data from nationally aggregated data that can produce errors quantifying some hydrological processes. The coupling of feedbacks at multiple scales is an emerging issue to understand in order to improve predictions of ecosystem responses to climate changes and vice versa (Rietkerk et al., 2011). Local characteristics, e.g. micro-climate, can influence global processes, but also urban water managers have to start accounting for the challenges posed by changing climate patterns as extreme rainfalls and droughts. Therefore, it is crucial to downscale results from global models to urban level, to provide managers and politicians at local and regional level of the expected changes at the scale of their operations and decision power (Gleick, 2010b).

8.5.7 The way forward

Cities are drivers of major resources flows. Accelerated changes in cities and hinterland pose threats to resource security in cities. At the same time, these threats are opportunities for a new and secondary based resource management in sustainable urban resource metabolism. Coping with these threats and opportunities is a global challenge with a lot of complexity. To address these challenges, we need a temporal and spatial multi-scale understanding of resource flows and the dynamics and uncertainties associated with each scale. This thesisoses the implementation of local solutions to solve – to a large extent – the global challenges humanity faces today. We believe that to solve global resource problems and to achieve sustainable resource metabolism in cities of tomorrow, mankind has to start today by solving the “metabolic” problems of cities.

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Summary

Summary

Historically, urban resource management has been fostered by innovation and technology developments and has driven population growth and urbanization. Current and near future global urbanization urges for a reconsideration of the organization and dynamics of resources in cities. **Chapter 2** presents a historical review of the urban resources management and urban planning. The review describes how, with increasing infrastructural and technological development, the local impacts of urban consumption has been shifted to other tempo-spatial scales. The main conclusion is that our current urban un-sustainability is rooted in massive resource consumption and waste production beyond natural limits, and the absence of flows from waste to resources. Therefore, sustainable urban development requires a new approach based on the integration of novel ways of resource management into a design and planning of the urban environment.

With accelerating global changes, cities have to cope with growing pressures, especially for resource supply. Our hypothesis is that urban systems and their direct peri-urban surroundings can – to a large extent – become self-sufficient in resources. Cities can reduce their waste production by a restructuring at the smallest spatial scale possible. Cities may be considered as resource reservoirs and producers of secondary resources. To proof this concept, we investigated in **Chapter 3** the potentials to harvest energy and water in the Netherlands – on an average yearly basis. Results showed large potentials to meet up to 100% of the electricity demand, 55% of the heat demand and 52% of the tap water demand at national scale. However, there are restrictions to harvest these potentials due to flow dynamics, urban typology and technological efficiencies. Therefore, to estimate the actual harvest potentials, dynamic modeling is required considering heterogeneous characteristics of the urban areas at finer temporal and spatial scales.

In **Chapter 4,** we propose the novel urban harvest approach (UHA), as a tool for sustainable urban resource planning. UHA is based on the principle that urban systems and their direct peri-urban surroundings can become self-sufficient. UHA starts with a baseline assessment, followed by implementation of three strategies. The first strategy is to reduce the demand. The second strategy is to reduce outputs by recovery, cascading and recycling. The third strategy is to multi-source the remaining demand by using renewable and local sources. UHA is a systematic approach, which starts from the building scale and scales up to block, neighborhood and city level and takes stock of the dynamics and non-linearities of urban resource flows. Four indicators describe the urban metabolism of a given resource at any of the spatial scales, namely, Demand Minimization Index, Waste Output Minimization Index, Self- Sufficiency Index and Export Resources Index. To test the UHA and support our hypothesis, we evaluated the urban metabolism for water from building unit to city level. Yearly dynamic water balances were modeled for different scenarios in the Netherlands.

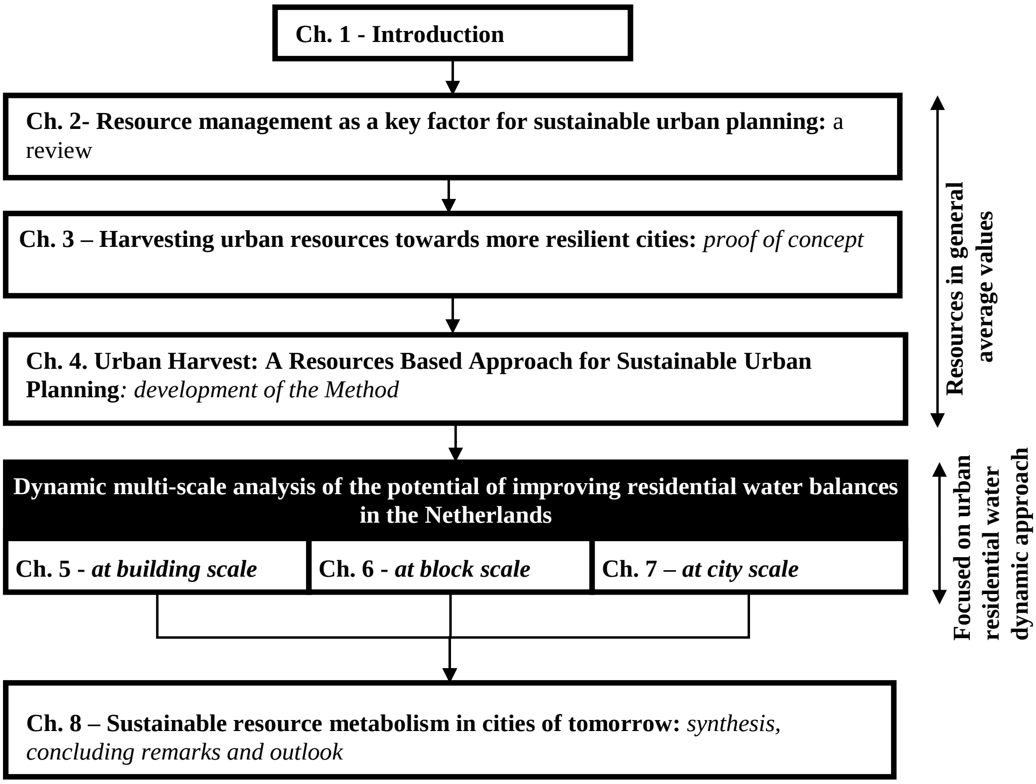

Figure 1 Schematic representation of the content of this thesis

After testing and developing the UHA method on averaged water, spatial scales and yearly basis, our further research concentrated on the dynamic modeling approach. The aim was to more adequately assess the actual resource potential at different tempo-spatial scales, see Fig. 1.

At building level, two building types were selected: a freestanding house and a mid-rise apartment flat (**Chapter 5**). The studied scenarios included: demand minimization, light grey water (LGW) recycling and rainwater harvesting (multi-sourcing) to cater for toilet and laundry water, second quality water (D_{Q2}). Results showed that water saving devices may reduce 35% of the conventional demand. Recycling of LGW can supply up to 20% of the minimized demand (100% of D_{Q2}). For conventional demand, rainwater harvest may supply approximately 14% and 18% of the apartment flat and of the freestanding house demand, respectively. To harvest these potentials, different system specifications, related to the household type, are required. Two constraints with respect to recycling and multi-sourcing were identified. They are related to the demand and to the fraction harvested from the potential amount of resources available. Constraints related to the demand are a function of the grey water production and available rainfall. Meanwhile, constraints related to the fraction harvested are a function of the temporal pattern, and storage and treatment capacities.

In **Chapter 6** seasonal dynamic water balances were investigated at city block level. Two city blocks were analyzed: a low-density and a high-density block. The scenarios considered demand minimization, LGW recycling and rainwater harvesting to cater for demand of second quality water, D_{Q2}. Moreover the implementation of green roofs was also analyzed. Results showed major seasonal variations in the water balance of the low-density block. For the low-density block, 18% input minimization and self-sufficiency was achieved. The waste output index, WOI (waste/demand), was reduced from 97% to 73%. For the high-density block, 23% input minimization, 18% self-sufficiency, and WOI reductions from 123% to 104% were achieved.

In **Chapter 7** we investigated the water balance at city scale in terms of a sustainable urban water metabolism, with the small city of Wageningen, the Netherlands, as validation case. To achieve optimal results, heterogeneities of the different areas (neighborhood) should be considered. This implies that cities require a portfolio of measures to improve urban water metabolism according to the neighborhood or block characteristics. A combination of measures showed a reduction of 14% of the water demand of the city, and a self-sufficiency of 34%. Heterogeneities in cities can be seen as opportunities for resource exchange. In the studied case, the city has a potential to export a volume of secondary water equal to the 37% of its own demand to peri-urban areas. Results showed that different resource streams have to be managed at different scales. Moreover, a combination of centralized and decentralized measures is needed to minimize urban impacts on the natural water cycle. Not only internal characteristics of the city are important, the external environment will also partly determine the options. Three options are identified to improve the urban water metabolism: (i) technology implementation; (ii) changes in the urban surfaces; and (iii) resource exchange.

Evaluating the urban water metabolism requires a multi-scale approach. Moreover, it has to be adaptive and flexible to cope with the stochastically driven dynamics of the urban water balance. The described UHA relates urban characteristics to water harvesting potentials, thus aiming to foster a re-thinking of our current urban water systems. UHA can be used by urban planners and decision makers to understand the urban system and its internal resources flows and to provide tailored solutions for existing and new urban areas (**Chapter 8**). For supplying the human population in dense urban areas with adequate resources such as food, energy and water, urban resource management according UHA needs to be extended to the agro-industrial complex. In addition, food, water, nutrient and other resource management systems should be considered at regional, river catchment or urbanized delta scale in order to fully exploit sustainable resource potentials.

Samenvatting

Samenvatting

In het verleden werd het beheer en gebruik van grondstoffen in stedelijke gebieden door innovatie en technologische ontwikkelingen gestimuleerd. Dit heeft vervolgens de bevolkingsgroei en verstedelijking verder laten toenemen. De wereldwijde verstedelijking vraagt nu om een herziening van het beheer van hulpbronnen en grondstoffen in en rondom steden. **Hoofdstuk 2** geeft van deze ontwikkeling in relatie tot stedelijke planning een historisch overzicht. Het beschrijft hoe de lokale effecten van stedelijke consumptie naar andere tijd-ruimte schalen zijn verschoven door toenemende infrastructurele en technologische ontwikkeling. De belangrijkste conclusie is dat onze huidige stedelijke ontwikkeling inmiddels niet duurzaam meer is. Er is een enorm verbruik van hulpbronnen en productie van afval, die de natuurlijke grenzen van duurzaamheid overschrijden. Duurzame ontwikkeling vraagt daarom om een nieuwe aanpak, gebaseerd op de integratie van nieuwe manieren van beheer van grondstoffen in ontwerp en planning van stedelijke gebieden.

Door versnelde wereldwijde veranderingen moeten steden rekening houden met de toenemende druk op de aanvoer en schaarste van grondstoffen. Onze hypothese is dat stedelijke systemen en hun directe peri-urbane omgeving - voor een groot deel - zelfvoorzienend in grondstoffen kunnen worden, en zo hun externe afhankelijkheid van aanvoer van (schaarse) grondstoffen kunnen verminderen. Steden kunnen beschouwd worden als producenten van primaire en secundaire grondstoffen. Volgens onze hypothese, moet deze zelfvoorziening uitgaan van de kleinst mogelijke ruimtelijke schaal. Het bewijs van dit concept hebben we onderzocht in **hoofdstuk 3**. In dit hoofdstuk werden de mogelijkheden om energie en water in Nederland te 'oogsten' geëvalueerd, uitgaande van gemiddelde jaarcijfers. De resultaten op nationale schaal laten zien dat het mogelijk is om aan 100% van de elektriciteitsvraag, 55% van de warmtevraag en 52% van de watervraag te voldoen. In werkelijkheid zijn er echter beperkingen aan deze mogelijkheden tot oogsten als gevolg van de dynamiek in grondstof- en energiestromen, stedelijke typologie en technologische (in)efficiëntie. Om de werkelijke oogstpotenties te kunnen bepalen is daarom dynamische modellering nodig op relatief fijne tijd- en ruimteschalen.

In **hoofdstuk 4** stellen wij de Urban Harvest Approach (UHA) voor als instrument voor een duurzame planning van stedelijke grondstoffen. UHA is gebaseerd op het principe dat stedelijke systemen en hun directe peri-urbane omgeving voor een aantal grondstoffen zelfvoorzienend kunnen worden. UHA begint met een basisevaluatie, gevolgd door het implementeren van drie strategieën. De eerste strategie is het verminderen van de vraag. De tweede strategie is reductie van afval door het herwinnen, cascaderen en recyclen van grondstofstromen. De derde strategie is om de resterende vraag te voorzien met verschillende hernieuwbare en lokale bronnen (*multi-sourcing*). UHA is een systematische aanpak, van gebouw tot stedelijk niveau. Bovendien houdt UHA rekening met de dynamiek en de niet-lineariteit van de stedelijke grondstofstromen. Vier indicatoren beschrijven het stedelijke metabolisme van een bepaalde hulpbron op elk van de ruimtelijke schalen. Dit zijn: de *Demand Minimization Index* (*DMI*), *Waste Output Index* (*WOI*), *Self- Sufficiency Index* (*SSI*) en *Export Resources Index* (*ERI*). Om de UHA te testen, evalueerden we het stedelijk metabolisme voor water op de schaal van gebouwen, huizenblokken, wijken, de buurten en uiteindelijk op stadsniveau. Verschillende scenario's voor jaarlijkse dynamische waterbalansen werden gemodelleerd uitgaande van Nederlandse klimaatgegevens.

Na het testen en ontwikkelen van de UHA-methode voor jaargemiddelde watergegevens en vaste ruimtelijke schalen, concentreerde ons verdere onderzoek zich op een dynamische modellering-aanpak. Het doel hiervan was om het werkelijke potentieel beter te kunnen beoordelen op verschillende tijd-ruimte schalen (Fig. 1).

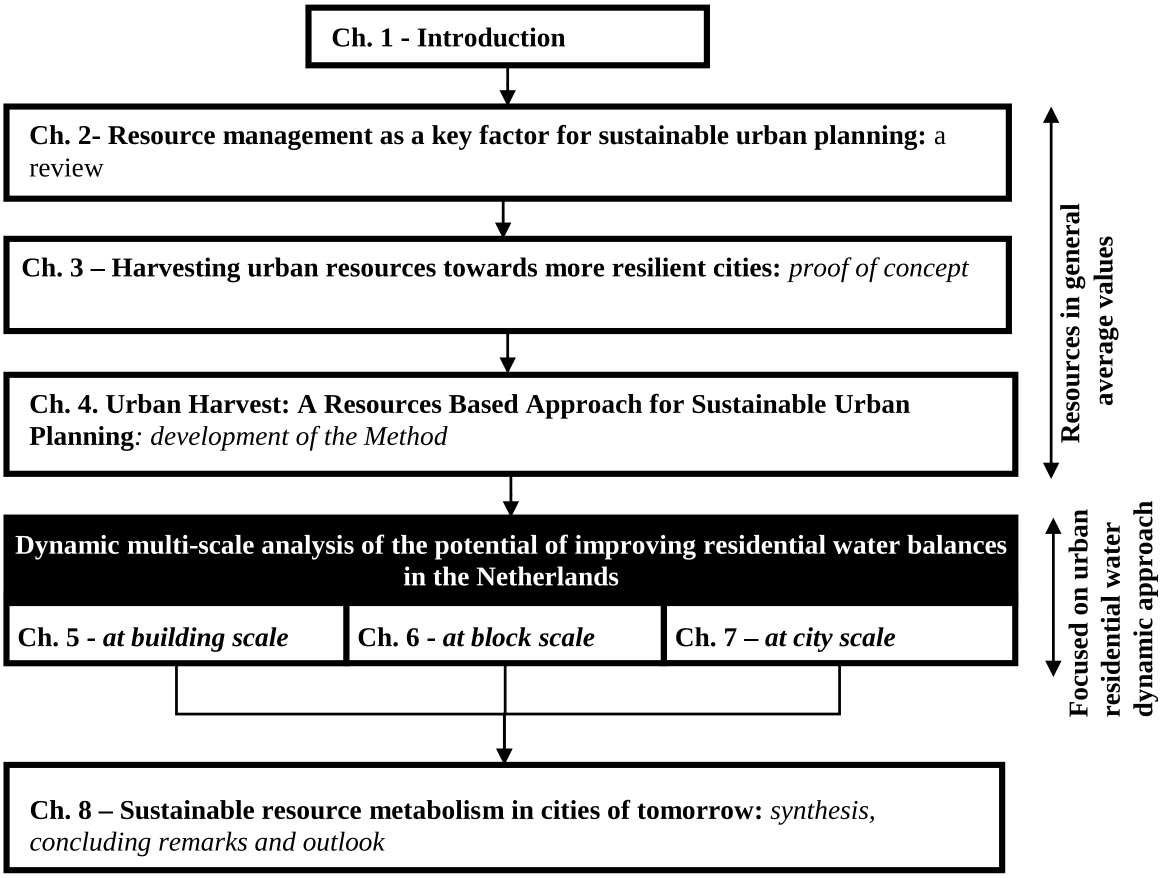

Fig 1. Schematische weergave van de inhoud van dit proefschrift

Op gebouwniveau (**hoofdstuk 5**) zijn twee typen gebouwen geselecteerd: een vrijstaand huis en een appartement. De onderzochte scenario's bevatten verschillende strategieën zoals het minimaliseren van de vraag, en het verkrijgen van secundaire kwaliteit water voor toiletspoeling en wasmachinegebruik door recyclen van licht grijs water (LGW) en het opvangen van regenwater (*multi-sourcing*). De resultaten tonen aan dat waterbesparende apparatuur 35% van de conventionele vraag kan verminderen. Recyclen van LGW kan 20% van de geminimaliseerde vraag leveren (100% van de vraag van water met secundaire kwaliteit). Om deze mogelijkheden te benutten, zijn andere systeemspecificaties, gerelateerd aan het gebouwtype, nodig. Twee beperkingen met betrekking tot *recycling* en *multi-sourcing* werden geïdentificeerd. Zij zijn gerelateerd aan de vraag en de geoogste fractie van het aanwezige potentieel. Beperkingen met betrekking tot de vraag zijn gerelateerd aan productie van grijswater en de beschikbare neerslag. Verder hangen beperkingen met betrekking tot de geoogste fractie af van het temporele patroon, de opslag en de capaciteiten voor behandeling van het water.

In **hoofdstuk 6** werden seizoensgebonden dynamische waterbalansen onderzocht op het niveau van stedelijke huizenblokken. Twee huizenblokken zijn geanalyseerd: één met een lage dichtheid en één met een hoge dichtheid. In de scenario's onderzochten we de minimalisering van de vraag van water met drinkwater kwaliteit, en LGW-recycling en de opvang van regenwater om te voorzien in de vraag van secundaire kwaliteit water. Bovendien is het gebruik van groene daken voor waterretentie ook geanalyseerd. De resultaten tonen grote seizoensgebonden variaties in de waterbalans van het huizenblok met lage dichtheid. Voor dit type huizenblok werd 18% input-minimalisering en zelfvoorziening bereikt. De *Waste Output Index*, *WOI* (afval / vraag), werd teruggebracht van 97% naar 73%. Voor het huizenblok met hoge dichtheid werd 23% input-minimalisering, 18% zelfvoorziening, en een vermindering in *WOI* van 123% naar 104% bereikt.

In **hoofdstuk 7** werd de waterhuishouding op stedelijke schaal onderzocht. Wageningen, een kleine Nederlandse stad, werd gebruikt als casus om de resultaten te valideren. De resultaten toonden aan dat specifieke karakteristieken van de verschillende gebieden (buurten) in de scenario's moeten worden meegenomen om optimale resultaten te bereiken. Dit houdt in dat steden een portfolio aan maatregelen tot hun beschikking moeten hebben om het stedelijk water-metabolisme te verbeteren, door juist rekening te houden met de kenmerken van de buurt of het huizenblok. Een combinatie van maatregelen leverde een vermindering op van 14% van de stedelijke watervraag en een zelfvoorzieningsgraad van 34%. Lokaal bepaalde stedelijke karakteristieken kunnen als kansen voor uitwisseling van grondstoffen (waaronder water) worden gezien. In de onderzochte gevallen heeft de stad vaak het potentieel om secundair water te exporteren. De resultaten tonen ook aan dat de verschillende grondstofstromen op verschillende ruimtelijk schalen moeten worden beheerd. Bovendien is een combinatie van gecentraliseerde en gedecentraliseerde maatregelen nodig. Verder zijn voor bepaalde mogelijkheden niet alleen de interne kenmerken van de stad belangrijk maar ook de externe omgeving. Er zijn drie opties geïdentificeerd om de stedelijke waterkringloop te verbeteren: (i) technologie implementatie, (ii) veranderingen in de stedelijke oppervlakken, en (iii) grondstof uitwisseling door export en import op de diverse ruimtelijke schalen.

Kortom, het evalueren van het stedelijk watermetabolisme vraagt om een dynamische benadering op verschillende ruimteschalen. Zo'n benadering is adaptief en flexibel en kan omgaan met de stochastisch gedreven dynamiek van de stedelijke waterhuishouding. De beschreven UHA verbindt stedelijke kenmerken met mogelijkheden om water te oogsten en her te gebruiken, en zo de stedelijke water kringloop te helpen verduurzamen. UHA kan gebruikt worden door stedelijke planners en beleidsmakers om het stedelijke systeem en zijn interne hulpbronnenstromen te begrijpen en om oplossingen op maat te vinden (**hoofdstuk 8**). Voor de bevoorrading van voldoende hulpbronnen, zoals voedsel, energie en water, in dichtbevolkte stedelijke gebieden, is het nodig om, naast UHA voor de stedelijke systemen, een dergelijke benadering ook voor agro-industriële complexen mee te nemen. Dit vormt daarom een belangrijk punt voor toekomstig onderzoek. Daarnaast moeten voedsel, water, nutriënten en andere management systemen voor grondstoffen worden beschouwd op de schaal van de regio, het stroomgebied of de verstedelijkte delta om het potentieel van alle duurzame hulpbronnen ten volle te benutten.

Table of abbreviations

Symbol	Definition
CS	Combined sewer
DIA	Disconnected impervious area
hh	Household
LGW	Light grey water
PUH	Potential Urban Harvest
PV	Photovoltaic
Qr	Un-used remaining Quality
Qs	Quality surplus
RS	Resource Management
SD	Sustainable Development
SS	Separated sewer
Ti	Total inputs
To	Total outputs
UHA	Urban Harvest Approach
UMTH	Urban Maximum Technical Harvest
UP	Urban Planning
UrbAT	Urban Average Tissue
UrbAT-NL	Dutch Urban Average Tissue
UT	Urban Tissue

Table of units

Symbol	Units
d	Day
GJ	Giga Joule
h	Hour
ha	Hectare
kg	Kilogram
l	Liter
m	Meter
mg	Milligram
min	Minutes
MWh	Megawatt hour
p	Person
y	Year

Table of symbols

Symbol	Definition and units
A^i	Area of surface *i* in m² or in ha
ds/dt	Change in storage per unit of time
D	Actual demand in volume per time per unit of study. E.g. ($l\ p^{-1}\ d^{-1}$), ($m^3hh^{-1}\ y^{-1}$), ($m^3\ block^{-1}\ season^{-1}$)
D_{con}	Conventional demand in volume per time per unit of study. E.g. as *D*
D_{Q1}	Demand of potable water in volume per time per unit of study. E.g. as *D*
D_{Q2}	Demand of non-potable water m³ in volume per time per unit of study. E.g. as *D*
D_{Q2}^{ind}	Indoor demand of non-potable water m³ in volume per time per unit of study. E.g. as *D*
D_{Q2}^{out}	Outdoor demand of non-potable water m³ in volume per time per unit of study. E.g. as *D*
DMI	Demand Minimization Index [-]
DWW	Domestic wastewater m³ in volume per time per unit of study. E.g. as *D*
Ei	External input in volume per time per unit of study. E.g. as *D*
Ei_{Q1}	External input to supply D_{Q1} for domestic use in volume per time per unit of study. E.g. as *D*
$Ei_{Q1}^{i\&b}$	External input to supply D_{Q1} for industries and businesses m³ in volume per time per unit of study. E.g. as *D*
Ei_{Q2}^{ind}	External input to supply D_{Q2}^{ind} in volume per time per unit of study. E.g. as *D*
Ei_{Q2}^{out}	External input to supply D_{Q2}^{out} in volume per time per unit of study. E.g. as *D*
Er_{Q2}	Exported resources of secondary quality in volume per time per unit of study. E.g. as *D*
ET	Evapotranspiration in volume per time per unit of study. E.g. as *D. (Optionally can be expressed in mm h^{-1} given a specific area where the evapotranspiration occurs)*
ET_{act}^{i}	Actual Evapotranspiration from surface *i* in volume per time per unit of study. E.g. as *D (Optionally in mm h^{-1} as ET)*
ET_{pot}	Potential Evapotranspiration in volume per time per unit of study. E.g. as *D. (Optionally in mm h^{-1} as ET)*
I^i	Infiltration through surface *i* in volume per time per unit of study. E.g. as *D. (Optionally in mm h^{-1} as ET)*
Ir_{Q2}	Imported resources of secondary quality in volume per time per unit of study. E.g. as *D (Optionally in mm h^{-1} as ET)*
k	Volumetric treatment capacity in volume per time E.g. as $m^3\ d^{-1}$
k_{soil}	Soil hydraulic conductivity mm h^{-1}
M_{pot}	Potential multi-sourcing in volume per time per unit of study. E.g. as *D*
M_{act}	Actual multi-sourcing in volume per time per unit of study. E.g. as *D*
N_{rec}	Natural recharge in volume per time per unit of study. E.g. as *D*
O^{CS}	Overflow of the combined sewer system in volume per time per unit of study. E.g. as *D*
$O^{S\&T}$	Overflow of storage and treatment unit in volume per time per unit of study. E.g. as *D*
O^{SS}	Overflow of the separated sewer system in volume per time per unit of study. E.g. as *D*
P^i	Precipitation falling in surface *i* in volume per time per unit of study . E.g. as *D. (Optionally in mm h^{-1} as ET)*
R_{pot}	Potential recycling in volume per time per unit of study. E.g. as *D*
R_{act}	Actual recycling in volume per time per unit of study. E.g. as *D*
RC	Runoff Coefficient [-]
RC_e	Effective runoff collected by the combined sewer [-]
Rh_{Q2}^{ind}	Resources harvested to supply D_{Q2}^{ind} in volume per time per unit of study. E.g. as *D*
REI	Resource Export Index [-]

Rh_{Q2}^{out}	Resources harvested to supply D_{Q2}^{out} in volume per time per unit of study. E.g. as *D*
Ro_{pot}^{roof}	Potential roof runoff m³ in volume per time per unit of study. E.g. as *D*
Ro_{act}^{roof}	Actual roof runoff m³ in volume per time per unit of study. E.g. as *D*
Ro^{i}	Runoff of surface *i* in volume per time per unit of study. E.g. as *D*
Ro^{CS}	Runoff discharged into the combined sewer system in volume per time per unit of study. E.g. as *D*
Ro^{SS}	Runoff discharged into the separated sewer system in volume per time per unit of study. E.g. as *D*
RT	Hydraulic residence time [day]
S^{block}	Block storage capacity (sum of all storage units) in volume [m³]
s	Actual storage in the block in volume [m³]
S^{CS}	Storage capacity of the combined sewer system in volume E.g. l or m³
s^{CS}	Actual storage in the combined sewer system in volume E.g. l or m³
S^{i}	Storage capacity of surface *i* in volume E.g. l or m³. *(Optionally can be expressed in mm given a specific area* A^{i}*)*
s^{i}	Actual storage in surface *i* in volume E.g. l or m³. *(Optionally in mm as in* S^{i}*)*
S^{roof}	Storage capacity of roof surface in volume E.g. l or m³. *(Optionally in mm as in* S^{i}*)*
s^{roof}	Actual storage in roof in volume E.g. l or m³. *(Optionally in mm as in* S^{i}*)*
$S^{S\&T}$	Storage capacity of storage and treatment unit in volume E.g. l or m³
$s^{S\&T}$	Actual storage in storage and treatment unit in volume E.g. l or m³
S^{SS}	Storage capacity of the separated sewer system in volume [m³]
s^{SS}	Actual storage in the separated sewer system in volume [m³]
SSI	Self-sufficiency Index [-]
VE	Volumetric efficiency [-]
We	Waste exported in volume per time per unit of study. E.g. as *D*
WOI	Waster Output Index [-]
WW	Wastewater in volume per time per unit of study. E.g. as *D*
$WW_{i\&b}$	Wastewater from industries and businesses in volume per time per unit of study. E.g. as *D*

Table of subscripts

Symbol	Definition
act	Actual
con	Conventional
e	Effective
hh	household
i&b	Industries and business
pot	Potential
Q1	Quality 1 – Potable water
Q2	Quality 2 – Non-potable water
rec	Recycled
ss	Sub-systmen
soil	Soil

Table of superscripts

Symbol	Definition
block	Block
CS	Combined sewer
i&b	Industries and business
ind	Indoor
out	Outdoor
roof	Roof
S&T	Storage and treatment
SS	Separated system

About the author

Claudia Marcela Agudelo Vera was born on 28th of October 1979 in Bogotá, Colombia. In 2001 she graduated as Civil engineer from the Universidad Nacional de Colombia. She worked for five years as a structural design engineer at Proyectistas Civiles Asociados in Colombia. She participated in the structural design of residential complex, office and commercial buildings. From 2005-2007 she followed the master Urban Environmental Management at Wageningen University. During her internship, she worked on promoting knowledge exchange between the Netherlands, Germany and Spain in the field of sustainable enterprise. During her master thesis, she worked on the development of a multi-criteria framework for the selection of urban sanitation systems. In September 2007, she started her PhD project within the European project “SWITCH”. Sustainable Water management Improving Tomorrow’s Cities’ Health. During the year 2008-2009 she worked part time as docent at Wageningen University teaching and supporting education activities in the master courses Urban Environmental Management and Managing Urban Infrastructure. Her main interest is finding innovative and tailor-made solutions towards sustainable urban systems, by integrating resources management, technology implementation and innovative governance and planning models.

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Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment

C E R T I F I C A T E

The Netherlands Research School for the
Socio-Economic and Natural Sciences of the Environment
(SENSE), declares that

Claudia Marcela Agudelo Vera

born on 28 October 1979 in Bogotá, Colombia

has successfully fulfilled all requirements of the
Educational Programme of SENSE.

Wageningen, 20 June 2012

the Chairman of the SENSE board

Prof. dr. Rik Leemans

the SENSE Director of Education

Dr. Ad van Dommelen

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

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The SENSE Research School declares that **Ms. Claudia Marcela Agudelo Vera** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 53 ECTS, including the following activities:

SENSE PhD courses

- Environmental Research in Context
- Research Context Activity: Co-organizing symposium on Sustainable Cities - Closing water, energy and material cycles, 17 May 2010, Wageningen
- Research Methodology I: from topic to proposal

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- Water Risk Management
- Safe and Sustainable Sanitation
- Teaching and supervising Thesis students
- Teaching Methodology and Skills
- Techniques for Writing and Presenting a Scientific Paper

Management and didactic activities

- Co organizing and chairing a session in the Conference The Future of Urban Water Solutions for Liveable and Resilient Cities UNESCO, Paris, France – 24-26 January 2011
- Lecturing in diverse courses of the Urban Environmental Management Master
- Student supervision of master thesis

Oral Presentations

- *Multi-criteria framework for the selection of urban sanitation systems.* 2nd scientific SWITCH meeting, November 2007, Tel-Aviv, Israel
- *URBAN Water Tissue analysing the urban water harvest potential,* Smart and Sustainable Built environments, June 2009, Delft, Netherlands.
- *Urban harvest approach, a resource based tool for urban design.* SENSE Symposium Climate Proofing Cities, December 2009, Katwoude, Netherlands
- *Urban Harvest Approach: Towards sustainable resource management in cities.* Third International Conference on Eco-Efficiency - Modelling and Evaluation for Sustainability, June 2010, Egmond aan Zee, Netherlands
- *Harvesting domestic urban water to achieve neutral cities.* Water Cities in Transition Conference, January 2012, Amsterdam, Netherlands

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