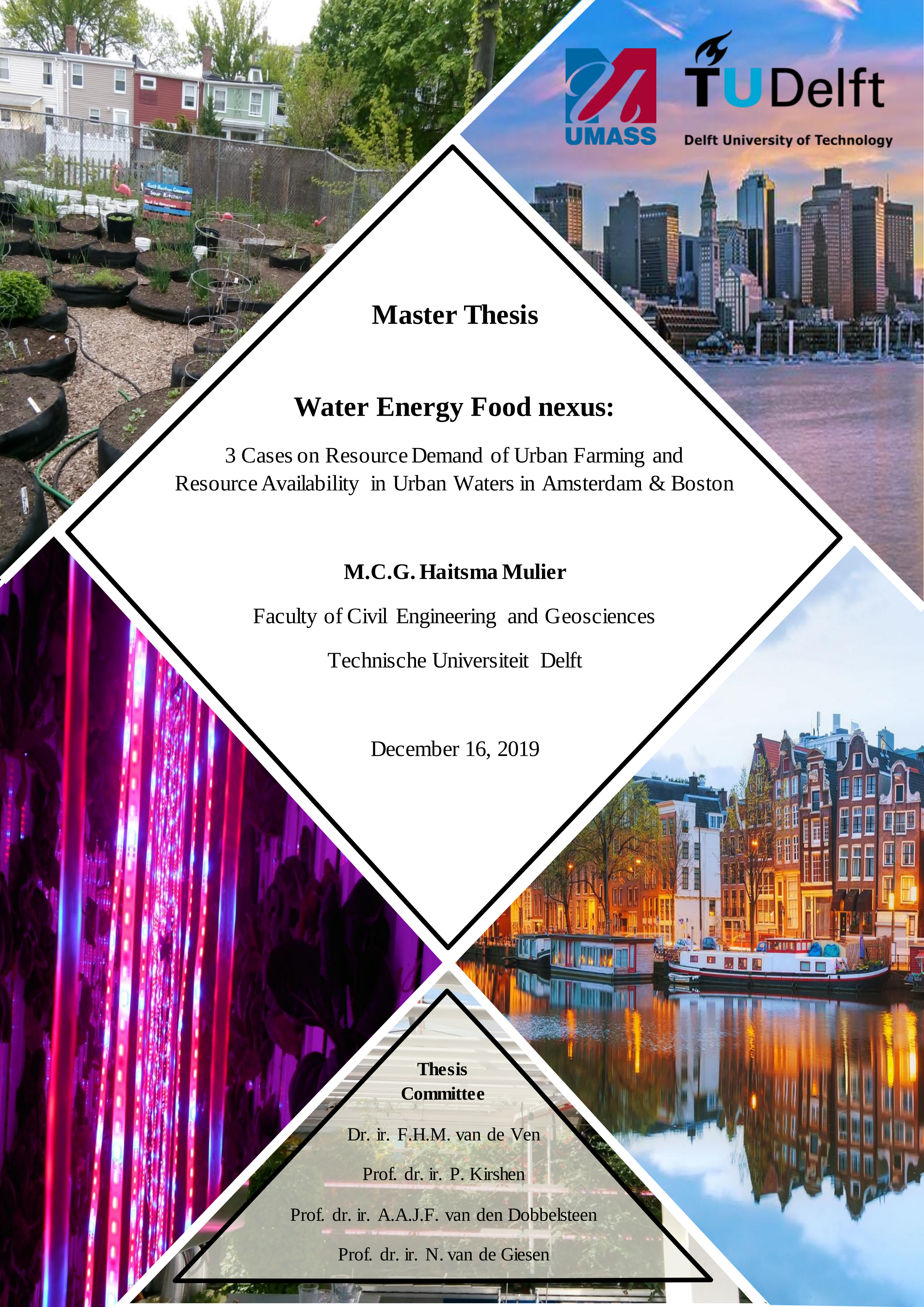

Master Thesis

Water Energy Food nexus:

3 Cases on Resource Demand of Urban Farming and Resource Availability in Urban Waters in Amsterdam & Boston

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Abstract

Urban agriculture lies at the core of the Water Energy Food nexus and seems to provide a partial answer to confront modern trends such as population growth, climate change and resource depletion by increasing food security in cities and enhancing sustainability in an urban realm. The assembly of a WEF nexus framework taught, however, that most work that has been published on the nexus is very hypothetical and that the acquisition of quantitative data poses the biggest challenge in WEF nexus research. The mere absence of data collected at a local level impedes informed decision making on nexus sector integration and feasibility of sustainable solutions.

This study attempts to bridge the existing knowledge gap and aimed to contribute to the quantification of the nexus regarding urban agriculture. It investigates the water, energy and nutrient demand of urban farms along with the presence of those resources in urban waters at three case study sites. Demands for water and nutrients (nitrogen & phosphorus) at a greenhouse in Amsterdam and a community farm and a container farm in East-Boston could be met by resources present in urban waters (rainwater and wastewater) in the direct vicinity. Whether enough energy is available to run each of these farms is related to the type of agriculture which is applied.

Keywords: Water Energy Food Nexus, Urban Farming, Resource Reuse, Circularity, Urban Water

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1 Introduction

Most urban systems for the provision of food, water and energy (FWE) to residents and businesses are relatively large-scale networks, often operated independently by separate organizations or companies without much awareness of linkages to social and environmental systems. Decentralization in water, energy and food management could be a sustainable solution, while simultaneously encompassing more interactions and interdependencies of FWE services (Daigger, 2009; Kurian, 2017). Consistent with the existing trend of a growing demand for locally produced food, urban agriculture and local, decentralized food systems are becoming a worldwide movement.

Consumer interest in local foods is reflected in the continued growth of the number of farmers markets. The number of farmers' markets in the USA rose from 1,755 in 1994 to 2,756 in 1998 to 5,274 in 2009 (USDA AMS, 2009). At the start of 2018, already over 8,700 local farmers markets could be found in the US (USDA AMS, 2018). The occurrence of community supported agricultural organizations (CSAOs) showed a similar pattern. The number of CSAOs increased from 2 in 1986 to 761 in 2001 and to 1,144 in 2005 (Adam, 2006).

Although definitions of 'locally produced food' slightly differ, and literature is inconsistent in its use of definitions, a general trend can be noticed. Brown (2003) found that local products were perceived to be of higher quality and lower price by the majority of consumers. Findings from South Carolina even show that consumers are willing to pay on average 27% more for local produce (Carpio & Isengildina-Massa, 2009).

Also in the scientific world, urban agriculture has been the topic of an increasing amount of published articles in scientific databases on the topic recently (fig. 1).

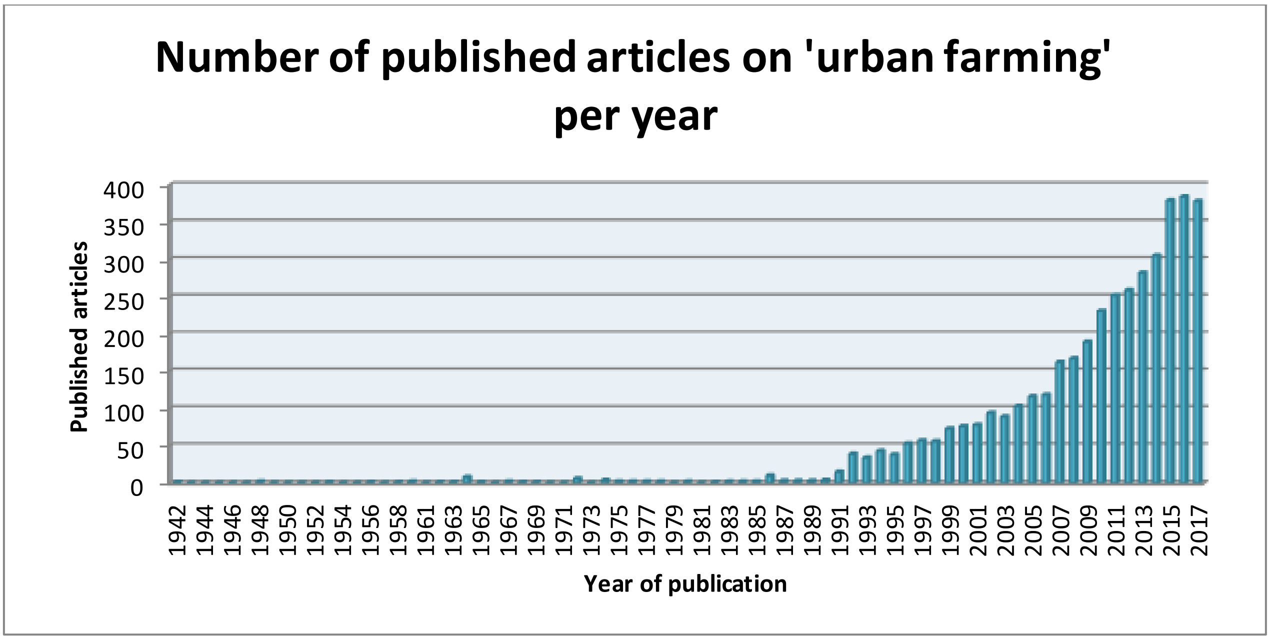


Figure 1 Number of articles published on 'urban farming' per year in the Web of Science database

1.1 Definition of urban agriculture

Before we continue, it is key to provide the definition of urban agriculture that will be utilized in this article, especially since different definitions of urban agriculture are being used in literature.

- According to Zezza & Tasciotti (2010) urban agriculture is the production of crop and livestock goods within cities and towns.
- Moustier & Mbaye (1999) narrowed it down to "agriculture located within a city or on its periphery, of which the products must at least partly be destined for the city and for which alternative agricultural and non-agricultural uses of resources are possible".
- But the most extensive description is from Mougeot (2000): "Urban agriculture is an industry located within (intra-urban) or on the fringe (peri-urban) of a town, a city or a metropolis, which grows or raises, processes and distributes a diversity of food and non-food products, (re-)using largely human and material resources, products and services found in and around that urban area, and in turn supplying human and material resources, products and services largely to that urban area."

Although these definitions are in essence very similar, there are also considerable deviations. Some set much more elaborate requirements for resource origin and area of consumption than others.

Moreover, one can doubt what the definition of an urban area exactly is. What is to be considered "urban" is contentious. Of course, it relates to the characteristic of a town or a city, but if a city is defined as a large town (Oxford Dictionaries, 2010), then what is a town? Exact definitions of a town differ from place to place. But the concept is clear. It is a place with a relatively high density of buildings and people.

On the definition of agriculture as 'the practice of farming, including cultivation of the soil for the growing of crops and the rearing of animals to provide food, wool, and other products' exists more consensus (Oxford Dictionaries, 2010). However, as this thesis will focus on arable farming, and thus livestock farming will not be taken into account, a practical and new definition for urban agriculture will be utilized in this article, combining the previous descriptions.

Urban agriculture is:

The production of crops, which must at least partly be destined for the city, and located within or on the fringe of a village, town, city or a metropolis.

Certain global trends promote the introduction or expansion of farming initiatives in cities, as this form of agriculture is believed to respond adequately or even overcome some of the biggest challenges the world faces nowadays, such as population growth, urbanisation, climate change, environmental pollution and resource depletion. Many of these challenges influence food security negatively.

1.2 Food security

The concept of food security is based on three elements: food availability, food access and utilisation. Food availability is affected by production and distribution of food, whereas food access includes affordability and whether or not food preferences (e.g. cultural norms) are met in sufficient quantities (Leck et al., 2015). The utilisation aspect deals with the nutritional value and food safety. When sufficient, affordable, culturally appropriate, nutritious food is physically available, and people are able to meet their dietary needs, areas and/or communities are considered to be food secure (FAO, 1996).

Before the time-space compression had started, in ancient civilizations (like the Mayas), urban food production was abundant and served food security in daily life and especially, self-sustainability in times of war, trade conflicts (Barthel & Isendahl, 2013). Nowadays, in the western world, food availability is more secure, due to connections with worldwide food production and relatively reliable transport networks. Nevertheless, in 2013, 14.3 % of American households were food insecure for at least some time and 5.6 % experienced such a low food security that eating patterns were disrupted because of a reduced food intake, as a result of the household's lack of money and other resources for food (Coleman-Jensen et al., 2014). The prevalence of food insecurity was most common in principal cities of metropolitan areas (16.7%). However, nothing was found about potential logistical problems for food supply to cities. What was found is that food security is strongly income-related. Rates of food insecurity in American households with annual incomes below the official poverty line (42.1%) were substantially higher than the national average.

Not only high food prices or unavailability of food can cause food insecurity. Also the logistics with regard to obtaining groceries are playing a role. The expansion of megastore supermarkets has forced the smaller, neighbourhood grocery shops to close, thereby creating regions where affordable, varied food is only accessible to those who have access to a car, or those able to pay public transportation costs (Guy et al., 2004).

Low food-secure people acquire more obesity-promoting foods compared to food-secure participants (Nackers & Appelhans, 2013). These findings correlate with the identification of a positive relationships between food insecurity and obesity by Adams et al. (2003). Beside obesity, food insecurity is associated with a broad spectrum of other health problems, including mental health problems such as depression and anxiety in children and mothers from low-income families (Whitaker et al., 2006). Ensuring food security may improve these health problems (Cook et al, 2004)

1.3 Grand Challenges

Food security is linked to some of the grand challenges that humanity faces these days. Population growth, urbanisation, climate change and variability, shifting resource use patterns, environmental change, poverty and inequitable access to social services all influence food security on both a global as well as on a local level (Kurian, 2014).

1.3.1 Population growth

The first of these challenges, is the vastly increasing human population on the planet.
According to the United Nations' Department of Economic and Social Affairs, the amount of people will grow from 7.55 billion by 2017 to 8.6 billion in 2030 and from 9.8 billion in 2050 to 11.2 billion by the start of the next century (UN DESA, 2017). All these people need to be fed. Population growth combined with the shift in diet in developing countries, is projected increase the food production requirements in the future by 70% and resource competition might pose a fundamental issue (Fabiola & De Rosa, 2016). Fortunately, from the 1990's on, the rate of global food production has increased quicker than the rate of global population growth. Holt-Giménez et al. (2012) claimed that in 2012 the world produced already enough food for 10 billion people, more than the world's projected population by 2050. However, food is not allocated adequately. Nowadays, hunger is caused by poverty and inequality, not by scarcity (Holt-Giménez et al., 2012).

1.3.2 Urbanisation

Next to population growth, urbanisation jeopardizes the food security of a certain part of the population. Global urbanization rates are currently around 2% annually. In developed countries this demographic phenomenon usually takes place at a slower pace (World Bank, 2016-1). This year-long trend resulted in the fact, that in 2016, 54% of the global population, the largest percentage until then, lived in a city (World Bank, 2016-2).
This means that in the future not only enough food needs to be produced to feed more people, at the same time, consumers and thus the demand for food are more concentrated than ever. Because of the large local demand for food, away from large-scale production sites located outside the urban areas, urban populations in general experience a lower food security than rural communities (Opitz et al., 2015; Walsh & Van Rooyen, 2014).

For a more equal food security, a better allocation of food resources must thus be realized. However, in order to become less reliant on other areas with a more copious food security, urban societies can take matters into their own hands, running agricultural initiatives in the city. When next to conventional agricultural sites new incentives in cities will start to produce food products, a larger production can be realised. Following the theory of Smith (1776), the larger the production of a good, the lower its price on the market. In this way, urban agriculture cannot only increase the availability of nutritious food in a city, but also increase the accessibility by making the food more affordable.

1.3.3 Environmental challenges

One of the pollution threats that arises from urban areas, is that all the people living there are producing sanitary organic waste. This needs to be treated before being discharged in order to prevent deoxygenation of natural waters, which is a treat to aquatic life (Metcalf & Eddy, 2003). Moreover, nutrients in sewage and stormwater runoff can cause eutrophication of waters, if not treated properly, and can lead to oxygen depletion and reduction in biodiversity.
Besides the threat that extra sanitary waste brings along, the required extra food production to provide for the growing and more prosperous population can challenge the environment. Tukker (2006) found that the food system as a whole is one of the largest contributors to the environmental impact in society, food transportation was identified as a major component of that impact. Reducing

transport of edible goods, by producing locally, would thus have a positive effect on reducing the societal environmental impact.

According to Coley et al. (2009), there is however a break-even point for travel distances by local consumers and large-scale food transportation in terms of carbon emissions. When the purchase of local vegetables requires a round-trip journey of more than 6.7 km, carbon emissions are likely to be greater than the emissions in a large-scale, centralized food production chain.

The same is true for emissions released during generation of energy for large scale irrigation with massive pumping requirements and the energy required to transport water to urban farms. This raises the question if water supply to conventional large-scale farms is indeed more energy intensive than getting water to urban farms. Obviously, this would depend on the distance that the water needs to travel, the characteristics of the piping system that it travels through and the local climate conditions.

When only a small distance needs to be travelled for local food, local production appears to be more ecologically sustainable. However, any ecological benefit from using less fuel for transport could be outweighed by the need for massive water inputs (Born & Purcell, 2006). Therefore, urban agriculture is only environmentally beneficial when the environmental costs of transport are higher than the emissions caused by water pumping and should from this point of view only take place in urban areas with sufficient rain and wastewater supply to water the farms.

1.3.4 Climate change

Cities, compared to rural areas, are particularly vulnerable to climate change (Gondhalekar & Ramsauer, 2017). For example, the high density of built and sealed surfaces causes an urban heat island effect in warm weather and flooding as a result of heavy rain (EEA, 2012; Kuttler, 2010).

Next to the demographic challenges, climate change, can legitimize the expansion of urban farming initiatives. Crops need a certain temperature and water feed during different growing stages, but the availability of natural resources feeding the traditional agricultural plots, like water and energy, is projected to change due to climate change. In general, crops will have to cope with more extreme weather conditions. Depending on the location of farming, farmers and their cultivated plants also will have to adapt to phenomena like dry spells and heavy rains, in other words, the sector needs to cope without or with an excess of water resources more often (Trenberth et al., 2013).

Heat waves are likely to become more frequent with global warming (IPCC, 2007). Although increasing carbon dioxide concentrations will directly increase the efficiencies of resource utilization of crops, and although global warming will create more advantageous conditions for agriculture in areas such as Northern Europe, where low temperatures used to limit agriculture, globally the crop yields have decreased by 1–2% per decade over the past century, due to climate change (Olesen and Bindi, 2002; Wiebe et al., 2015). Global warming will increase the length of the growing period in the global north and may turn areas that were too cold before into suitable farming land. However, negative effects of climate change on food production will particularly be felt in low latitude regions (Fischer et al., 2005). Physiological processes in crops get disturbed by excessive heat. Also, reduction in moisture availability or extreme heat can shorten limits the length of the growing season in tropical regions (IPCC, 2014).

In many forms of urban agriculture, the growing conditions, such as water provision and energy supply via light and favourable temperature, can be controlled (partially) depending on the availability of the resource.

By implementing storage facilities, and only adding the optimum water, energy and nutrients to the crop, resources can be spared, and extremes can be smoothened, which is convenient during both times of scarcity and excess. In this way, the adverse effect of climate change on agricultural production can be minimized. In addition, urban agriculture showcases possibilities to re-use resources from the urban environment, thereby reducing transport and treatment emissions, and providing a humble contribution to limiting climate change.

1.3.5 Scarcity of resources

In order to farm, several resources are required. Water is needed for photosynthesis, which provides the plants with glucose and allows a crop to grow. Another crucial resource is energy. Not only can most plants only grow within certain temperature ranges, plants also need energy in the form of light to perform photosynthetic, energy consuming reactions. In traditional outdoor agriculture, this energy is provided by the sun, but when the production takes place indoors, and the farm is not a greenhouse allowing enough sunlight inside, energy needs to be added via lamps and heaters. Finally, crops require nutrients. Nutrients are indispensable for growth and development, for biochemical reactions, and for the production of organic materials such as carbohydrates, proteins, fats, vitamins (Roy et al., 2006).

1.3.5.1 Water

Agriculture is currently the largest water consuming sector at the global level, accounting for 70% of total withdrawal (Fabiola & De Rosa, 2016). Differences between countries, however, are large. In 2016, the agricultural sector in The Netherlands used a total of 120.1 million m^3 of water (0.7% of national water use), from which 20.1 million m^3 was surface water, 43.6 million m3 was tap water and 56.4 million m^3 was groundwater (CBS, 2017-1). In the US, a gigantic amount of water (174,422 million m^3) was used in the agricultural sector in 2010, accounting for 32% of the national freshwater withdrawals that year (fig. 2) (EIA,2017-1; EIA,2017-2; Maupin et al., 2014).

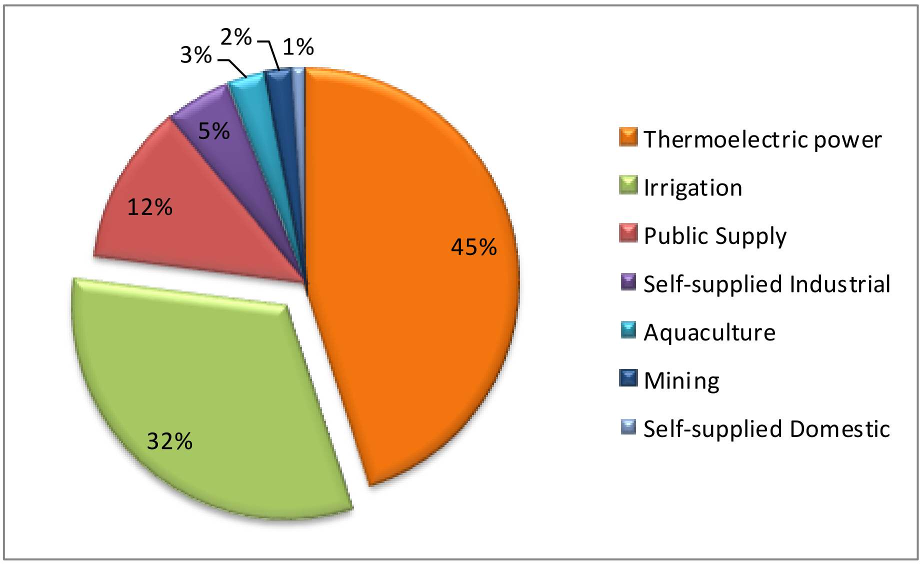


Figure 2

Freshwater withdrawals per sector in the United States of America in 2010.
(Data source: Maupin et al., 2014)

In urban areas, the ratios are different, as in the urban water cycle more than 80% of the water is used by households, industrial and commercial sectors (Carey, 2013). A study in Toronto pointed out that the inputs of water increased marginally less than the population growth (Sahely et al., 2003). Given the fact that both the world population and the percentage of the population living in urban areas will increase, it seems likely that the urban water demand will rise as well.

Although urban agriculture only accounts for a small part of this enormous water use, urban agricultural initiatives, like any agricultural initiative, need water. Fact is that every city on earth contains at least has two water flows: rain and wastewater. These flows are often considered waste flows. Via sewer and drainage systems, cities often try to discharge them as fast as possible. Retention of this water, however, has many advantages (e.g. possibilities for water reuse, nutrient & energy recovery and a reduction of flood risk). Why would we try to get rid of a valuable resource, when it can be used nearby?
Both waste and rain water have their challenges for use in urban agriculture. Being fully dependent on the clean rainwater, saves money on treatment costs, but makes the production susceptible to droughts. Building storage to catch water during wetter periods can solve this, but those require space and financial resources. Wastewater is able to provide a more constant water supply, but this stream has been polluted, and is therefore unsuitable for direct reuse.

An assessment on required quantity for agricultural production and available water resources with various temporal, quality, and management cost properties should prove which of the two sources or what combination of them should be applied in order to make the farm water secure.

1.3.5.2 Energy

Food production and supply chain logistics account for about 30% of total global energy consumption and more than 70% of the global energy consumption occurs in urban areas (IEA, 2008; Fabiola & De Rosa, 2016). However, urban agriculture, or agriculture as a whole, is only responsible for a relatively small part of global energy consumption (fig. 3). In 2018, the Dutch agricultural sector was expected to use 170 PJ of energy (8% of national energy use) and in the USA 1,130 PJ of energy was used by farms, accounting for 1% of the national energy use in 2018 (ECN, 2017; EIA,2017-1; EIA,2017-2).

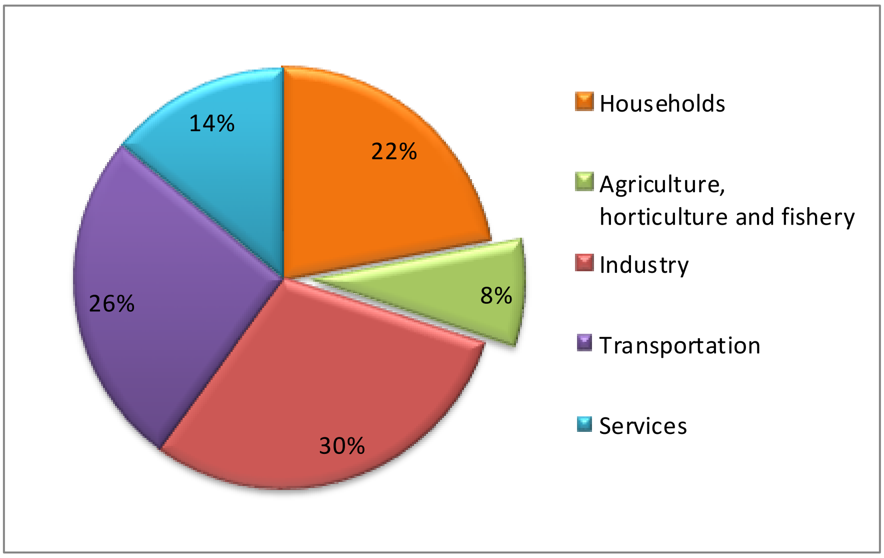


Figure 3

Final energy use per sector in the Netherlands
(Data source: ECN, 2017)

This large amount of energy may potentially be recovered from the two urban water sources mentioned in the water section. Apart from the potential height energy from both sources that may be present in sloped areas, wastewaters often contain residual heat. This thermal energy can be harvested via heat exchangers. When wastewater with a high organic content is treated anaerobically, energy can be recovered too. After some screens and a grid chamber, a simple methanogenic upflow anaerobic sludge blanket rector (UASB) can be installed, converting the biodegradable organic matter in the water into biogas.

1.3.5.3 Nutrients

Another global challenge, supporting the implementation of urban agriculture, is the depletion of resources to produce plant fertilizer. Via fertilizers, nutrients are artificially added to crops, with the intention to create optimal growing conditions of the plant. Agricultural crops, like all plants, need to be supplied with macronutrients and micronutrients. All of nutrients are equally important, regardless of the amount required, and need to be added in a balanced ratio (Roy et al., 2006).

So-called macronutrients, like nitrogen, phosphorus and potassium, are the elements, that after carbon, hydrogen and oxygen, are most abundant in dry plant matter (table 10, section 6.4), they are often added during the production process using so called NPK-fertilizers. This research will focus on nutrients in the form of nitrogen and phosphorus, as these compounds can be harvested relatively easily from urban wastewaters.

The nitrogen-element by itself, is not rare. However, it needs to be present in a certain form for plants being able to absorb it, and those particular configurations are a lot scarcer. Phosphate availability is a whole different story. With 82% of the global phosphate demand, the agricultural fertilizer industry is the largest consumer of the resource (Schroder et al., 2009). However, limited accessibility and depletion of the phosphorus stocks, are jeopardizing the fertilizer production in the future. Cordell et al. (2009) project the non-renewable resource, nowadays mined from phosphate containing rock, may be depleted between 2060 and 2110.

The realization that a phosphorus shortage can result in a reduced food security, may contribute to a societal cry for sustainability and may encourage the development towards a more circular agro-economy. By placing agricultural production locations in an urban environment, use can be made of resources that are otherwise wasted in the urban system. Wastewater streams for example are a famous source of phosphorus and nitrogen bound compounds. Harvesting these can be done via a range of different techniques (Sengupta et al., 2015). 70 to 92 % of nitrogen can be recovered from anaerobic digestate (the waste product of biogas production) via air stripping of ammonia. Phosphorus can be recovered from wastewater streams in the form of fertilizer (struvite) through chemical precipitation. This process has an efficiency of 80 to 99%. When a recovery in the form of fish/animal feeds and biofuel is preferred, constructed wetlands can be used. Those recover 83–87 % of nitrogen and 70–85 % of phosphorus from wastewaters, through biological assimilation.

In cases where the streams were left untreated before, recovery of nitrogen and phosphorus from and urban wastewaters and urban agricultural streams, not only reduced natural resource depletion, it also results in a reduction of the eutrophication problem as additional benefit.

1.4 Water Energy Food nexus

If certain conditions, such as the presence of sufficient amounts of water, nutrients and space are met in combination with accessibility to consumers, urban agriculture seems to provide a part of the answer to confront the modern trends such as population growth, urbanisation, climate change, environmental pollution and resource depletion by increasing food security in cities, reducing inequity in food accessibility and enhancing sustainability.

The challenges mentioned before all influence stocks or fluxes in the so-called Water Energy Food nexus (fig. 4).
Formal published recognition of the three-way mutual interactions did not appear until 2008, only three years before the renowned Bonn conference in 2011 (Fabiola & De Rosa, 2016). Before then, the idea that the three nexus pillars were intensively related wasn't studied and sectors were predominantly approached as independent siloes and at most only two of them were combined in research (Endo et al., 2017). The realization that links among the three sectors are inextricable, ensure that the water-energy-food (WEF) nexus is becoming more prominent on political agendas (Leck et al., 2015). Ever since that moment, the number of studies on the nexus has skyrocketed.

From the analysis of this nexus, it becomes clear that the three resources, water energy and food, are interlinked extensively. Water and energy are needed for food production. Food degrades releasing both energy and water. Energy on its turn is needed for transportation and treatment of water and water is often used for cooling during the production process of electric power, closing the circle. Over the past few years a movement has started to create a more circular and sustainable economy. Changes in power generation, agricultural production and water management are part of that. This may cause the traditional interlinkages to change.
More details on the links in the Water Energy Food nexus will be provided in chapter 5-8 in a framework on the nexus. For this thesis, the focus will be on rain- and wastewater links to urban agriculture from the nexus perspective.

Figure 4 Urban water energy food nexus

Since a high concentration of diverse human activities takes place in cities, interactions among FEW sectors are enabled by co-location (Ramaswami et al., 2017). Implementation of integrated local systems providing food, energy, and water, with optimal resource use to meet local demands, is therefore most likely to be successful within city boundaries.

Agriculture lies at the core of the urban Water Energy Food nexus; therefore, it is not surprising that urban agriculture as a solution is able to partially solve multiple problems at once. For example, climate change adaptation shows synergies with strategies to increase resource efficiency and circulation. Stored excess water from heavy rain events can be used to water farms. An increasing urban population produces an increasing amount of waste water from which nutrients for fertilizers can be recovered that have the potential to feed agriculture in the city. Urban farming on the other hand produces food for the increasing urban population, and so on.

Moreover, due to feedbacks in the Water-Energy-Food nexus, urban agriculture tends to affect many more components and links in the nexus as well. When water storages for storm and rainwater are created, in order to secure water availability for the urban farm, flood risks during heavy storm events may be reduced, as sewer systems have to cope with fewer water at peak moments. Local treatment and reuse of water in farms not only result in a smaller requirement for energy production, cutting down on pumping costs, they may also allow the reduction of the capacity or treatment steps of municipal wastewater treatment plants. Due to all the feedbacks, urban agriculture can increase resource-efficiency, and this circularity could reduce the footprint in urban areas while being cost-effective at the same time. More details on the feedbacks in the Water Energy Food nexus will be provided in chapter 5-8 (framework of analysis).

1.5 Spatial planning

Urban agriculture sounds promising. Why don't we solve all major problems of the world, by simply implementing urban agriculture? Quickly, complications are coming up. One of the most prominent complications concerns the room this farming activity requires. All the measures to accommodate urban farms and all the infrastructure to capture, store and treat and transport water in order to make the facility as circular as possible need space. And in a city space is limited.

1.5.1 Decentralized systems

In present-day's society, centralized production and large-scale distribution infrastructure provide the main mechanisms for running the economy (Leung Pah Hang et al., 2017). In most developed urban areas in the world water treatment process is no exception. It takes place at large scale wastewater treatment plants. Sewage (and sometimes stormwater) captured in large parts of the city is collected and transported towards these facilities that are often located just outside or on the edge of the urban area. This centralized treatment allows for efficiently treating large quantities of water, while experts are available for monitoring the process to ensure optimal treatment performances, maintenance and safety.

Centralized systems are however causing problems, such as uneven economic development, unequal access to goods, unsustainable resource consumption and detrimental impacts on ecosystems (Leung Pah Hang et al., 2017). Local production systems, defined as local networks of geographically co-located heterogeneous processes, have been advocated as a possible sustainable alternative (Curtis, 2003; Johansson et al., 2005).

Water treatment in local, decentralized systems displays other characteristics that come along with a diverse set of advantages and disadvantages. First, since water is captured locally, it doesn't need to be transported over long distances as its source is nearby, saving energy on pumping. Another characteristic of local treatment is that it is generally dealing with smaller quantities of water, resulting in the fact that installations are considerably smaller than the centralized versions. However, if instead of a single large-scale treatment plant, multiple decentralized systems are installed, monitoring and maintenance issues could arise.

Local production systems offer geographical proximity between different processes and could consequently be integrated in a synergistic manner (Leung Pah Hang et al., 2017). Local agricultural production systems linked with local wastewater treatments systems for example could achieve a higher degree of resource efficiency as heat losses and deterioration of organic material can be significantly reduced compared to the centralized systems.

Decentralization of FWE services has consequences for urban and spatial planning and development as the implementation of decentralized FWE systems impacts the spatial arrangement of cities. The conceptualization of urban policy, on the other hand, has large impacts on whether the decentralized FWE-nexus can emerge.

Risks and benefits as well as spatial implications for integrated and resilient urban areas have not extensively been analysed and addressed, particularly under changes in climate, urbanization, rural dynamics, globalization and population.

1.6 Research

In this master thesis research, the interactions within the FWE nexus will be studied from the interactive perspectives of flows, actors, and areas. The focus will be on rain- and wastewater links to urban agriculture from a Water Energy Food nexus perspective. As described before, water from rain & sewers and nutrients & energy present in wastewaters urban areas can be used to feed farms in cities and it would be good to know in what extent. Therefore, the first research question of this thesis is as follows:

Can some or all of the demands for water, energy and nutrients (nitrogen & phosphorus) for urban agricultural initiatives be met by resources present in urban waters (rain water and wastewater) in the direct urban environment? And how will this affect the rest of the system?

The implementation of urban farms needs to be supported from a food security and circularity point of view. However, the hydrological and spatial aspects can be hurdles to start an agricultural business in the city and to operate it as sustainable as possible with the resources present in the surroundings. To help policy makers formulate appealing plans, which will allow for a sustainable development and encourage urban farming, recommendations for spatial planning will be given. They will be formulated by answering the following question:

What hydrological and spatial measures need to be taken in order to facilitate urban agriculture initiatives to grow crops without requiring resource inputs from outside the city in terms of water, energy and nutrients?

1.6.1 Advancing the field

First of all, this research will provide a framework to analyse the nexus around urban agriculture systematically in future studies, by providing a clear insight on the role of urban farming in the water-energy-food nexus. Such a systematic tool can be used to determine the effect of changes in interlinkages and is not yet available. Another way this research is providing added value to research on urban agriculture and urban circularity lays in the fact that real life data are collected. As this study will be recording data of resource use and availability in and near urban farms to examine the feasibility of connecting supply and demand of resources by linking the urban agricultural and the wastewater sector, the recommendations and conclusions will be based on data collected in the field instead of using modelled data and assumptions. This provides a more realistic perspective on the feasibility than the models that were used up until now did, as production at optimal efficiency is rare in reality, especially when a farm has no commercial intent.

1.6.2 Approach

Water, nutrient and energy fluxes in urban systems for food production, will be studied at three case study sites, two in Boston (MA, USA) and one in Amsterdam (the Netherlands). To assure a systematic analysis of the Water Energy Food nexus related to urban agriculture at the case study sites, a framework has to be formulated (chapter x). This framework of analysis will be followed, when answering the research questions mentioned above. Potential fluxes for locally produced energy and available urban water sources (rain and/or waste) will be investigated.

The areas to be included are a district or neighbourhood in Boston and Amsterdam, which will be the primary focal points of analysis, as these locations are characterized by the presence and/or development of many urban farms. On site, local stakeholders can be interviewed in order to let them participate in the scenario and system development. Their experiences and vision in urban farming will be evaluated and together with the data concerning resource fluxes at local urban agricultural sites, this info will result in a future-proof recommendation for urban farm development which aims to increase chances of successful implementation.

2 Urban farming

As described in the introduction, urban agriculture is the production of crops, which must at least partly be destined for the city, located within or on the fringe of a village, town, city or a metropolis. The farming industry in cities comes in many forms and sizes and there is not one overarching description, as the range of its manifestations is so wide. Therefore, it useful to develop and idea of all that urban agriculture entails. In this chapter some of the most frequently applied forms and jargon in the field of urban agriculture are discussed, along with definitions of some very specific technologies that are common in the sector. This section, however, will be commencing by revealing possible urban farming sites.

2.1 Location

Naturally, urban agricultural locations are partially defined by the implicit nature of the term urban farming, though at the same time the manifold locations where these farms arise are partially responsible for making the range of manifestations of urban agriculture so diverse. As space in cities is limited, a creative approach to finding suitable farming locations may pay-off. Smit & Nasr (1992) stated that all urban areas have a number of vacant and under-utilized surfaces that can be used for agriculture.

a. First of all, sites with steep slopes and wetlands are not suitable for built-up uses. Their best use is for agriculture. Steep slopes, for example, can be converted into terraces, which can support horticulture while preventing erosion. Wetlands might be suitable for rice production.
b. Smit & Nasr (1992) indicated that many urban areas are home to pieces of vast under-utilized or unutilized tracts of land. These idle lands, that are often public or quasi-public, include land surrounding airport runways, along roadsides, in low-density residential or university areas and parks. Because of the (semi-) public nature of those locations, issues such as theft and lead poisoning from combusted fuel should be taken into account and growing crops not meant for human dietary consumption are preferred.
c. Cities are naturally subject to change. This brings along a natural change in spatial arrangement over time, resulting in temporarily idle lands. These lands can be used for agriculture, without being permanent or even long-term. It can be a very adequate interim use as long as can be guaranteed that the agricultural production is allowed for a minimum of one season, so that the farmer will see the fruit of their effort.
   At development sites inside the city boundaries, where urban rearrangement took place, or where destruction of old buildings is completed, but where construction hasn't taken off, lots are empty. Besides, expanding cities often temporarily have idle land available at the edge. These areas/plots are perfect for urban farming. It is even possible for old office or factory buildings to be converted into mushroom and greenhouse agriculture.
   Floodplains can also be used. Cattle can graze on them, but when the time period between floods is regular and long enough to cover one growing season, they are also adequate for interim use by arable farming.
d. Community lands, with community farms, are very often associated with the idea of urban food production. However, urban community farming goes beyond the community farm. School gardens also belong to this category.

e. Private property holds many opportunities for urban cultivation of crops too. Household surfaces where food can be grown include (back)yards, rooftops, balconies and facades of buildings facing the sun, and their potential for growing vegetables, fruits and micro-livestock for consumption is largely untapped.

2.2 Why is urban farming different?

Ostensibly, the only difference between farming and urban farming, is the fact that with urban farming agricultural production takes place within a city's boundaries, whereas conventional farming takes place in rural areas. However, this seemingly small dissimilarity has shown to brings along a large possibility for other deviations in the way the farms are operated.

2.2.1 Small scale

First of all, due to a limited amount of space available in cities, urban farms are generally operating at a smaller scale than conventional rural farms. In order to profit from economies of scale, innovative solutions in the urban sector are not uncommon. The production on the small pieces of land that urban farms have at their disposal is often increased by expanding the cultivation surface vertically or by controlling the climate and (artificial) light conditions in the facility. Vertical farming, where the production is taking place in vertically stacked layers, is a very space efficient way of producing crops, and therefore common in commercially oriented urban farms. However, it requires a financial investment that might not be worth it for non-commercial farms.

2.3 Business models and benefits

Because of the small-scale nature of urban farms, it might show to be hard to operate an urban farm in a financially viable way. However, there are different ways farming can add value to society besides running a farm commercially. Smit & Nasr (1992) even claimed in an all-embracing statement that: 'Urban agriculture is the largest and most efficient tool available to transform urban wastes into food and jobs, with by-products of an improved living environment, better public health, improved equity, energy savings, natural resources savings, land and water savings and urban management cost reductions.'

2.3.1 Food security

It is widely accepted that local food production has the ability to increase local food security (Gondhalekar & Ramsauer, 2017). Urban farmsteads offer a source of agroeconomic autonomy to the urban population and saved millions of people from starvation in cities during the 1900s (Barthel & Isendahl, 2013). This isn't surprising, as local crop cultivation enhances physical availability and affordable access to food, making urban regions less dependent on production in and transportation from faraway regions, less prone to fluctuating geopolitical relations and less affected by decisions of major nutrition corporations for food supply.

2.3.2 Recreation

However, performing urban agriculture can serve more functions than just food production. It potentially has the ability to bring along a variety of social benefits too. Allotment gardens, where people can garden and/or grow food on a small-scaled, individual and non-commercial basis, are mainly meant for recreation, just as public urban gardens.

2.3.3 Social cohesion

Besides serving recreational objectives, urban agriculture can also serve communities by enhancing social cohesion. Community farms, where neighbours work together cultivating plants, can provide an opportunity for social gathering and might provide a space to organize community related events. Interaction with fellow residents can build community spirit and solidarity, therefore improving the liveability and social resilience in areas where social networks comprised of neighbours are otherwise uncommon. Besides contributing to social cohesion, community farms have the potential to provide a combination of the benefits mentioned before, as they have the ability to provide an opportunity for recreation, increase local food security and support education on food.

2.3.4 Education

The educational objective is even stronger present in school farms, which are predominantly established for instilling in children the techniques and habits of growing what they eat, while improving the nutritional status and consequently the health of students (Smit & Nasr, 1992). This might seem redundant, however, articles as the one in the Washington Post shown in figure 5 prove that many people in the western world lack understanding of where their food comes from.

The Washington Post
Democracy Dies in Darkness

The surprising number of American adults who think chocolate milk comes from brown cows

By Caitlin Dewey June 15

Seven percent of American adults believe chocolate milk comes from brown cows, according to a recent online survey commissioned by the Innovation Center of U.S. Dairy. Here are a few other things Americans get wrong. (Elyse Samuels/The Washington Post)

Seven percent of all American adults believe that chocolate milk comes from brown cows, according to a nationally representative online survey commissioned by the Innovation Center of U.S. Dairy.

If you do the math, that works out to 16.4 million misinformed, milk-drinking people. The equivalent of the population of Pennsylvania (and then some!) does not know that chocolate milk is milk, cocoa and sugar.

Figure 5

Article in the Washington Post showing alarming percentages of people unaware of where their food is coming from (Source: Dewey, 2017)

2.3.5 Serving ideologies

Some urban farms however mainly serve an ideology and are not directed to create another outcome other than serving as an example for healthy or environmentally friendly living. Simply the fact that gardens/farms provide a green space to relax or inspire creative thoughts in the built environment is their sole goal. Other farming initiatives are established to support growing greens for their own private restaurants. Some of these initiatives might purely use their city farm for green image-building or even green-washing. However, many of these farms are established to invigorate their ideal of local and sustainable production and simply use it as their trademark.

2.3.6 Providing an insight into consequences of consumption behaviour

In the conventional large-scale food production chain, a disparity exists in water and energy withdrawals between the food cultivation sites and the consumer's location. The burden of recourse extraction and the place where most consumers profit from the production do often not coincide. Virtually, water and energy are imported into cities through food and consumers don't necessarily notice the harm that excessive or resource intensive consumption does to the environment. Local culture could change that by simply allowing people to see the consequences of their behaviour, for example that consuming water intensive crops could lead to local water shortages.

2.3.7 Urban climate and flood resilience

Irrespective of social and health benefits, urban agriculture has the ability to help cities achieve climate adaptation goals and can contribute to the resilience of cities (Barthel & Isendahl, 2013). Besides, multiple challenges unique to urban areas can be addressed simultaneously with the help of urban agriculture. First of all, there is heat stress. Urban areas are generally warmer than their surrounding natural areas, which can pose health issues in vulnerable groups of the population. Not only are cities currently warmer, heat stress as a result of climate change is predicted to increase twice as much in cities as in rural areas (Wouters et al., 2017). Additional green spaces, like extra (public) gardens or urban agriculture, increase the amount of vegetation and therefore transpiration in urban areas. Vegetation drains latent heat from the area and can effectively mitigate the effect of urban heat islands (Qiu et al., 2013).

Besides heat stress, urban areas are at greater risk of facing water nuisance during heavy rain events. Rains result in up to 4 times less runoff in natural areas than in urban regions as water has less opportunities to infiltrate due to the large portion of paved surfaces (Markovič et al., 2014). Green areas, whether used for farming, aesthetics or recreation, support vegetation, which is grown in soil. Soil can store water and let water infiltrate in the subsoil, reducing water nuisance compared to an all-paved situation. Therefore, the establishment of urban farms has a positive impact on local flood reduction.

2.3.8 Economy

Urban agriculture can benefit the urban economy too. By substituting the import of food products by commercial urban farming, a vibrant production, processing, packaging and marketing industry can arise which creates local jobs, near consumers. When combined with 'waste' recycling as essential agricultural input products, cities can transform from only consumers of food into important resource-conserving, sustainable generators of these products (Smit & Nasr, 1992).

2.3.9 'Waste' recycling

Not only does the implementation of urban agriculture bring along spatial challenges and social benefits, it also provides a great opportunity for sustainable reuse of materials from the urban system that were previously regarded as waste and as a problem to be disposed of. Nowadays cities are primarily open loop systems with one-way flows of resources (Smit & Nasr, 1992). Using urban by-products of this linear system, such as sewage or solid organic waste like food waste, as inputs in farms blurs the line between wastes and resources. Using urban agriculture as connecting link can kill two birds with one stone, by reducing the amount of waste output of a city as well as conserving raw natural resources by reducing their input. By recycling and transforming wastes into resources, urban farms have the ability to stand at the base of a closed loop resource systems, which cities historically already were before the process of time-space compression got started. The continuous production of (sanitary) waste in cities and dense local infrastructure transporting it, result in a great availability and easy access to resources for urban farming.

Links between agriculture and waste management can be realized on different scales. Modern day wastewater treatment systems in cities and rural agriculture have been based on principles of economies of scale. However, urban agriculture is often taking place in small-scale facilities and also modern biological water treatment technologies seem to favour smaller set ups (Smit & Nasr, 1992). Nevertheless, some hurdles need to be overcome before small scale water treatment are brought back in the urban landscape.

In recent history, waste management and water treatment have been taking place out of sight of the people, and for no apparent reason other than the local presence of maintenance staff and economies of scale advantage that hold for old-fashioned techniques, we seem married to the idea that we have to continue to use our existing centralized sewage systems. Gondhalekar & Ramsauer (2017) stated that many treatment systems in Europe and the USA are old and are in need of large-scale renovation. Many new treatment techniques that are more energy efficient and have a (higher) resource capturing potential have come on the market in the past decades. Why not combine the measures needed for a transition towards resource harvesting and conversion to small-scale treatment all at once? The treatment systems need to be replaced anyways.

2.4 Operating systems of urban farms

Agriculture can occur in a wide variety of ways. The limited availability of space in the city and the abundance of pollution require creative solutions to grow crops in urban areas. Innovative techniques therefore seem to be more frequently applied in professional urban farms than traditional farms situated in rural regions. Many of them are less prevalent in community farms than in commercial facilities due to the substantial financial investment that is required to purchase and install these technologies.

2.4.1 Open field farming

Of course, there is the traditional open field farming, but in urban settings many other budget friendly methods are applied. Some farms, for example, are making use of raised beds, where clean soil is put in bags, pots or buckets and elevated from ground level or entrenched in the authentic soil. This way contact with the original soil can be evaded, which is a very simple yet effective method to prevent soil contamination from ending up in crops, which can potentially be harmful to human health (Kessier, 2013).

2.4.2 Indoor culture

Modern technologies, which generally require a higher investment, also allow agriculture production to take place indoors, where growing conditions are easier to manipulate. Some urban farms are established inside shipping containers or dwellings, which are equipped with a controlled lighting and climate system and have the added advantage of optimal resource recycling and reduced/absent contamination and need for pesticides (Kurian, 2014). The climate and light controlled locations, however, are accompanied by a relatively high and costly energy input. The artificial light schedule, providing plants with light 24/7, results in rapid growth cycles and consequently a higher yield per unit area than traditional agriculture. Besides, shipping containers are mobile, which means that these growing facilities can be placed on almost any vacant space in a city and can easily be lifted and transported to elsewhere when required. This flexibility makes for an ideal interim usage of temporarily idle lands.

Greenhouse farming is another type of indoor farming. Although greenhouses are generally less mobile than shipping containers, the two cultivation methods share many characteristics. An added benefit of greenhouse farming compared to other types of indoor culture, is that the farm makes use of sunlight, reducing energy costs for lighting. On the other hand, in warm climates or on hot days, the glass walls and roof result in a substantial energy requirement for cooling.

In many indoor farms, however, the annual freezing and thawing cycles that occur in temperature climates do not always enter the building, and as a result the pathogen built-up in the soil does not get neutralized by frost, especially in climate-controlled systems, where temperatures are high year-round (Ten Caat, 2017). To overcome this problem, and to prevent soil-borne diseases, a couple of ingenious new soil free culture methods have been developed. Besides, both absence of good soil or presence of contaminated soil could be a reason to apply soil-less culture.

(Commercial) soil-less systems are often accompanied by high-density crop yield, which can either lead to a minimal use of land for the same production or a maximal yield per surface area (Jensen, 1981). Graamans (2015) showed that annual yields from hydroponic culture could be as much as 5 to 20 times larger than those of conventional open field agriculture (Graamans, 2015). Soil-less systems are available in a few varieties (Kurian, 2014).

2.4.2.1 Hydroponics

Hydroponic systems feature seedlings planted in floating rafts, with the roots of the crop suspended inside growing channels or basins filled with a nutrient solution. This technique requires the constant recirculation of the nutrient containing water, which can be very energy intensive. On the other hand, it allows to control root temperatures, either by cooling or heating the solution (Ten Caat, 2017).

2.4.2.2 Nutrient-film techniques

A variant on hydroponic systems are nutrient-film techniques, where roots growing on nutrient films are periodically flooded. The nutrient film technique features a thin layer of nutrient solution at the base of a root holding channel rather than on a deep layer of water. Pumps ensure an upward vertical movement of water from the storage tank into the channel, enriching the water with nutrients from the solution. Consequently, gravitational flow drains excess water back into the storage tank (Ten Caat, 2017; Kurian, 2014). This method requires a significantly smaller amount of nutrient solution than the conventional hydroponics. Besides, the reduced volumes of water also facilitate a smaller energy consumption for heating and cooling of the water, although it is harder to maintain a constant temperature.

2.4.2.3 Aeroponics

Another, though less common, culture method is aeroponics, where nutrients and water are sprayed on the crop roots which are suspended in mid-air. This technology is even more water efficient than the nutrient film system, and can be very space efficient, especially when the spraying chambers are stacked (Ten Caat, 2017). Stacking beds, however, could lead to uneven growth of the crops due to varieties in received light intensity. Besides, this technology is seen as relatively complex and hard to maintain. One of the biggest benefits of this system, however, is that it is very lightweight, which makes it easier to install them on top of buildings that cannot carry a large load (Kurian, 2014**).**

2.4.2.4 Aquaponics

Aquaponics is a century old culture system, where aquaculture and arable farming are intertwined. Faeces with potassium, phosphorus and ammonium produced by the fish function as a nutrient source for (vegetable) crops (Kurian, 2014). The nutrient-rich wastewater is pumped through the soil in which the crops are embedded. Bacteria in this soil transform the ammonium into nitrogen, which can be used by the plants to grow. The plants on their turn filter the water, so that it can be reused in the aquacultural tanks. Although the fish still need an external food source and the plants need additional micronutrients like iron, calcium, potassium and magnesium, aquaponic farming is a biological cultivation method that reuses raw material maximally and reduces the need for (artificial) fertilizer. Moreover, aquaponic food and fish production features a lower water usage compared to separated greenhouse vegetable growth and standard fish production (Ten Caat, 2017).

All in all, urban farming is a very diverse phenomenon. Therefore, every site should be examined individually, as each has a unique location, ideology and operating system, and many hybrid forms exist too. All of these aspects can affect how a farm is run and consequently influence how resources are managed.

3 Case study site descriptions: Farms & neighbourhoods

For this study, three case study farms were examined. First of all, there is a rooftop greenhouse situated on top of a large hotel in Amsterdam. An open field community farm in East Boston and a commercial container farm in East Boston constitute the other two cases.
All of these initiatives are characterized by different objectives, all kinds of core values, various modes of operation, diverse ways of securing supply and addition of resources and a multifarious set of crops that they grow. In short, they represent three completely different types of urban agriculture.
Analysing systems in different cities, countries (and even continents) allowed to study the influence of different circumstances, various policies and diverse engineered systems on the feasibility of the connection between the urban waters and the farms inside the city.

3.1 Amsterdam: QO hotel (Rooftop greenhouse as showpiece of sustainability)

The case study in Amsterdam was executed in the brand new QO hotel in the Amstelkwartier district, a former industrial zone that is slowly being converted into a more residential area, as the city of Amsterdam is trying to deal with a shortage in housing.
The hotel aims to be sustainable in its operation. Besides being connected to an Aquifer Thermal Energy Storage and supporting an intelligent façade influencing the amount of sunlight entering the hotel rooms to facilitate optimal climate control in the rooms, the greenhouse situated on the rooftop plays a crucial role to achieve this goal.

Located on the 22nd floor, at 76 m above street level, the greenhouse is filled with the state of the art aquaponic, hydroponics and vertical farming technology (see photograph on top of the page). It has direct benefits such as fresh produce for the hotel’s restaurants and kitchens, but most definitely also creates opportunities for marketing and increased exposure of the hotel in the competitive hospitality industry. Besides, it showcases opportunities for resource recycling inside the hotel. Premature calculations of Metabolic (2017) predicted a 99% water efficiency in the greenhouse and a highly efficient usage of nutrients because of the aquaponic system that uses fish excreta as nutrient supply for the plants.

System number	Crops	Location
1	Tomatoes, cucumber	Middle south side
2	Flowers	North & south side near the windows
3	Herbs and sprouts	Middle north side
4	Aquaponic system	Partially out of order

Table 1 Crop types grown in each of the four subsystems of the QO hotel greenhouse

The greenhouse is divided in 4 subsystems. Each subsystem grows a different variety of crops and is separately monitored for its water and nutrient requirements (table 1). Three out of the four subsystems are purely hydroponic systems. Water is flowing through a fertilizing filter and is guided to the plants in cocomat gutters in which the crops are rooting. One subsystem is an aquaponic system. During the data collection period, however, the aquaponic system was not yet in use. It will potentially be removed in the near future as the operation will be very labour intensive and the yield (projected to be around 60 fish a year) will be too low to be profitable. Halfway during the data collection period, this subsystem was employed as hydroponic system, just like the other three. The other three hydroponic systems were operating during the entire data collection period.

The hotel's restaurant aims to use local products for its meals. The yield is being recorded manually by the cook using a logbook in the greenhouse. According to the chef de cuisine, about 5% of what is presented on the plate is coming from the greenhouse at the roof of the hotel. Besides the obvious restaurant essentials like cherry tomatoes and cucumbers, mainly unconventional crops such as lemon basil and edible flowers are grown, resulting in a total of 40 to 50 different crops.

3.1.1 Water system

The greenhouse makes use of stagnant water in the building. Water in pipelines of hotel rooms that have not been in use for a while needs to be refreshed in order to prevent legionella growth in the water system. The water that is withdrawn from these pipelines is lead to a reverse osmosis system inside the hotel, from where it is transported to the hotel rooftop after treatment. In the greenhouse at the rooftop a small reservoir is present, where water is collected and ready for application (fig. 6).

An automatic computer operated system, Priva, collects data on the volume of water that is circulating through the greenhouse. Each of the farm's subsystems has its own water meter, to keep track of the water that is being circulated through it. Since the system is recycling water internally, by recapturing water that trickled past the crops through the hydroponic gutters, not only the consumed water volume by plant uptake is recorded, but also the recycled portion of water is included in the water count (fig. 7).

A meter that is keeping track of the inflow of water to the greenhouse, which compensates for the water uptake by plants and water lost through evaporation and therefore gives information on the consumed water volume, is however not present and could not be installed due to the complex and sealed connections with the water system in other parts of the hotel.

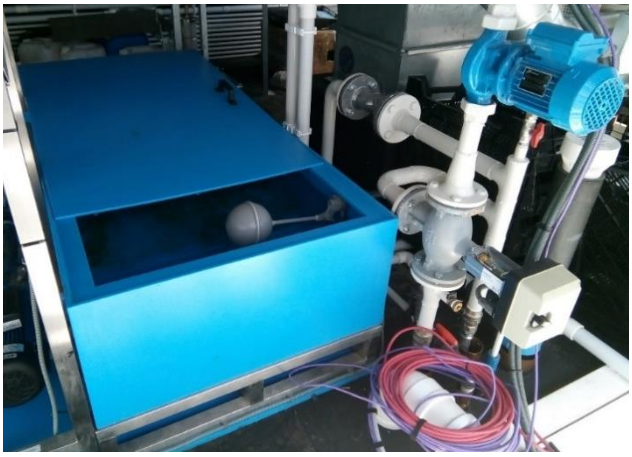


Figure 6 The water system of the hotel with the water reservoir

Figure 7 Hydroponic water gutters in which plant are rooted

3.1.2 Energy system

The energy for the plants is delivered by multiple sources. First of all, there is the solar radiation entering through the 230 m^2 glass roof surface of the greenhouse. With the greenhouse situated on top of one of Amsterdam's highest buildings, maximum use is being made of daylight, as no other building are blocking the sun's beams. Radiation data have been collected by the weather station on top of the hotel. For a while there was a dip in the radiation measured around noon. That turned out to be caused by the pole near the radiation meter that created a small shadow over the meter. This problem is now solved and the radiation data are collected without disturbances.

The second energy source that this farm relies on is heat. The hotel is connected to a combined heat and power installation (CHP), which generates electricity and useful heat at the same time. In winter the temperature in the greenhouse is controlled by a 47°C warm pipeline radiating heat captured from residual heat in the hotel and supplemented by burning cooking oil. In summer however, the temperature in the greenhouse exceeds the ideal range and the heat supply is disconnected. Moreover, thermal energy from the hotel's wastewater is recovered by a heat exchanger. No use is made of natural gas.

3.1.2.1 Energy consumers

The greenhouse is home to a multitude of energy requiring processes. First of all, it supports a wide variety of lights, all used for different purposes. Some fluorescent light tubes (which are almost always switched off) are used for visual aid during night time work (24 * 2 * 58W), while others are energy saving LED lights are emitting either blue or red light in order to support plant growth (32 * 200W & 12 * 115W) (fig. 8).

Another large power consumer in the greenhouse is a computer system with Priva software which automatically controls the climate settings indoors and measure the optimal resource feed to the crops. This computer system is quite large, and even though no more than 10% of its capacity is used, it is likely a significant electricity consumer in the greenhouse.

Whereas other greenhouses often use ventilators to cool down the air inside, this greenhouse ventilates the air by simply opening the windows on the roof. This process only occasionally requires a small amount of energy.

As explained before, the water that is being used in the farm is treated by a reverse osmosis installation before being transported to the greenhouse. Since high pressures are required to push the untreated water through the cleaning membranes, these installations are generally quite energy intensive. However, how much energy this installation requires exactly is not monitored.

Several pumps are installed at the hotel in order to get the water to the crops in the greenhouse. There is a pump present right after the RO system, which is meant to pump water up to the rooftop where the greenhouse is situated. This pump operates with pressures from 8 to 10 bars, since a height difference of 76 meters has to be covered. Inside the greenhouse, small pumps are pumping water from a small reservoir through the pipeline system to the crops. This pump has a significantly smaller energy requirement than the previous booster.

Unfortunately, the Priva system is only monitoring energy consumption for heating and lighting inside the greenhouse. There is no information available on the energy consumption of the operating computers or the reverse osmosis treatment and the pumps that are transporting the water to the top floor of the building and through the farm.

Figure 8 Electricity consuming technologies in the greenhouse:
pumps (top left), LED lights (top right) computer operation system(bottom)

3.1.3 Nutrient supply

During the data collection period, the greenhouse made use of two types of fertilizer. The aquaponic system for nutrient recycling was not yet operating. Initially, an artificial (synthetic) fertilizer was applied through an automated system. After a few months, however, the artificial fertilizer was gradually replaced by organic fertilizer, as that fitted both the ideals of the hotel better and it had a positive effect on the acidity of the circulated water as it created a pH buffer in the otherwise very pure reverse osmosis effluent.

3.1.3.1 Artificial fertilizer

The nutrients are applied to the circulating water through an automated dispenser installed in each subsystem of the farm (fig. 9). Each subsystem has a conductivity meter, measuring the EC, in order to give an indication of the nutrient concentrations. Once the EC drops below a critical value, the system reacts by adding a certain amount of fertilizer to the water stream. EC however, doesn't differentiate between different nutrients. Consequently, it could be that a sufficiently high EC is caused by ions that are not required by the crops in the concentrations present in the feed water, whereas that same feed water can be depleted from other crucial nutrients. Therefore, a horticulturist has to pay close attention to the crops, to verify the automatic nutrient addition system and to adjust the fertilizer settings manually whenever needed. Alternatively, the water needs to be refreshed on a regular basis, causing outliers in water consumption. After the replacement of the old water, the new water can be sent through a nutrient filter again, to make sure the water has the ultimate composition of its solution to stimulate crop growth.

Figure 9 Artificial nutrient dispenser system

Two fertilizer fluids are used simultaneously, but always in exactly the same amount. The nutrient fluids (table 2) are kept separately in order to make sure that no precipitation reactions can occur between compounds like magnesium and calcium. These chemical reactions should be avoided to prevent scaling in the dispenser system.

Nutrient	**Concentration (mol/l)**
NH_4	0.09
K	0.65
N_{tot}	1.64
Ca	0.57
Mg	0.21
NO_3	1.55
Cl	0.17
SO_4	0.21
P	0.17

Nutrient	**Concentration (mmol/l)**
Fe	3.23
Mn	1.18
Zn	0.66
B	4.38
Cu	0.07
Mo	0.07

Table 2 Composition of artificial fertilizer mixture added at the QO hotel (Data source: Ammerlaan, 2018)

3.1.3.2 Organic fertilizer

Three types of organic fertilizer were applied depending on the crops in each subsystem and their current growing stage. First of all, OPF-723 was fed to young plants and vegetables. OPF-428 was given to crops in their blossoming or fruit bearing stage and to herbs specifically. OPF-525 was applied universally.

The organic fertilizer was poured to the system manually straight from the jerrycans, and therefore, data on the applied volume were not collected automatically. More information on the composition of each type of organic fertilizer is displayed in table 3.

Type	**Growing stage**	**Nutrient**	**Lower limit** *(mass percentage)*	**Upper limit** *(mass percentage)*
OPF 7-2-3	Young plants *Mainly applied to: vegetables*	Nitrogen (N)	6.8	7.3
		Phosphorus (P2O5)	2.5	2.8
		Potassium (K)	2.2	2.5
		Silicium (SiOH4)	2.2	2.5
		Boron (B), Calcium (Ca), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Sodium (Na), Sulfur (S), Zinc (Zn)	Traces	Traces
OPF 5-2-5	In between *Mainly applied to: universal*	Nitrogen (N)	4.8	5.2
		Phosphorus (P2O5)	2	2.5
		Potassium (K)	5	5.5
		Silicium (SiOH4)	5	5.5
		Calcium (Ca), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Sodium (Na), Sulfur (S), Zinc (Zn)	Traces	Traces
OPF 4-2-8	Blossoming & fruit-bearing crops *Mainly applied to: herbs*	Nitrogen (N)	3.3	4.2
		Phosphorus (P2O5)	1.6	1.6
		Potassium (K2O)	6.9	7.8
		Calcium (Ca), Copper (Cu), Iron (Fe), Magnesium (Mg), Manganese (Mn), Silicium (Si), Sulfur (S), Zinc (Zn)	Traces	Traces

Table 3 Composition of each type of organic fertilizer applied at the QO greenhouse

3.1.4 Neighbourhood description: Amsterdam Amstelkwartier

The Amstelkwartier quarter in the Amsterdam-Oost district of the Dutch capital is located along the Amstel riverbank. According to a Waternet employee, before the construction of residential dwellings in the Amstelkwartier, a large wastewater treatment plant for the city of Amsterdam was located at the exact location of the hotel and as a result (remnants of) large collection pipelines run under the neighbourhood. If those are pipelines still carrying large amounts of wastewater is however unknown.

The former industrial zone is converted into a green neighbourhood intended for residential, recreational and commercial purposes (Gemeente Amsterdam, 2018). The reorganisation of the area takes place in three distinct phases. The first phase, during which 1500 residences and the QO hotel were built, is about to be finished. After soil remediation works have been completed, more dwellings will be realized and a park will be created in the very centre of the neighbourhood.

3.1.4.1 Zoning

Figure 10 shows the design plan of the first phase of development and provides a clear overview of the land use in the area and the presence of open spaces that can potentially be used for installing infrastructure required for coupling sewer systems and agricultural initiatives in the region.

As can be seen, the area is densely built, but sports wide streets, which are simultaneously used for traffic and parking and two large scale patio gardens. The park that will be constructed in the next phase of the development plan of the area, will also provide open space in the neighbourhood. Most dwellings in the direct vicinity of the hotel are 6 to 7 stories high, built following the latest regulations and have flat roofs. On the opposite side of the Amstelstroomlaan, the buildings are more low-rise. However, large roof surfaces are present on top some office buildings and shops. All these open spaces could potentially be used for potential rainwater collection and storage.

Figure 10 *Development plan Amstelkwartier.*
The QO hotel's location is indicated by the red inverted drop sign
(Source: Dienst Ruimtelijke Ordening Gemeente Amsterdam, 2011)

3.2 Boston: Corner Stalk Farm (Commercial container farm)

Corner Stalk Farm is a farm located in East Boston. This farm, situated at the edge of a residential area near the Boston Bay Marina in Chelsea Creek at a parking lot of the garage next door, is operated in four shipping containers that have been converted into a farming production site (see photograph on top of the page). The farm mostly has a commercial purpose. They sell their goods to small vendors, local restaurants, via Amazon Fresh and at the Boston Public Market.

The crops are all grown from scratch inside the containers. First, seedlings are grown in horizontal fashion for 3 weeks. Afterwards they are relocated and spend 3 to 5 weeks in vertically positioned towers before they can be harvested. Using this configuration, the farming operation is more than twice as space efficient as conventional agriculture. On 35m^2 of land, 78 m^2 (840 ft^2) of growing surface is created.
The towers basically work as a hydroponic system and are stuffed with rock wool, which functions as a growing medium for the plant roots. Therefore, technically it is a combination between an aeroponic and a hydroponic system, as between the rock wool also air is present.
The plants are growing in horizontal direction, at a 90-degree angle with the ground surface. Crops that can resist the resulting gravitational pull have specifically been chosen. Basil, different types of lettuces and green onion are being grown and the production will soon be expanded by growing marijuana, because this high value crop is thought to increase the profit margin of the farm, which otherwise sells its products for a relatively high price at the highly competitive market, due to its relatively expansive production process.

Each container costs about $80,000, which is a large investment for a small grower. However, because the climate conditions inside the container can be controlled, a year-round, 24/7 production is facilitated. This allows for multiple growing cycles each year, making container farming financially rewarding. Almost every month (11 to 12 times a year) a tower generates crops that can be harvested. Since each container has 256 vertical towers, harvesting takes place on a daily basis.

Although Corner Stalk Farm grows its crops in four containers on the terrain, only one of the containers is used as case study site, as the four containers are comparable in production and thus in resource use. This way, less measuring equipment was required and the farmer would not have to spend as much time on data collection.

Figure 11 *Indoor layout of the container farm with on both sides two rows of growing towers with LED lights in between*

3.2.1 Water system

Corner Stalk Farm is not directly connected to the city's water supply itself. In order to attain such a connection, trenching the street and installing extra pipelines would be required. The estimated costs for such an operation are around $10,000, which is obviously a lot of money for a small grower. The farm manager had not looked into his farm's water consumption yet, as water use is included in the rent. No water meters were present, and the farmer initially estimated to use around 50 gallons of water a day per container.

The water supply to the containers is ensured by thick garden hoses connected to a nearby tap. Also, inside the container, a garden tap was present. Water from the garden hose outside, enters the container via the garden tap inside and flows into an installation with 6 water barrels (of 55 gallon each) where the fluid is stored (fig. 12). One of the barrels was always kept full as a reserve to prevent cavitation of the pump. From the remaining barrels, water is being pumped through small pipelines towards the top of the vertical crop towers. There it is released in the rock wool and distributed downwards by gravity.

The water that has not been used by the crops along this pathway, is collected at the bottom of the towers and transported backwards to the pump. Another way in which the farms reuses water, is by capturing the condensed water at the air-conditioner and returning it back to the water system. In this way, a large part of the water is being circulated multiple times through the container, before it finally leaves the container as water vapour.

Although the farmer is generally satisfied with the water system, he described it as a Rube Goldberg machine – an unnecessarily complicated machine used for a simple task – and suggested that some improvements would be made. For example, currently, each container is supporting 6 separate water tanks of 55 gallons. However, a single water barrel with the combined volume equal to 6 separate ones, would be more space efficient and sturdy, as no cross-connections and plumbing would be required.

Figure 12
Built-in water storage

3.2.2 Energy system

As the container does not have any windows, it makes no use of natural sunlight. All the energy needed for the growing process is provided via thick electricity cables, with a cross section around 4 cm wide. Outside each container a small meter cupboard was present, with lots of switches, safety fuses and wiring inside. However, originally, no electricity meters were installed, and an inventory had to be made on the electrical system.

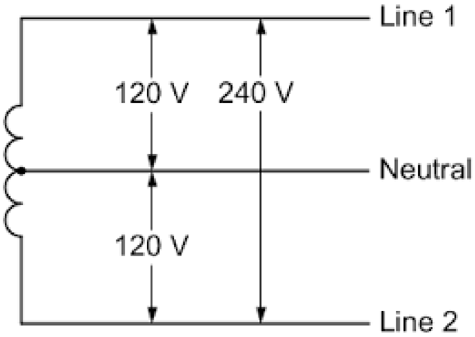


Figure 13

Three-wire electric power distribution

The system turned out to be a single phase, three-wire electric power distribution, meaning a system with three wires, from which the middle wire is neutral (0V) (figure 13). In each of the other wires, a current with a maximum effective voltage of 120V is transmitted in sine waves. Because the waves in the two wires are exactly 180° out of phase with each other, those two maximum effective voltages can be added, resulting in a circuit that supplies 240 V. The complexity required the installation of a very specific energy meter and an electrician to install it.

All kinds of energy consumers are connected to the power supply described above. First of all, a pump is present in every shipping container to transport water from the water storage barrels, via pipelines running along the ceiling of the container. Besides, every container supports a total of 70,000 LED lights providing blue and red light to the crops (fig. 14). These LEDs were present in two rows of 128 strips per container, drawing 2 amperes and running vertically between two rows of towers, with the crops facing them.

Although LEDs are relatively energy efficient, they still produce heat as a side product. In winter, this heat is enough to keep the temperature in the container in the optimal range for the crops to grow. However, in summer cooling is needed. The air conditioning that is installed for this purpose, is thought to be the biggest energy consumer at the farm. There is however, no information available on the distribution of the energy requirements for all the different consumers.

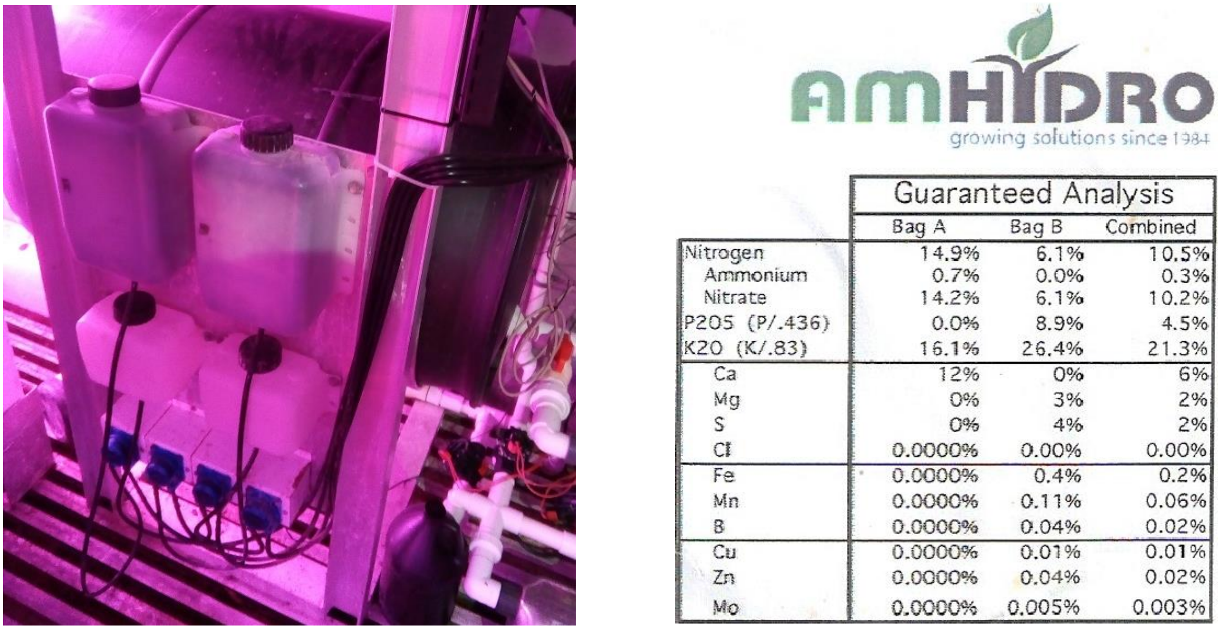
Figure 14 *The two biggest energy consumers at the farm: LED lights (left) and air conditioning (right)*

3.2.3 Nutrient supply

Corner Stalk Farm uses a hydroponic system, and thus cultivates crops on a growing medium other than soil. The soil is replaced by rock wool. Consequently, all the nutrients that crops require must be added through fertilizer additions. Nutrients are dosed based on the electric conductivity (EC) of the water that is being circulated through the farm.

Fertilizer is delivered in two separate bags. When still in solid state, the dose is manually measured on a scale before it is being dissolved. Equal parts of bag A and bag B concentrates are then added into dispensers that release concentrate into the system, depending on EC measurement values, in order to obtain the target EC of 2.0 mS/cm. Concentrates of bag A and bag B should never be mixed directly together in order to prevent the precipitation of calcium, phosphorus and sulphur, which would make those compounds unavailable to the plants.

The fertilizer used in this farm is provided by American Hydroponics and is said to be a ‘high performance growth nutrient formulation developed to push plant productivity specifically for lettuce’ (Amhydro, 2019). Its composition is displayed in figure 15.



Guaranteed Analysis

	Bag A	Bag B	Combined
Nitrogen	14.9%	6.1%	10.5%
Ammonium	0.7%	0.0%	0.3%
Nitrate	14.2%	6.1%	10.2%
P2O5 (P/.436)	0.0%	8.9%	4.5%
K2O (K/.83)	16.1%	26.4%	21.3%
Ca	12%	0%	6%
Mg	0%	3%	2%
S	0%	4%	2%
Cl	0.0000%	0.00%	0.00%
Fe	0.0000%	0.4%	0.2%
Mn	0.0000%	0.11%	0.06%
B	0.0000%	0.04%	0.02%
Cu	0.0000%	0.01%	0.01%
Zn	0.0000%	0.04%	0.02%
Mo	0.0000%	0.005%	0.003%

Figure 15 Nutrient dispenser system at Corner Stalk Farm (left) and fertilizer composition displaying mass percentages of solid nutrient powder (right)

3.3 Boston: Eastie Farm (Open field community farm)

Eastie Farm is a community farm situated at Jeffries Point in East Boston at an empty housing lot. Community building and thereby improving the social livelihood of the area, is the main purpose. This is achieved by gardening together and providing space for community events.

The farm is run by volunteers from the local community. On Saturdays, they come together to work in the garden. Except from the board, the work force assembly is varying vastly every week, as participation is voluntary and casual.

Crop (combination)	**Total cultivation area (m^2)**
Empty	1.3
Garlic	6.3
Garlic & beets	3.7
Garlic & carrot	3.1
Kale-peas-spinach	10.1
Onions & carrots	4.1
Unknown	1.0

Table 4

Total raised bed area per crop (combination) at Eastie Farm

At the start of the data collection growing season the farm did not have a permanent permit to cultivate the soil – the permit was obtained earlier the next year. Therefore, the farm was operated in a temporary fashion. As the soil at the farming lot is contaminated with lead and paint, which does not allow the crops to be planted directly in the soil, the farm was forced to make use of a low cost, temporary solution in the form of raised beds.

In total there are 29 circular beds and 2 rectangular raised beds located at the farm, which grow a wide variety of crops. Many beds were used to cultivate multiple different vegetables. For example, some were used for growing kale in centre, peas in the inner circle surrounding the kale and spinach in the outer circle. Table 4 shows the total cultivation area for each crop (combination). Harvested crops are partially donated to the soup kitchen and partially divided between the volunteers that help at the farm.

3.3.1 Water system

Rain water is being collected from the neighbouring roofs, transported through rain-pipes and stored in 55-gallon rain barrels on the ground (fig. 16). This entire system is gravity operated and set up cleverly by connecting several barrels located at different heights to prevent the formation of thin layers of water that are very susceptible to temperature changes. Little taps are installed at the bottom of the barrels and volunteers carry the water from the barrels to the crops.

Since one of the neighbouring roofs is made of wood which has been chemically treated, the water collected from that roof cannot directly be applied to the crops. However, it is used for other water consuming activities at the farm, like sheet mulching.

During dry periods, or at times when water consumption is high, it can happen that the rain barrels run dry. At those times, a garden hose is connected to a neighbour´s tap, and drinking water is used to water the crops.

Besides for watering crops and sheet mulching, the water stored in the barrels is used for washing hands after farm work or is used by kids playing around. Therefore, it is not to be expected that the water consumption at Eastie Farm has a high efficiency from an agricultural perspective.

3.3.2 Energy system

No electricity is used at Eastie Farm. Water is transported from roofs to rain barrels by gravity and from the barrels to the crops by watering cans carried by volunteers. The only energy that is consumed in the growing process is sunlight.

3.3.3 Nutrient supply

Eastie Farm produces its own organic fertilizer by composting domestic food scraps produced by 3-4 people and industrial sawdust in three composting containers (fig. 16). More people would like to contribute to the food waste composting, but there is not enough space on the premises to accommodate more compost containers. Sawdust is applied to the compost containers in order to reduce bad odour that is coming from food waste composting, thus causing less inconvenience for the neighbourhood.

Figure 16 Resource supply systems at Eastie Farm:

- *Rainwater collection system (top)*
- *Manual water supply (middle)*
- *Composting containers (bottom)*

3.4 Neighbourhood description: East Boston

East Boston is a neighbourhood which is part of the city of Boston and was once a centre for shipbuilding. Nowadays it hosts the city's airport and is home to a part of the Port of Boston and 7% of Boston's total population. Traditionally, East Boston has always been a neighbourhood of immigrants (City of Boston, 2019). Of its 44,989 residents in 2015, a 17% growth from 2000, more than half was foreign born and 58% has Hispanic/Latino roots (BPDA, 2017).

Neighbourhood homes include many traditional triple-deckers and many buildings date back to the 19th century (BLC, 1994). Approximately 70% to 75% of East Boston households have been rentals, many off which are affordable housing (BPDA, 2017). Boarded up window frames, flaking paint and rotting wood in constructions testify to overdue maintenance, which is likely a consequence of the relatively harsh socio-economic conditions in this part of town.

East Boston is surrounded by water bodies and is located on the opposite side of the Boston Main Channel from the rest of the city, providing an amazing view on downtown Boston from across the water. The city's housing shortage, combined with the neighbourhood's location close to downtown and the beautiful views it provides, have led to the process of gentrification taking place. Especially along the waterside, a lot of high-end development is taking place and the original population is pushed aside by those who are financially better-of.

3.4.1 Zoning

Both Corner Stalk Farm and Eastie Farm are located in a residential housing block (fig. 17). Apart from private gardens, inside those blocks no public open spaces are present which could be used for wastewater treatment facilities or potential water capturing and storage.

Corner Stalk Farm is located on a private parking lot of the neighbouring garage. Other nearby open spaces mostly belong to dwellings with a commercial or industrial character and are located at lower altitudes, making gravitational transport of prospectively captured water difficult. Small treatment stations or water storage basins could however be located here in absence of a better option. For rainwater capturing purposes plenty of roofs are present, as many free-standing homes are located in the uphill area. These could serve as rainwater harvesting surfaces.

The surroundings of Eastie Farm also host many dwellings which could capture rain. Even though local water harvesting and storage options, like rooftop water collection on neighbouring dwellings, seem ideal, they depend on the mercy and support of private home owners. A public space to capture, accommodate and treat water could prove more sustainable on the long-term.
One block away from Eastie Farm the East Boston Greenway is located, which is essentially a public park, especially created to prevent water nuisance from tidal waves and stormwater. Areas in this park could potentially be used to capture, store and treat water for Eastie Farm if the farm's premises and surrounding privately owned surfaces cannot supply sufficient water. Storage in the park, however, cannot be implemented in endless quantities, as the park's primary function should not be undermined. Moreover, it must be kept in mind that this park is still about 150 m away from the farm and has an altitude several meters lower than Eastie Farm, what could be challenge for regularly watering crops.

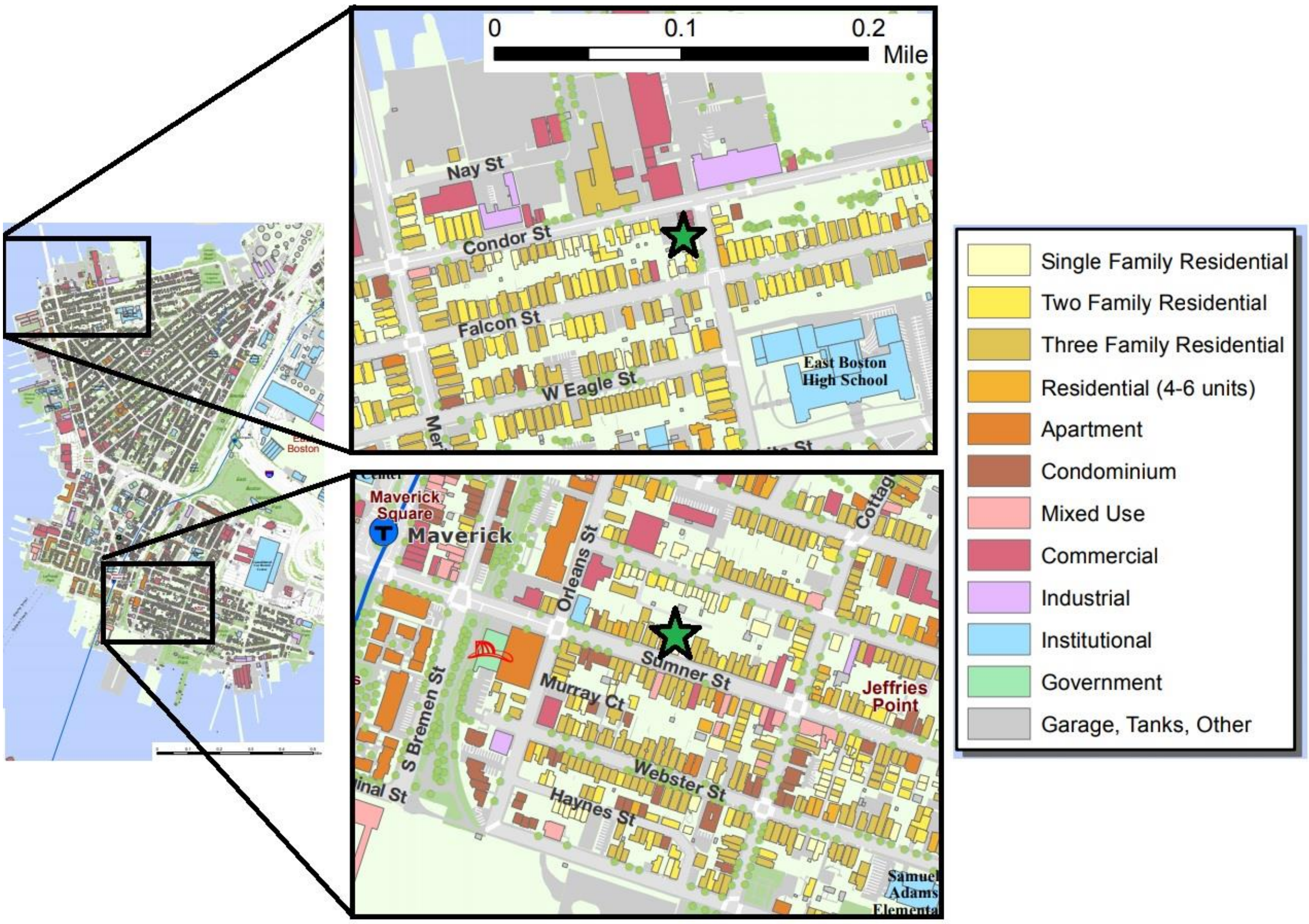


Figure 17 *Zoning map for East Boston, with the surroundings of Corner Stalk Farm (top) and Eastie Farm (bottom) in greater detail*
(Adapted from source: BPDA, 2016)

4 Methodology

The road to answering the research questions stated in the introduction was intricate and multipronged. This chapter describes all the steps taken to answer the questions.

4.1 Framework

Since the research questions stated in the introduction are dependent on the position of urban agriculture embedded in the complex web of interactions between water, energy and food, the first step that was taken to answer them was to create a framework of the WEF nexus, to develop a feeling for the complexity of the nexus and the role of urban agriculture. For the sake of completeness, the framework aimed to provide a holistic overview of the nexus, incorporating all its stocks and interactions. This was done through an extensive literature review on the nexus based on articles that appeared till early 2018 on Google Scholar and Web of Science. Initially, articles covering all three pillars of the WEF nexus were studied, however, thereafter studies on bilateral and unilateral silos were used to fill the knowledge gaps and enhance the completeness of the nexus overview in the framework presented in this report. At first, stocks and links were identified qualitatively. Surprisingly, even articles attempting to describe the entire nexus showed a noticeable variety in their focus, resulting in the fact that studying a large diversity of articles culminated in an extensive nexus web as shown in this study (chapter 5-8). Where a handful of other studies had attempted to describe WEF nexus qualitatively, this literature research not only targeted completeness, but also aimed to go one step further, by quantifying the relations, through incorporating data found in case studies executed by other scholars in this overview. Since percentages and parameters might be location dependent, where possible, data from studies performed in the western world were used. The data collected there were believed to provide the largest similarity with the situation at the sites where the case studies for this research were executed, due to the comparable layout of the economies and engineered systems.

Within the water energy food nexus, many different flows occur. Qualifying all the streams in such an extensive network of flows and stocks requires a very extended research even if it would be done at one case study site alone. Therefore, it would be natural to single out (a) certain flow(s), which haven't been studied a lot, and study them in greater detail. That is exactly what this research did. For the case studies that were executed, only several links of the framework proved to be relevant, namely the ones relating sewage and rainwater with agricultural practices. Therefore, despite the initially broad approach that was utilized in the framework, the focus of this report will zoom in on key components of the nexus framework.

4.2 Case study selection

After the framework was created the research was split in two distinct parts due to the multi-faceted nature of the research questions, as some components are related to the technical system, whereas others are more policy related. This distinction will be followed in this methodology chapter too.

The approach to answer first research question, the one related to the physical system will be discussed first. This includes the process of getting to know the water, energy and nutrients demands in urban farms, as well as the availability of these resources in the urban waters and how the demand and availability compare. The method to answer the second research question, dealing with policy and social issues, like zoning policies, spatial recommendations and organizational structures will be discussed afterwards.

However, it all starts with clearly delineating the limits of the question, initially with respect to the content, but in a later stadium this included spatial demarcation as well.

4.2.1 Delineation of the research boundaries

Since so many (potential) links exist with urban agriculture in cities, focus streams for resource availability were selected. This study aimed to find out if demands for water, energy and nutrients for urban agricultural initiatives could be met by resources present in urban waters. Since both ‘urban waters’ and ‘nutrients’ are broad terms, it might show necessary to define them more precisely. The urban waters that are targeted in this research as resource stocks are local sewage, and rainwater that fell in the nearby vicinity, and which could be stored in a wide variety of rainwater collection facilities. The links are formed by waterflows from these source stocks, the sewer and rainwater collection sites, to the receiving stockholders: the farms, where these resources will be processed into food.

The nutrients that will be considered are nitrogen, phosphorus and potassium, as those are the macronutrients, that after carbon, hydrogen and oxygen – which are incorporated by plants though water and air – are the elements most abundant in plant matter. All other nutrients are simply required at rates way lower than the macronutrients.

4.2.1.1 Delineation of the study area

An important step in the analysis of a case study is to define the geographic boundaries of the system under investigation. Therefore, when the framework is applied in actual case studies, a clear case study site must be outlined. For this research case studies were executed in both Amsterdam and Boston, as both cities are characterized by an innovative economy, liberal population and the presence and development of a variety of urban farms. Although the quantification of flows and stocks in the framework will draw upon a wide range of data of different studies and datasets from all over the world, the case studies in this work, however, are distinctly American and Dutch in the respect that it reviews data collected on site and by various levels of government and other American and Dutch institutions. Therefore, this study shows the type of data typically available for American and Dutch cities and shows where data gaps exist in those environments.

After selecting the focus cities, actual case study sites and corresponding areas had to be found where these links and stocks could be measured and/or analysed. On a local level, this was done using a bottom up approach, meaning that the starting point for the case study delineation was finding suitable farms. Not every farm was automatically suited as case study site. First of all, they had to be within the city boundaries and needed to grow crops for human consumption. Besides a participating farm had to operate at a scale large enough to actually be able to measure resource use using regular equipment, and seriously enough to ensure continued production.

Finally, once suitable farms were located, their operators needed to be asked (and convinced) to cooperate with this study. This was often the hardest part. Initially farms were contacted via digital or telephonic enquiry, but it was proven more successful when a visit in person was made. Once an urban farming initiative showed willingness to participate, the study area delineation for that particular case was continued.

The study area was delineated combining the areas that could potentially be used to meet the water demand of the urban farm under investigation. Both rainwater and sewage water were analysed as potential water source to the farm. However, both streams and nature of their collection infrastructure have different properties and as a result, the rain water and sewage water supply areas would partially overlap but were not entirely the same. More on the delineation of the rainwater catchment and sewage drainage area and quantification of these flows is described in section 4.3.

4.2.2 Localise stakeholders

It is advisable to contact different stakeholders, depending on the case and the focus streams that are studied. When talking about circularity in combination with urban farming, a wide range of stakeholder groups, including farmers, utility companies, scientists, advocacy groups, policy makers and inhabitants, come to mind. Obviously, before a real-life decision is made and can be implemented, both the ones that are in power, and ones that are not but will be affected by decisions on the matter, like the local population, should be consulted. In this thesis, however, the stakeholders that are taken into account are the urban case study farms themselves, local utility companies (water and sewer companies) and spatial planners from the municipality.

It must be realised, that the same type of responsibilities, knowledge and rights might be allocated to a different set of institutions and legal persons, depending on the geographic location of the case study site and corresponding administrative boundaries. This difference in location can result in local differentiation in laws, culture and/or organisational structure and could potentially require a different working method considering data collection on policy and the physical WEF system.

In Amsterdam, the authors personal knowledge of the water management system and institutional setup served to identify the key players in urban farming and wastewater management. Besides the Dutch case study farm itself, which was found after tips from an Amsterdam think tank on metropolitan solutions (AMS), the municipality of Amsterdam and the local water authority (Waternet) were noted as institutions that had to be involved and questioned.

In Boston, stakeholders were localized through professor Paul Kirshen, who has many connections in the local water sector. By networking with these initial connections, including an urban farmer/community worker and sewer experts (BWSC), an analysis of the local playing field considering urban farming and wastewater was sketched.

Further analysis of the situation took it from there and through some referrals by initial connections, other stakeholders in the form of an urban farmer and the local water resources company (MWRA) were identified and involved. Moreover, a specialist at the local water authority of the watershed (CRWA) was interviewed on her expertise with resource recycling from urban waters. More information on the relation between and responsibilities of the stakeholders will be provided in chapter 11.

Not all information for quantification of the data was open source. Therefore, this study was partially dependent on stakeholders for data collection and stakeholders were asked for information in their field that could be useful for this study.

In Amsterdam the municipality was asked to provide zoning maps and development plans for the neighbourhood. Waternet, the local water authority, was requested to share information on the layout of the sewer system and the quality of the sewage.

In Boston the information was a bit more fragmented as a range of institutions were responsible for different parts of the water system. The Boston Water and Sewer Commission (BWSC) was asked to deliver maps of the sewer pipelines in the case study area and the Massachusetts Water Resources Authority (MWRA) was asked to share information on the wastewater quality.

Obviously, case study sites were involved in data collection on site, as not only meters were installed that had to be read by people on site, but also information of their operation system and resource supply chain were crucial for the study. However, the case study farms could not always provide all the data on their resource supply systems, like fertilizer composition and computer monitoring systems themselves. Therefore, in Amsterdam, those data had to be gathered from third parties, like the fertilizer suppliers (Plant Health Cure & Leo Ammerlaan) and a company specialized in computer systems monitoring environmental and control conditions in horticulture (Priva).

4.3 Analysis of the physical system

After key stakeholders were localized and the research boundaries were qualitatively and spatially defined, it was time for the quantification step and determine how strong the links with the focus streams in the nexus at our case study sites are. Therefore, the research process had to be broken down in several sub steps, as different streams were under investigation.

4.3.1 Resource consumption at urban farms

First of all, the resource consumption at farms was studied. Besides the obvious need for a labour force to take care of the plants and perform harvesting activities, in the context of the WEF nexus, the focal points in a requirement analysis of urban farms are on water, energy and nutrients. Estimates on resource consumption at farms are often generated using theoretical transpiration models (Mekonnen & Hoekstra, 2011; Barbosa et al., 2015). Although at least they give an indication on resource requirements of farms, it would be better to test the resource requirements in the field, because in reality farms are rarely operated at a 100% efficiency level.
One can imagine that especially at farms without a commercial purpose, and with a high participation rate of volunteers without a professional background in farming, efficiency rates deviate from the lab ideal. Besides, water, energy and nutrient demands differ per growing stage of the agricultural products (FAOSTAT, 2017). Therefore, providing a general daily resource need is tricky, and an indication of the resource requirements should be given over the entire growing season.

This thesis, however, aims to quantify resource consumption at farms in the field. The procedure for data collection and data analysis depended on the technical installation, mode of operation and available crew at each case study site and was therefore executed in a widely different way at each farm (more information on the site-specific installations can be found in chapter 3). In this section the measurement instruments that were used, and the process of data collection and analysis for each of the case studies that was followed will be explained.

4.3.1.1 **Amsterdam – QO**

In the Amsterdam greenhouse, the daily energy and nutrient demand as well as water circulation data were studied.

4.3.1.1.1 Water use

In the QO hotel in Amsterdam water data for every of the four sub-installations were recorded by an automatically operated computer system for horticultural applications provided and managed by a company called Priva. Since the water supply system is a closed and complex engineered system, it was not possible to install water meters to directly measure the net water use of the greenhouse. Luckily, the Priva system recorded how much water was flowing through the irrigation gutters. However, since the system was recirculating, a complicating factor was introduced. The excess water that is not taken up by the plants is captured and recirculated into the farm watering system, passing the meter again and again. Therefore, the recorded data do not necessarily (in fact very unlikely) represent the net water consumption. Since this total water flow data were the only water data available at this site, it was decided to work with these data. Fortunately, the head of greenhouse operations, an experienced horticulturalist, was able to estimate the water efficiency and figured it would be around 95%. Water loss in hydroponic systems such as the one in the QO hotel occurs in two main ways, through (evapo-)transpiration and through leaks. Given the efficiency estimated by the operating farmer, 95% of the water that is passing the water flow meter, will return there for another cycle, which means that 5% of the water that is flowing through the meter is not available for the next round and needs to be refilled. Given the brand-new, state of the art greenhouse, this is a conservative estimate, as some suppliers of recirculating hydroponic systems claim their system only loses about 1.5% of water daily due to evaporation (Baptista, 2014).

During the data collection period, Teamviewer, a software program used to log in to the greenhouse computer from an external location, allowed the author to register water circulation data for every subsystem on a daily basis. Consequently, the water circulation data for the four subsystems were totalled and a 5% portion of this total was taken to simulate the circulation effect described before, where only 5% of the total circulated water flow measured by the system was considered to be the net water use or water demand that had to be met by external sources

4.3.1.1.2 Energy use

Energy data were collected automatically by the Priva operation system, after the settings in the software were changed at the start of the data collection period. This enabled the extraction of CSV-files on the incoming solar radiation and electric power used by lighting and the heat produced by the heater with a 5-minute time resolution. Also, the radiation blocked from entering the greenhouse by curtains was recorded. All these data were recorded in kW and could be loaded into Excel for further analysis.

For each 5-minute time interval, the total energy consumption for each activity was calculated in kilowatt-hours by dividing the power by a factor 12. Finally, the energy consumption for 12 intervals per hours and 24 hours per day were added, which resulted in the total daily electric power consumption for each activity. By multiplying the radiation (in W/m^2) by the window surface, and consequently subtracting the blocked radiation, the total net incoming radiation was computed. Afterwards, graphs were added to visually clarify the daily fluctuation in energy use for lighting and heating and the incoming solar radiation.

No energy data were available on the power consumption of the large pumps that push the water from the basement of the hotel towards the greenhouse on the 21st floor and the smaller pumps that allows the water to be transported through the greenhouse itself. However, the energy needed to operate the big booster was estimated by multiplying the height of the building with the weight of the consumed water that was pumped up 76 meters.

4.3.1.1.3 Fertilizer use

Fertilizer addition was still in an experimental phase when data collection started. At first, only artificial fertilizer was added, but the horticulturalist decided to gradually switch to organic fertilizer during the data collection period, mainly because it offered a buffer capacity for acidity. Data on both types of nutrient addition were collected in different ways.

Information on the addition of artificial fertilizer, which was released by dispensers that operated automatically to compensate for changes in EC, could not be extracted automatically from the Priva system. The system only stored the data for a day and for each of the four subsystems in the greenhouse independently. However, the data could be acquired by logging in daily via Teamviewer to gather the data from the system. The daily consumption of artificial fertilizer solution from all four subsystems was then added, which resulted in the total volume of added fertilizer solution. Information on the composition of the fertilizer solution was requested from the manufacturer (Leo Ammerlaan). Since the data on the composition of the fertilizer were provided in molar concentration, this was multiplied by the molar mass, resulting in the concentration in grams per litre for each of the three nutrients under investigation (table 5). Multiplying this concentration by the amount of fertilizer solution that was added resulted in the final dry weight fertilizer consumption. To prevent inconclusive measurements from skewing the data, it was decided to leave data collected over an incomplete runtime (less than a full day) out of consideration for further analysis.

	Nitrogen	**Potassium**	**Phosphorus**
Concentration (mol/l)	1.6	0.6	0.2
Molar mass (g/mol)	14.0	39.1	31.0
Concentration (g/l)	22.9	25.2	5.4

Table 5 Mass concentration of macronutrients in the artificial fertilizer derived from their molar concentrations

The data on the addition of organic fertilizer were gathered more primitively. Three types of organic fertilizer were in use, each for a different growing stage, and each had a slightly different composition. The volume of the empty (part of) jerrycans for each organic fertilizer was measured using a ruler. Consequently, the information on the consumed solution volume was combined with information on the chemical composition of the solution as shown on the packaging. Further information for clarification was requested from the manufacturer Plant Health Cure B.V..

Concentrations of the nutrients were given as percentages of the total solution. The upper composition limit was used to calculate the nutrient use in order to make sure that in any case an overestimation of the nutrient use is made instead of an underestimation. Presuming that the percentages on the packaging concern the mass fraction, they could be multiplied by the total consumed solution volume and by the density of the solution (1300 g/L). This would result in the mass of the molecules carrying the nutrients under investigation. Only for nitrogen the elemental concentration was provided. Since we were interested in the mass of the elemental form of each nutrient a molar mass calculation had to be executed.

$$Mass\ ratio\ of\ phosphorus\ in\ P_2O_5 = \frac{2 * 30.97}{2 * 30.97 + 5 * 16.00} = \frac{61.94}{141.94} = 0.436$$

$$Mass\ ratio\ of\ potassium\ in\ K_2O\ = \frac{2 * 39.10}{2 * 39.10\ +\ 16.00}) = \frac{78.2}{94.2} = 0.83$$

The mass ratio was then multiplied by the consumed mass of the molecule to obtain the mass of the elemental nutrients in the solution.

Although the addition was irregular, the crops had continuous access to the organic fertilizer ever since it was first applied. Therefore, the total organic fertilizer consumption over a few weeks (from the 6th of July till the 24th of August), totalling 50 days, was averaged over the time to provide an approximation of the daily application.

4.3.1.2 <u>**Boston – Corner Stalk Farm**</u>

At Corner Stalk container farm, the daily energy and nutrient demand as well as water circulation data were studied.

4.3.1.2.1 Water use

The water barrels at Corner Stalk Farm were filled every few days through a garden hose connection with the drinking water network of the city. In order to measure this incoming water flow, in one of the farm's containers a digital garden hose water meter, a RainWave RW-9FM, was installed, which recorded the flow in gallon (fig. 18). Every time the water storage barrels were filled, the water meter would turn on automatically, and the total water feed could be read from the display. Consequently, this value needed to be written down manually in a data collection sheet to be stored. For this purpose, a Google Docs spreadsheet was created, which could be accessed by both the farmer and the researchers.

The average daily water use was then calculated by dividing the added water volume by the amount of days between the day that the water supply was recorded and the previous time water was supplied to the storage system. Afterwards, this value was converted from gallons to litres (by multiplying by 3.79 gallon/litre), for easy comparison in SI units with the other case studies in this thesis.

Figure 18

Water meter attached to the inlet of one of the containers with a hose connecting the tap and the meters to the storage barrels

Figure 19

Baodain single phase three wire energy meter

4.3.1.2.2 Energy use

Since the energy supply system turned out to make use of a single phase, three-wire electric power distribution, it required the installation of a very specific energy meter and an electrician to install it. It was decided to install the Baodain single phase three wire energy meter, which could be connected to a data logger (fig. 19). However, this data logging feature was not used, because of financial restrictions.

The analogous electricity meter displayed the cumulative energy use (in kWh) since the installation and had to be read manually, on a daily basis, to get to know the daily energy consumption. Because the meter was read much less regularly, the average daily water use was calculated by dividing the difference in cumulative energy reading by the amount of days between each reading date.

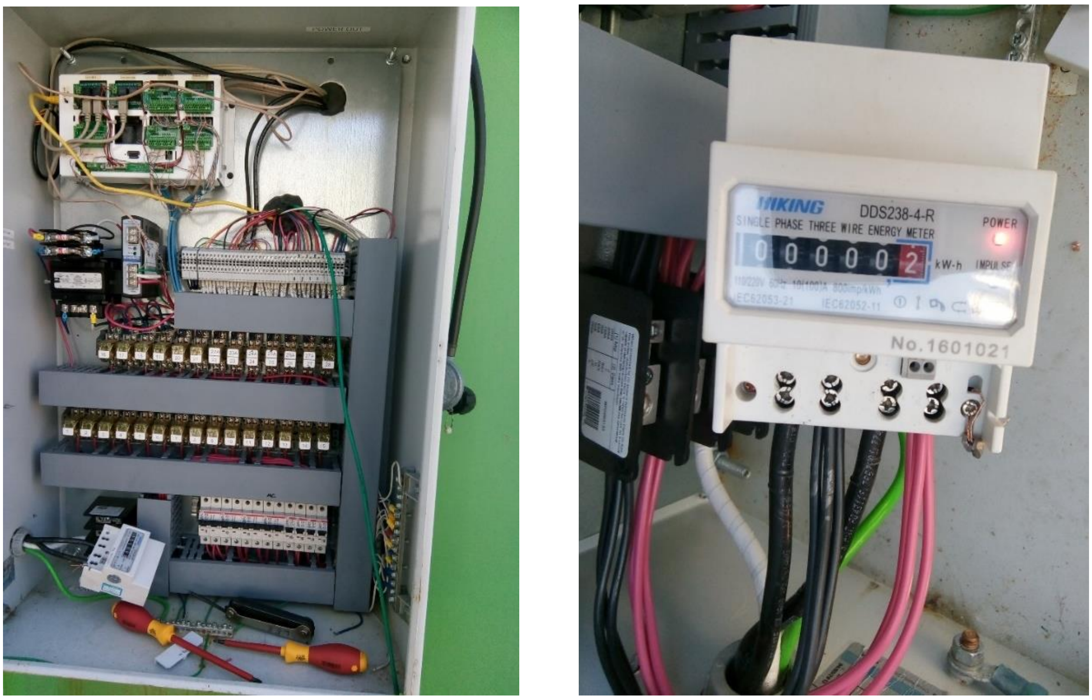


Figure 20 Installation of the electricity meter in the meter cupboard

4.3.1.2.3 Fertilizer use

Fertilizer use at Corner Stalk Farm was monitored by weighing dry fertilizer (in oz) before adding it to the system as a solution. Information on the chemical composition of the fertilizer was supplied by the manufacturer and in possession of the farmer himself.

Figure 15 (section 3.2.3) shows that fertilizer dosages with equal additions from each bag, consist for 10.5% out of nitrogen. Mass percentages of both elemental phosphorus and potassium were derived from the given table, by making use of the molar mass calculations (see below).

$$Mass\ ratio\ of\ phosphorus\ in\ P_2O_5 = \frac{2 * 30.97}{2 * 30.97 + 5 * 16.00} = \frac{61.94}{141.94} = 0.436$$

0.436 * 4.5% = 1.96% phosphorus present in combined solution of bag A and B

$$Mass\ ratio\ of\ potassium\ in\ K_2O = \frac{2 * 39.10}{2 * 39.10 + 16.00}) = \frac{78.2}{94.2} = 0.83$$

0.83 * 21.3% = 17.68% of potassium present in combined solution of bag A and B

After the fertilizer use in ounce was converted into grams (using 28.350 gram/oz), the dry fertilizer weight was multiplied by these percentages in order to calculate the weight of each nutrient element that was supplied to the crops.

4.3.1.3 Boston – Eastie Farm

Collection of energy data is not applicable at this case study site, since no electricity is used for the crop cultivation, irrigation and maintenance.

4.3.1.3.1 *Water use*

Just like at Corner Stalk Farm, water consumption data at Eastie Farm were measured by digital garden hose water meters (RainWave RW-9FM) that were read each day when water was withdrawn from storage barrels by farm volunteers.

Figure 21 Water meter attached to the garden hose outlet of one of the rainwater barrels

The daily water use data were collected in a Google Docs document that was shared with all the farm volunteers that were highly involved in managing and execute the growing operation. Google docs was chosen as data collection medium, as it provided easy access for the data collector and allowed to monitor data collection from a distance by researcher.

Since five water meters were in use at the farms, all installed at different barrels and garden hoses, the water uses from all five systems were totalled and converted from gallons into litres.

It was assumed that nobody watered the plants on days that no data were collected in the online spreadsheet. However, since there was no automatically controlled water system present that ensured continuous water supply and since the water was only brought to the crops using watering cans on (semi-)dry days, the discontinuous availability of water data represents the need for daily manual water addition effortlessly, and no averaging was needed to obtain daily water consumption data.

4.3.1.3.2 *Fertilizer use*

Fertilizer was added in the form of compost, using buckets with a volume of 5 gallons each. On a data collection sheet attached to the compost containers farm volunteers could keep tally of the amount of buckets of compost that they applied to the garden. Designated farm volunteers could then put the collected data in the online Google Document.

This study did not carry out a chemical analysis of the compost that was used on site. However, other studies – mentioned in the framework (see section 8.2.2.1) – have demonstrated that the physical and chemical composition of compost is dependent on factors such as raw input products and maturity. Mladenov (2018) showed that the density of compost ranged between 0.17 and 0.39 g/cm^3, from which the highest value was used in this analysis, as that compost type (made of food and parkland waste) was most similar to the Eastie Farm input products. Of the investigated blends, the one that was thought to resemble the compost at Eastie Farm most was the compost made by combining food waste, mature compost and sawdust. After maturing for 60 days, this mixture consisted of 1.6% nitrogen, 0.6% phosphorus and 1.4% potassium (Lin, 2008). These percentages were multiplied by the volume of added compost and the density in order to calculate the amount of added nutrients to the community garden during the data collection period. Again, because compost was applied discontinuously, no averaging of the data was considered required to simulate daily demands.

4.3.2 Resource availability near case study farms

After determining the resource needs at the farms, the water, energy and nutrient availability near the farm were investigated. This was done by looking into the potential for rainwater harvesting and by quantifying wastewater flows passing the study sites.

4.3.2.1 Sewage water availability

The wastewater availability was determined by reaching out to the local sewer company to gain information on the lay-out of the local sewer system, data on the flows in that system and the composition of the sewage inside. These data were requested and provided by a range of institutions. In Boston, the Massachusetts Water Resources Authority (MRWA) shared data on the sewage water quality, whereas the Boston Water and Sewer Commission (BWSC) provided this research with pdf maps of the sewer system on a neighbourhood level. In Amsterdam, Waternet shared reports on wastewater quality and GIS-files on the local sewage system.

In neither of the two case study cities the authorities responsible for the local wastewater infrastructure monitored the dimension of water flows and water quality in sewer pipes at a local level. Therefore, use was made of the generic water quality data to get a grasp on local sewage resource availability. From the sewer layout maps the number of upstream connections from the point nearest to the urban farm under investigation could be identified. As it wasn't clear to which parts the sewer was connected outside of the sewer map that was provided, it was decided to conduct this study using only the upstream connection visible on the maps to prevent an overestimation of resource availability.

With the help of some basic assumptions and generic and demographic information, such as the average daily water consumption per person (107 litre per capita per day in Amsterdam and 155 litre per capita per day in Boston (Waternet, 2019; MWRA, 2016), and the average number of people per household (on average 2.36 persons in Boston (Census, 2018)), or detailed population density data (Amsterdam), the average dry weather flow in the public sewer at that location could be estimated.

In Amsterdam also the internal wastewater production of the hotel, which counts 288 rooms, was approximated. When assumed that half of the rooms are permanently filled with a least one guest, sanitary waste from at least 144 people could be captured.

Only the dry weather flow was considered in these analyses, as this is the sewage flow carrying the vast majority of energy and nutrients in the sewer. Given the concentrations and the average dry weather flow in the sewer pipelines nearby the case study sites, an estimate was be made on the availability of water, energy and nutrients that can be retrieved.

4.3.2.1.1 *Nutrient availability in sewage*

Multiplying the average concentration of a nutrient with the daily water volume passing the case study site through the sewer resulted in the average total potentially available daily nutrient load. Since the recovery efficiency depends on the methods used, the nutrient analysis focussed purely on availability.

Nitrogen uptake by plants mostly occurs through nitrate and ammonium. Therefore, those are the only two nitrogen forms that are considered during this analysis. Phosphorus calculations depended on the available data. In Amsterdam only information on the total phosphorus concentration was provided and therefore used in the nutrient availability analysis. Part of the phosphorus is however bound to other components and therefore more difficult to harvest. Hence in Boston, where data on the concentration of the solvable compound ortho-phosphorus were provided, this concentration was used during the calculations instead of the total phosphorus concentration.

4.3.2.1.2 *Energy availability in sewage*

The energy potential of the sewage near the agricultural facility, was calculated using the COD concentration in the sewage as explained in the framework (section 8.3.3). Combined with the calorific value for methane which can be produced during anaerobic digestion, the chemical energy content of the sewage amounts 12.5 MJ/kg COD. This energy can be released with a 100% efficiency for heat production. At Corner Stalk Farm and for certain activities at the QO hotel, however, electricity is consumed. In those cases, a biogas generator is required to transform the energy in requested form. Since those generators typically run at 35% efficiency, one kilogram of COD can only be converted into 1.2 kWh of electricity.

4.3.2.2 Rain water availability

In order to calculate the rainwater availability near the case study sites, rainfall data collected by local authorities were downloaded. Although climate is defined over a period of 30 year, this timespan was considered too long, as weather patterns from the early 1990s are likely to be outdated as precipitation patterns altered due to climate change. To make sure that the analysis is based on the latest rainfall patterns, a precipitation analysis period of 20 years was targeted. A longer rainfall analysis period would only increase the quality of the statistics, but was not thought to provide a more realistic picture on the rainfall situation.

In the Netherlands, the daily rainfall data were retrieved from the website of the Royal Netherlands Meteorological Institute (KNMI, 2019). Data are available for 50 locations in the Netherlands, of which the series recorded at Amsterdam Airport Schiphol was the nearest to the study site, and therefore selected for this research. An uninterrupted sequence of daily sums of precipitation was downloaded for a period of 20 years between January 1, 1999 and December 31, 2018.

The precipitation data for Boston were downloaded from the website of the National Weather Service Forecast Office (NWS, 2019). Rainfall data measured at the Boston Logan Airport measuring station were used, which is located in the East Boston neighbourhood, just like the American case study sites. Just like in the Dutch case, rain data for Boston which was recorded between January 1, 1999 and December 31, 2018, were downloaded. The measuring station at Boston Logan Airport, however, was close to being, but not entirely consecutive. Two days, August 23 and 24, 2003, are missing in the sequence.

The raw precipitation data have been edited in several steps in order to facilitate quantitative analysis in Excel. The American data, which were copied for each month separately, were added to an excel file for further analysis using the old school copy paste technique. Since the raw precipitation depth data were provided in inch, a conversion from this imperial unit to the metric unit for length was required. Therefore, the raw data were multiplied by 25.4 mm/inch in order to obtain the rainfall depth in millimetres.
The Dutch data didn't require such a conversion. However, after the downloaded CSV files were imported in excel, the sum of precipitation was rendered in 0.1mm per nychthemeron. This needed to be divided by a factor 10, to get it in the more comprehendible whole millimetres.
Traces of rain, which are small amounts of daily rainfall that are below the measuring limit, were defined as <0.01 inch/day in Boston and <0.1mm/day in the Netherlands and were labelled in the downloaded files as T (from trace) and -1 respectively. Since the trace rainfall amounts are very small, but were indicated in a way that made data analysis quite hard, they were replaced by zeroes to simplify further analysis.

After the data preparations mentioned before were completed, the quantitative analysis of rainwater availability could commence. Rainfall depths had to be multiplied by surface areas suitable for rainwater harvesting to obtain information on the available rainwater volume.

In some areas, like the Amsterdam Amstelkwartier and nearby Corner Stalk Farm, a separate sewer system is present, where rainwater is collected in a separate pipeline. The area draining into this pipeline is however unknown. An endless supply of water could be assumed so that during every rain event water storage tanks could be filled. However, this seems a large overestimation of the real situation. Moreover, the quality of this stormwater is dubious, whereas water collected on rooftops is relatively clean (section 7.1.1). To avoid potentially undesirable dependence on third parties, however, it was decided to determine the rainwater availability by multiplying the rain depth only by the roof area of the greenhouse and the container respectively.

In the case of Eastie Farm, where no central collection system for rainwater was present and where the farm does not own a roof for water collection either, the delineation of the rainwater collection area required a different approach. Here the total roof surface area in the block that could be used for rainwater harvesting was determined. Both flat and pitched roofs were identified within circles of 50 and 100 meters around the case study site and within the same block.

Not all water falling on these surfaces will be available for harvesting. According to Lancaster (2006) only 80 to 85% of rainfall on flat roofs will result in runoff. For pitched roofs this percentage is slightly higher (90%). To correct for this phenomenon, rooftop areas under investigation were multiplied by a runoff coefficient, depending on their slope (0.8 for flat roofs and 0.9 for pitched roofs) to calculate the effective surface, which could be multiplied by the rainfall depth in order to determine the potentially available rainfall volume that the surface could generate.

4.3.3 Water efficiency

For both Corner Stalk Farm and Eastie Farm the water efficiency of the operation was calculated. A similar analysis could not be done for the greenhouse in Amsterdam, as data about theoretical resource needs for the rare crops grown at the QO hotel were not available.

Month	**p-factor**
April	0.30
May	0.33
June	0.34
July	0.33
August	0.31
September	0.28
October	0.24

Table 6 The mean daily percentage of annual daytime hours 42° north (Source: FAO, 2019-1)

In order to determine the water efficiency of the two farms in Boston, the daily transpiration rate was calculated, using the Blaney-Criddle method as proposed by the FAO. It must be noted that the Penman-Monteith equation would have generated more accurate transpiration results, but since not all input data required for running this formula were known, the Blaney-Criddle method was applied. For this method, first of all, the mean daily temperature (T_{mean}) was determined at the Boston Logan Airport NWS weather station, followed by the determination of the mean daily percentage of annual daytime hours (p-factor) which depends on the time of year and the approximate latitude of the area. The mean daily factor of annual daytime hours at Boston's latitude of 42° north of the equator ranged between 0.30 and 0.34 (table 6). However, LED lights at Corner Stalk Farm provide light to the crops 24/7 and plants transpire the entire nychthemeron. Therefore, a p-factor of 1.0 was used to calculate the daily transpiration at the container farm. Subsequently, the (evapo-)transpiration (ET_0) of a reference grass crop in the local climate could be calculated using the equation 1.

$$ET_0 = p\,(0.46 * T_{mean} + 8) \qquad \text{(eq. 1)}$$

However, not all crops consume as much water as the reference crop. Moreover, to complete a growing cycle, several stages of crop development must be passed (table 7). Each crop in each stage has a characteristic crop factor (K_c) which describes the water use ratio of the crops in the 'field' compared to a reference grass crop (table 8).

Crop	**Duration total growing period**	**Duration of each growing stage**			
		Initial	**Crop development**	**Mid-season**	**Late season**
	Days	*Days*	*Days*	*Days*	*Days*
Carrots	150	25	35	70	20
Peas	100	20	30	35	15
Spinach	100	20	30	40	10
Onions	150	15	25	70	40
Greens	140	35	50	45	10
	75	20	30	15	10
Cabbage	140	25	30	65	20
Squash	120	25	35	35	25
Tomatoes	180	35	45	70	30

Table 7 Duration of growth stages for various crops (Data source: FAO, 2019-1)

Crop	**Crop factor K_c during each growing stage**			
	Initial	**Crop development**	**Mid-season**	**Late season**
Carrots	0.45	0.75	1.05	0.9
Peas	0.45	0.8	1.15	1.05
Spinach	0.45	0.6	1	0.9
Onions	0.5	0.75	1.05	0.85
Greens	0.45	0.6	1	0.9
Cabbage	0.45	0.75	1.05	0.9
Squash	0.45	0.7	0.9	0.75
Tomatoes	0.45	0.75	1.15	0.8

Table 8 Crop factor for various crops during different growth stages (Data source: FAO, 2019-1)

These values were used to calculate the transpiration of a reference crop. Because of the continuous production at the container farm, crops of all growing stages were cultivated simultaneously. Therefore, the weighted average of the crop factor for the shortest lettuce (greens) growing cycle was calculated (Kc = 0.68) and used in further calculations. Ultimately, on a daily basis, the crop water need (in mm/day) was calculated using equation 2.

$$ET_{crop} = ET_0 \times K_c \qquad \text{(eq. 2)}$$

The total ET of a crop is expressed in a water depth (in mm) and needed to be multiplied by a surface area to result in a required water volume for transpiration.

At Corner Stalk Farm this was done by simply multiplying the required water depth for lettuce by the total growing surface of 78 m^2 created in the container.

At Eastie Farm, where several crops are cultivated, the growing surface used to grow each type of crop needed to be determined as water requirements per crop vary. However, because crops were grown in mixed beds the exact surface used by each crop was hard – if not impossible - to determine. Therefore, the surface area was approximated using the average yield density per crop in the United States (FAOSTAT, 2017) combined with yield weight data of the farm (table 9).

Crop	**Yield density (kg/m^2)**
Cabbages	4.8
Carrots	4.8
Cauliflower	1.9
Garlic	1.7
Lettuce	3.4
Onions	6.7
Peas	0.5
Squash	2.6
Spinach	1.5
Tomatoes	8.7

Table 9

Average yield per hectare in the USA in 2017 (Data source: FAOSTAT, 2017)

The total required water volume for crop transpiration was then compared to the total water supply to the farm (both rainfall and manual application at Eastie Farm and automated supply at Corner Stalk Farm) in order to calculate the efficiency of the water supply.

4.3.4 Comparison of supply and demand

To answer the research question, resource demand and potential resource availability in urban waters in the direct urban environment needed to be compared.

4.3.4.1 Energy & Nutrients

In the case of nutrients (nitrogen & phosphorus) and energy needed and available for urban agricultural initiatives this was pretty straightforward, simply because dry water sewage flow is assumed constant during the year. If the average availability exceeds the average or even the peak demand, sewage can provide enough of these resources.

4.3.4.2 Water

Water supply and demand, however, vary throughout the year. For every day the rainfall volume falling on the catchment area was subtracted by the water demand, showing whether that day would experience a water surplus or a shortage, which would be translated in an increase or a reduction of the continuous storage respectively. Due to time limitations, real-time water demand data were only recorded during a part of the 2018 growing season. These demand data were used and copied for all years under investigation. Outside that time frame, the average water use measured during the study period was used to be able to simulate fluctuations in available storage volume year-round. A continuous storage simulation followed in Excel, using the following formula:

Storage (t) = IF(((Storage(t-1) + daily change in storage) > (Maximum Storage Capacity)); Maximum Storage Capacity; (Storage(t-1) + daily change in storage))

To overcome any dry periods at the start of the growing season, the storage tanks were simulated to get filled from January 1999 on with rainwater falling on the selected collection surfaces. At Corner Stalk Farm the water demand was continuous, without seasonal pauses, while water demand at Eastie Farm was assumed to start at April 28, lasting till November (mimicking the local growing season).

It is yet unclear whether the QO hotel greenhouse in Amsterdam will be able to operate year-round. Outdoor weather conditions have a greater impact on the crop production a greenhouse than on production in the container farm. The growing season in the Netherlands starts the 1st of April and lasts till the end of September, totalling 183 days. However, climate scenarios project that in 2085 the open field growing season will probably start as early as halfway February (KNMI, 2018). Therefore, two separate analyses were made for the greenhouse water assessment, one using a growing season from April till October and one from March till October.

During the growing season, the water demand would regularly exceed rainfall, draining the storage barrels again until another (winter) refill would kick-off.
Ultimately, the storage volume required to optimally use the water harvested from the selected surfaces needed to be determined. This was done by establishing the largest decline in continuous water storage over each of the 20 years analysed and based on the principle that the total volume was never allowed to run dry. Required storage thus did not correspond to the largest storage shortage or the maximum potential water storage, as not all of the rainwater that could be harvested and stored is required to cover droughts. Above the suggested storage volume, a spill was assumed.

For every case, a second assessment was made where a water shortage was allowed only once in the 20 years under investigation.

It must however be kept in mind that all these simulations assume that water leftovers from the previous year(s) remained in the barrels during the winter. Therefore, it would be wise to expend the suggested required storage volume to avoid any frost damage when the barrels are stored outside.

4.4 Governance

Besides the physical system analysis, the local governance scheme was analysed in order to eventually come up with future-proof recommendations with regard to (local resource reuse in) urban farming.

The urban WEF nexus is set apart from the WEF nexus in other areas due to the presence of dense infrastructure, which enhances the possibility of interconnecting the resources. However, the wide presence of buildings and infrastructure also reduces the available space for the realisation of even more facilities. Therefore, in Amsterdam an interview with Frank Bakkum (geographer of the department of spatial planning and sustainability at the municipality of Amsterdam) served among other things to explore a spatial planner's visions on futureproof urban circularity arrangements regarding urban farming.

Moreover, responsible parties for the piped water system in both of the case study cities were identified through interviews with other local stakeholders and by using personal knowledge of the author and its supervisors on the local institutional system. Consequently, Stefan Mol (energy, resources and water consultant at Waternet), Charlie Jewell (director of planning at the Boston Water and Sewer Commission) and Stephen Estes-Smargiassi (director of planning and sustainability at the Massachusetts Water Resources Authority) were questioned about the current status and characteristics of the local sewer system and preferred rainwater collection strategies.

Not only were stakeholders able to provide crucial information on the physical wastewater system, interviews and informal talks with all the stakeholders in this study served to find out what each stakeholder needs and what their interest is in urban agriculture. In addition, our sources from the farms and institutions were asked for their viewpoints on local sewage abstractions from the sewer system and on decentralized wastewater treatment for urban agricultural initiatives. Resistance as well as possibilities and even advice were topic of conversation. Furthermore, Julie Wood (Director of Projects at the Charles River Watershed Association) was interviewed on her experiences with projects on decentralized water treatment.

All the gathered information on governance, viewpoints and experiences might seem to be outside of the scope of the study initially, but this background knowledge eventually resulted in a holistic view on any hurdles for wastewater reuse in agriculture and synergies in ambitions between spatial planners, sewer companies and farmers. As much preferences as possible were taken into account when formulating a spatial recommendation for promoting circularity in urban agriculture, increasing the chance of successful implementation.

5 Framework of analysis on the local Water Energy Food Nexus

Water, energy, and food are lifelines for modern societies. In response to climate change and social changes including population growth, globalization and urbanization, the concept of the water–energy–food nexus emerged (Hoff, 2011; Endo et al., 2017).

5.1 From monodisciplinary thinking to nexus approach

As the name of the water-energy-food nexus implies, it aims to link the three sectors in its ranks. However, historically, those three industries have been studied in isolation, in so-called silos (Zhang & Vesselinov, 2017; Leung Pah Hang et al., 2017). In academia and specialist professions, there used to be a tendency to deconstruct complex natural systems and analyse them in separate disciplines (Allan et al., 2015). Existing institutional arrangements like government departments are also structured along those lines, with segregated funding mechanisms and spatial urban landscape, as well as legislative and regulatory barriers as a result (Leck et al., 2015).

Two-sector nexus thinking is also not new. Concepts and frameworks linking water and food (with land) do exist, but capture only a limited range of the complex WEF interconnections (Chang et al., 2016; Ringler et al., 2013). Much less is known on the link between energy with water and food with energy and the interactions of these three core resources with land (Ringler et al., 2013). However, the potential of the nexus approach is gradually realized and the benefits of developing tools for analysis and design that consider nexus interdependencies are recognized (Leung Pah Hang et al., 2017). These tools could facilitate coordinating policy and decision-making to minimise negative externalities and unforeseen consequences in tackling both local and global challenges (Leck et al., 2015).

Studying three-way resource interactions requires in-depth understandings of resource relationships and interconnections across multiple scales (Hussey and Pittock 2012; Peronne and Hornberger 2014). Besides the fact that very few people are expert in more than one of the nexus' sectors, let alone in all three, data and modelling constraints constitute key-barriers to the development of a holistic WEF nexus framework (Bazilian et al. 2011; Leck et al., 2015). Moreover, interactions among water, energy and food industries are highly complex and major uncertainties exist about their future development and effects of drivers of change from the outside (Peronne and Hornberger, 2014).

Climate change as well as population and economic growth intensify the existent relations between the water, energy and food systems, making the nexus ever more complex. Although the WEF nexus knows many inherent antagonisms as the development of one sector usually depletes resources in the two other sectors, it is apparent that interventions to improve the status of one sector, can also bring along positive impacts on the others (Chang et al., 2016). Understanding the synergies and antagonisms among the many parts of the urban system increases the scope for maximizing the benefits of a technology or policy implementation, ultimately resulting in closing the loop through resource recovery, while capturing true efficiency gains (Kurian, 2014).

The nexus approach requires that interrelating factors are brought together. When water systems, energy schemes and agricultural production are considered separately potential trade-offs and feedbacks might be overlooked and synergies can be missed out on. Therefore, it is important to abandon silo thinking.

5.2 Nexus

When creating a nexus framework, multiple considerations should be taken into account, as there are multiple ways to approach the design process. First of all, frameworks can be designed using either a top-down or a bottom-up approach. Feng et al. (2011) showed that, when either of the two methods were applied separately, the gap between the two model outcomes could be as high as 48%.

Secondly, there is the dilemma of how to deal with the complexity of scale. The fact that water, energy, food, social and institutional systems all take place at different and overlapping spatial scales, hampers the synchronisation of policies and physical interventions, as they are not necessarily suitable or effective at all scales. A solution to this challenging situation would be to create different arrangements of large and small scaled, centralized and decentralized systems at different scales to be effective while ensuring local suitability and acceptance at finer scales (Leck et al., 2015; Kurian, 2014).

Another major limitation for the urban nexus description is the availability and accuracy of data at city level. Those data tend to have a high degree of uncertainty, are incomplete or even non-existent. In addition, such information is quite scattered and needs to be collected from a wide range of institutes (Elliot et al. 2000; Sahely et al., 2003; Villarroel Walker et al., 2014). Furthermore, the fact is that when data were available for quantification of nexus components they were often very specific and only applicable to situations with distinct characteristics, which adds to the hesitation about the degree of applicability of the general nexus quantification in local studies.

Urban metabolism studies have been executed in order to determine energy efficiency, (potential for) material cycling, best practices of waste management, and required infrastructure in urban systems (Sahely et al., 2003). However, very often, those studies turned out to be sheer black box approaches, barely investigating the relations between the sectors within the urban region, only focussing on identifying and quantifying in and outflows of energy, water, material, and wastes into and out of the city.

5.3 This framework

In the following chapters a framework for a systematic analysis of the water-energy-food nexus will be provided. The systematic approach will facilitate normalizing research done on the nexus. Many relations in the nexus have been identified in earlier studies, but the links are rarely quantified. This is showing the importance of an elaborate framework.

As this framework is focussing on relations in the WEF nexus in the urban setting, it is better not to be used outside that scope. In an urban setting, the WEF nexus differs from the nexus in a rural or more generic perspective. On one hand, more links might appear as systems in cities are more easily connected because of short distances and a wider range of activities. On the other hand, focussing on the urban nexus will disregard links that occur inside the nexus, when they are not linked to a city.

Current frameworks are limited in their view as they largely represent a water centric perspective (Smajgl et al, 2016). This report attempts to equally weight every sector in the holistic framework and aims to provide an overview of the entire nexus surrounding urban farming across disciplines and across scales, visualizing trade-offs, feedback dynamics and synergies, and whenever possible providing tools on quantifying the interrelations. By not only visualizing antagonyms and synergies, but by quantifying WEF connections, a critical initial step is made to develop tailor-made integrated methods that contribute to reducing trade-offs and increasing synergies of three resources uses (Endo et al., 2017; Chang et al., 2016). This will be done by first taking a holistic perspective on the WEF nexus interlinkages, before zooming in to the local interrelations that are further studied in this thesis. A hybrid between the bottom-up and top-down approach forms was used, as initially the bigger picture of the nexus has been sketched by brainstorming (fig. 22). In this top-down nexus layout sketch additional resource stocks and flows of the WEF systems that could be found in general nexus studies were incorporated. The bottom-up approach has been applied while gathering quantitative information on the individual stocks and links. The synthesis of the top-down and bottom-up approaches creates a more complete framework by facilitating the identification of links without compromising on quantitative accuracy by using field data instead of general assumptions (Chang et al., 2016).

Outlining the boundaries of a nexus framework is a challenging task because of the many nexus transcending activities that only affect one of the water, energy or food stocks, but are not directly related to the other components of the web. Therefore, it is hard to draw a hard line surrounding the nexus, and the nexus boundary can best be represented by a porous dotted line encompassing WEF stocks and activities. This framework will neglect those of the relations that are peripheral and will purely focus on the relations that are taking place at the core of the nexus and on the connectivity between the three sectors.

When discussing the WEF-nexus, a distinction has to be made between stocks, where resources are being stored, and fluxes, which are influenced by stakeholders and represent the flows of a resource from one stock to another. The position of space, labour and capital as essential resources are considered as external boundary conditions, influencing the WEF nexus. The quantification of flows and stocks in this framework will draw upon a wide range of data of different studies and datasets from all over the world. Therefore, it is important to realize that the presented data on the flows of energy, water, nitrogen, phosphorus and potassium entering, leaving and circulating through four socio-economic sectors – water, food, energy, and waste handling flows – may differ from local systems. Besides, the framework provided here has not been scientifically tested on principles of conservation of energy and mass, but provides a general, yet quantified understanding of the order of magnitude of flows and stocks in order to get a grasp of how big the nexus actually is.

The quantified nexus framework in the following chapters will elaborate on stocks (chapter 6) and flows (chapter 7 & 8) as shown in overview figure **22** and is rooted in holistic systems thinking. By following this framework, a clear understanding of a real case in the greater context of the urban water-energy-food nexus will appear. Subsequently, chapter 9 discusses the position of urban agriculture within the WEF nexus.

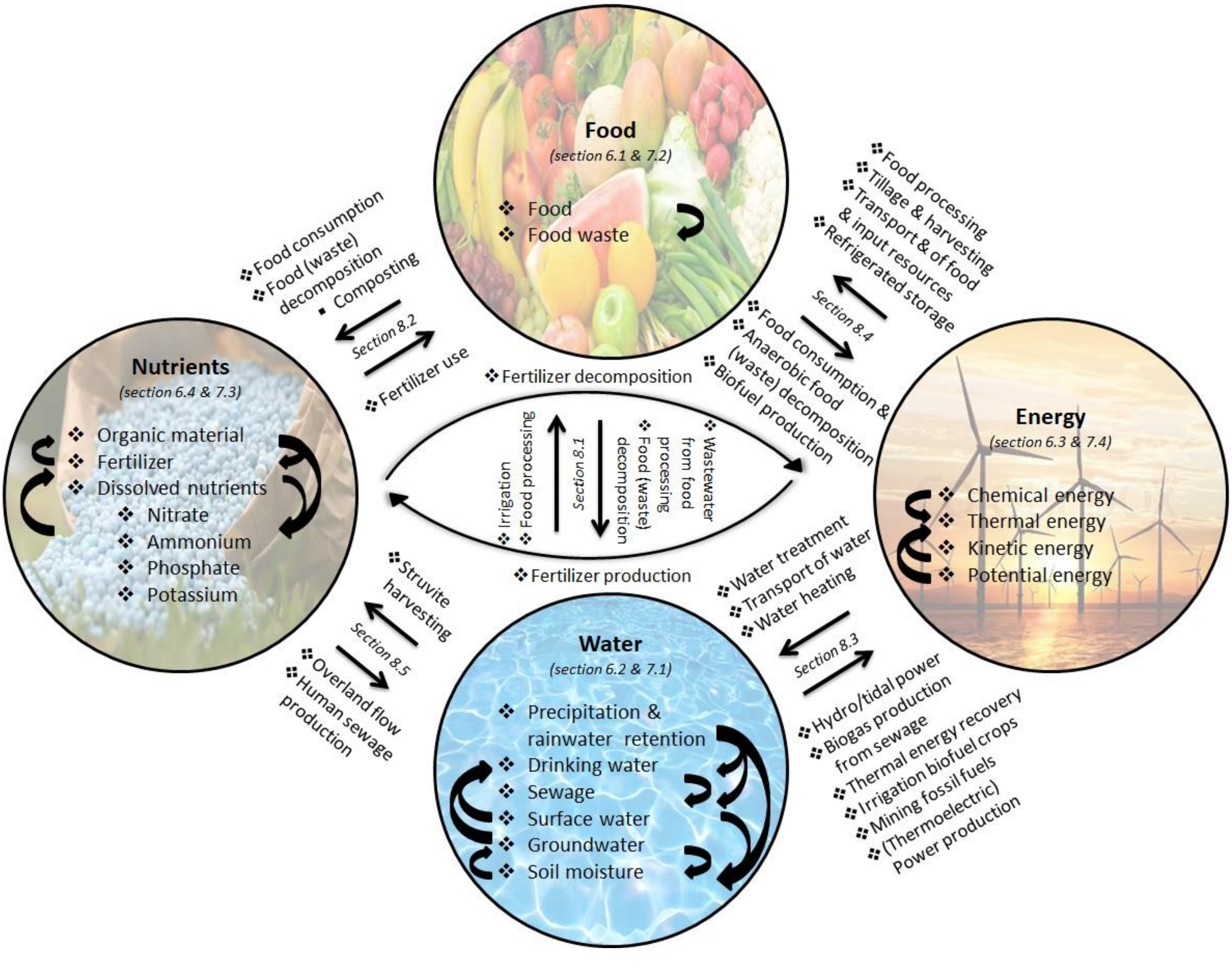


Figure 22 *WEF nexus framework displaying all stocks and flows under investigation. Chapters and sections discussing each of the nexus components are indicated*

6 Framework of Analysis: Stocks

Stocks are storage places in the system where goods (be it resources, semi-finished goods or end products) are stored, and can be filled and drained by flows. The four main stock categories in the water-energy-food nexus – water, energy, nutrients and food – can be visualized in a pyramid diagram with food at the apex of the pyramid, since food requires all three resources to grow (fig. 23). The base of the pyramid is formed by the three elemental resources: water, energy and nutrients. Underneath the base of the pyramid an extra layer is depicted, which represents the boundary conditions (land, labour and capital) that need to be fulfilled for nexus interactions to take place.

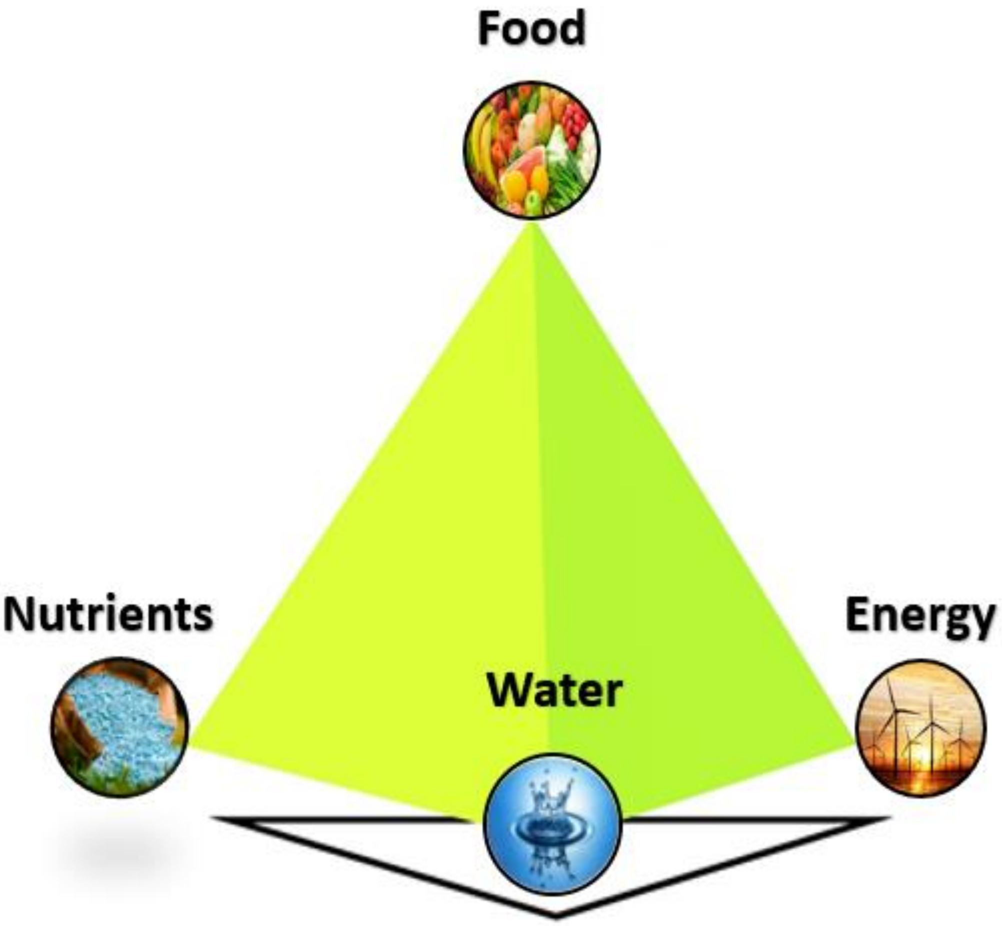
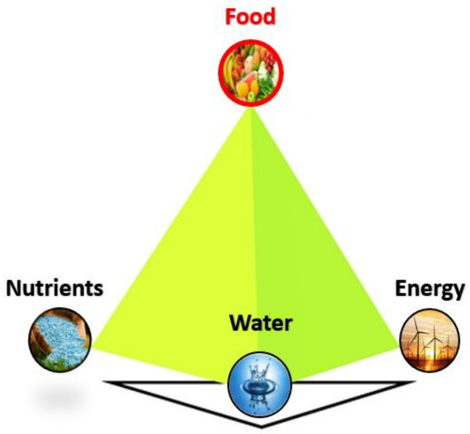


Figure 23 WEF nexus pyramid with the circles at the vertices representing resource stocks and the edges of the pyramid representing nexus interactions.
Water, nutrients and energy are situated at the base of the pyramid, as they are indispensable resources for growing food, which is displayed at the apex.

In this chapter, every stock category will be discussed and if needed subdivided into sub stocks, as the resources appear in different forms and locations and therefore will have varying characteristics.

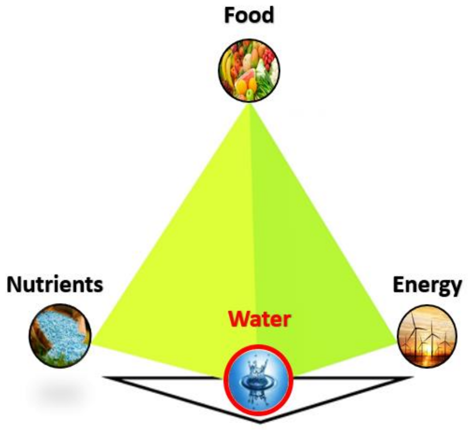
6.1 Food



The urban food sector refers to the food produced within the urban boundaries, as well as the food import and export (Villarroel Walker et al., 2014). Food as an end product of agricultural activities is in fact a stock storing all the three resources in the water-energy-food nexus, namely water, energy and nutrients. Following the definition of urban agriculture as defined in the introduction, the focus in this analysis is laid on crops, disregarding all non-vegan foods.

Crops store their resources in several different parts of the plant, namely in their leaves, roots, stem and/or fruits. The ratio of the partition of storage in the different parts differs per crops species. Depending on the crop, not every part is edible. However, in order to grow the edible parts, the non-edible parts need to be cultivated as well, all storing resources that are provided to them. Inedible parts as well as leftovers of consumption and/or food processing end up as food waste, which is only a concept made up by humans, as the waste product may be just as valuable as the consumed food water, energy and nutrient wise.

6.2 Water



Since the urban water sector includes a wide range of activities like water treatment, water supply, wastewater treatment, and hydrological processes such as precipitation, evaporation, runoff, and sewer inflow and infiltration, water is stored in various reservoirs and streams in the urban environment (Villarroel Walker et al., 2014). Water security, however, which is based on key elements like water access, water safety and water affordability, varies per source (Leck et al., 2015). Some of those stocks are natural, some are engineered, some can be used to deliver water to farming initiatives without health risks, whereas others are heavily polluted and will have to be treated first before they can be reused.

Different types of water stocks are colour coded in order to separate them based on their last origin and use. Water held in the soil profile after rainfall, from which vegetation and crops draw their water and transpire it to the atmosphere, is called green water. Allan et al (2015) stated that about 70% of the water in the food supply chain is green water. This water type, however, is said to look after itself. Vegetation or farmers simply cannot withdraw more water than recent rainfall, nor can they borrow green water from the future (Allan et al., 2015).

Blue water comprises waters sourced from surface or groundwater resources and is often used for irrigation, but competes with other water users in industry, the recreational sector and in the provision of domestic water services. Even though less blue than green water is used for agricultural production, blue water is more vulnerable to depletion and over-use when aquifers are not replenished in the following seasons. In contrast to green water, it can however be managed by storing water in (engineered) reservoirs (Allan et al., 2015).

Grey water is the collective term for wastewater from kitchens and bathrooms and black water has the lowest pathogenic quality as it includes excreta, urine and associated sludge (Kurian, 2014).

In the following section, different urban water stocks are described in further detail.

6.2.1 Surface water

The most obvious water stock in cities that comes to mind are surface water bodies. Whether they are natural or created artificially for aesthetic reasons, groundwater management, storm water storage or to enhance biodiversity; ponds, ditches, canals, rivers and lakes have the ability to store a lot of water.

In some cases the water level is fluctuating naturally, depending on the season or weather circumstances, in others it is managed by an authority on water issues, and extreme variations are prevented. A part of the freeboard of a surface water body can be used to store (storm)water during heavy rain events. This 'freeboard water' (the water volume between the normal surface water level and the maximum acceptable permanent surface water level) can be used for extraction in a sustainable way, supporting both water availability and restoring the original water level to allow for future stormwater intake.

6.2.2 Small scale rainwater retention

Also smaller structures, which might be used as storm water capturing systems, can be seen as a stock. Rain barrels and even entire flat rooftops have the ability to store rain water. If managed correctly, they are emptied before a (large) rain event and automatically fill during a rain shower, reducing the peak runoff to the sewer system, while retaining water for activities that require water.

6.2.3 Sewage

Wastewaters in sewer systems underneath an urban area are technically a flow themselves in the urban water balance, however, in this model we will consider sewage a stock, storing both water, energy and nutrients.

In developed countries most sanitary waste in urban areas is collected and transported via a sewer network to a treatment station, where it is treated before being discharged into the natural environment. Oftentimes, however, not only domestic sanitary waste is transported in sewer pipelines. Urban wastewater occurs in many different compositions and qualities and can consist of one or a combination of various effluents. Besides domestic effluent consisting of blackwater (excreta, urine and associated sludge) and greywater (kitchen and bathroom wastewater), it can also contain industrial, commercial and medical effluent or stormwater and other urban runoff (Kurian, 2014).

Sewer networks can be installed in different ways, but often consist of an extended network of pipelines reaching all around the urban area. Some systems are separate systems, which are disconnecting the stormwater from the sanitary waste collection system. Storm water pipelines are discharging runoff to nearby water bodies and the dry weather flow, which is containing water, human faeces and urine, containing constituents that can potentially be converted into biogas or fertilizer, is transported towards a treatment facility.

The other sewer version collects both sanitary wastewater and surface runoff. These systems are so-called combined sewer systems. During rain events, only the sanitary wastewater flow in combined systems is diluted, as in those systems the rainwater is mixed with the sanitary dry weather flow. Combined systems are designed for peaks in rainfall. The dry weather flow is normally only a small portion of the load that the pipelines are designed for.

The stormwater flow in both types of sewer systems is dependent on the rain intensity, the infiltration to the groundwater and on the catchment area as a whole.

The dry weather flow in the pipelines of both systems is dependent on the amount of upstream connections and the (drinking)water use of each person upstream, as the majority of that water is flushed or drained into the sewer after use. The average water consumption differs per geographic location. Even though sanitary flow experiences smaller fluctuations than stormwater flow, dry weather flow is not a constant flow. It varies in quantity and quality during a day (Henze & Comeau, 2008). Diurnal fluctuations in industrial wastewater production are likely to be correlated with working or operation hours and stormwater availability is influenced by rainfall.

The domestic wastewater flow is relatively constant in quality and consists for around 99 % of water with only 1 % of dissolved solids (Mara and Cairncross, 1989); Van der Hoek (2004)). Despite the bad water quality, the high availability of resources and the reliable supply make sewage a convenient source for irrigation water, especially in places where water is scarce.

6.2.4 Soil moisture

On a farm itself soil moisture is one of the major water stocks. Soil moisture is a general term for water contained in the pores and cracks in the upper, unsaturated part of the soil. This part is called the unsaturated zone or the vadose zone.

Under the influence of gravity, water drains from the unsaturated zone to the groundwater table. This water is then lost for root uptake. Water in the unsaturated zone, however, is available for transpiration by crops and soil evaporation. When the water content in the soil drops, water tends to bind to the soil more strongly and plants have to apply suction tension to overcome the tension by forces that work to retain water in the soil's pores (Waterloo et al., 2014).

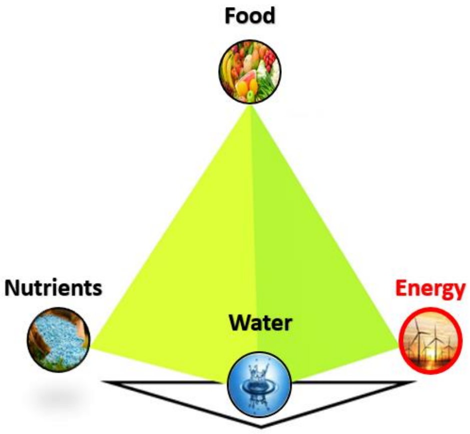
When gravity drainage stops, a certain amount of water is retained in the soil's pores. This is called the field capacity. In the Netherlands, a pF of 2.0 is associated with the field capacity, which follows from an average depth of the water table of 100 cm (Waterloo et al., 2014). The maximum suction that plants can apply is indicated by the wilting point. This means that all the water that forms the difference in the moisture content between the field capacity and the wilting point is available for plant uptake.

6.2.5 Groundwater

Groundwater is the water stock that occurs beneath the water table in soils and geologic formations that are fully saturated (Freeze & Cherry, 1979). Groundwater tables, and thus the dimension of the groundwater stock, fluctuate naturally, but can also be influenced by people. Yearly, 982 km^3 of groundwater is extracted globally, including 1 km^3/year in the Netherlands and 112 km^3/year in the USA and many areas worldwide report a risk of groundwater depletion (Margat & Van der Gun, 2013).

Generally, groundwater is relatively clean, as it has been filtered by the soil. Therefore, if geohydrological properties allow for it, groundwater can serve many purposes, including irrigation and domestic use, which globally account for 70% and 21% of groundwater withdrawals respectively (Margat & Van der Gun, 2013).

6.3 Energy



Energy occurs in many forms and as a consequence can be stored into various manners. Not only is it chemically stored inside food, different media are able to store thermal, potential and chemical energy. The energy types that are relevant in the water-energy-food nexus are depicted below.

6.3.1 Thermal energy

According to the first law of thermodynamics, thermal energy can be stored in any material that experiences a temperature change. However, the amount of energy stored depends on the specific heat of the material, the mass of the heated item and the change in temperature. Like every other material, water has the ability to store thermal energy. However, more than many other substances, water proves to be a very efficient energy storing medium. Due to its high specific heat (4,186 J/kg/°C) it can store large amounts of energy, when only a relatively small temperature increase is realized. On the flipside, if water cools down, a lot of energy is released as well.

Given the fact that sanitary waste often (seasonally) has a higher temperature than the (drinking) water entering the dwellings, energy is stored in wastewater. In the Boston the temperature of sewage inflow at the wastewater treatment plant ranged between 9°C and 29°C, averaging around 16°C over the entire year (MWRA, 2017). However, these measurements have been done after the wastewater had been travelling towards a plant and the wastewater has been exposed to media affected by the outside temperature. When warm water meets colder air or sewage pipelines in cold soils, thermal energy is drained from the water. Therefore, especially in winter, thermal heat can best be recovered through local decentralized heat exchangers.

6.3.2 Kinetic energy

Kinetic energy is basically energy that is stored in movement and its magnitude is dependent on the mass that is replaced as well as on the squared velocity of that mass. Flowing surface water as well as sewage possess kinetic energy, which can be harvested using turbines. When kinetic energy is harvested, one wants to reduce the amount of friction, as friction can reduce the amount of kinetic energy present in a flowing fluid. Pipelines with low friction coefficients, large diameters and short traveling distances would help decrease the amount of friction, reducing the losses (Elger et al., 2014).

6.3.3 Potential energy

When a unit of water is placed above a certain datum, e.g. an initial surface water level, potential energy is stored. The heavier the item and the higher it is placed above the datum, the more potential energy is created (Giancoli, 2005).

In the context of the water-energy-food nexus, this principle is used in the hydropower industry, where potential energy is converted into kinetic energy, which can be harvested by turbines. Moreover, it can be used during times of energy surpluses in the energy grid, when instead of getting rid of the excess energy, it can be stored by transporting water to a higher elevation. At times when the energy demand exceeds the availability, it can then be released by letting it run down.

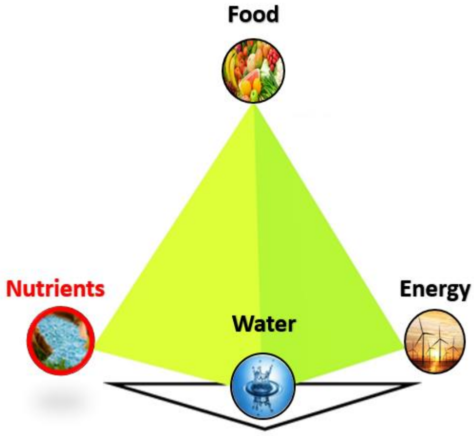
6.3.4 Chemical energy

Chemical reactions either consume or release energy. Which of the two scenarios occurs, can mathematically be calculated using the principle of enthalpy. All elements in their standard state have a standard enthalpy of formation of zero. Every non-elemental compound stores energy inside its structure, including fertilizer, food and biogas (Faure, 1998). A positive change in enthalpy occurs during an endothermic reaction. Endothermic reactions only occur when energy is added to the system, and thus won't occur spontaneously. The added energy is used to transform the reactants to a compound with a higher energy level. Exothermic reactions on the other hand can occur spontaneously and release energy to the surroundings.

6.4 Nutrients

Soil serves as a nutrient storage, which can provide nutrition to plants. Young soils tend to have high availability of phosphorus and potassium, which tend to get depleted over time, whereas nitrogen gradually accumulates in soils as they age (Houlton et al., 2008; Hedin et al., 2003; Walker & Syers, 1976; Vitousek & Howarth, 1991).

The three macronutrients, that after carbon, hydrogen and oxygen are most abundant in dry plant matter, are nitrogen, phosphorus and potassium (table 10). They are the elements that will be focussed on in this analysis.



Nitrogen is the most wide-spread of the nutrients that are studied in this thesis and is present in every pillar of the water-energy-food nexus (Villarroel Walker et al., 2014). Nitrogen flows through the urban system occur in many different molecular forms. For example, it is present in the atmosphere as elemental nitrogen (N_2) and nitrogen oxides (NO_x) and is absorbed from the soil by plants as NH_4^+ and NO_2. Consequently, crops, especially cereals, contain large amounts of nitrogen and it is also present in meat. Similarly, phosphorus and potassium are accumulated in plant cells and transported to or produced in urban areas in the form of edible crops and animal protein.

Nutrient (symbol)	**Forms absorbed**	**Concentration in plant dry**
	Macronutrients	
Nitrogen (N)	NH_4^+, NO_2	1.5%
Phosphorus (P, P_2O_5)	$H_2PO_4^-$, HPO_4^{2-}	0.1-0.4 %
Potassium (K, K_2O)	K^+	1-5 %
Sulphur (S)	SO_4^{2-}	0.1-0.4 %
Calcium (Ca)	Ca^{2+}	0.2-1.0 %
Magnesium (Mg)	Mg^{2+}	0.1-0.4 %
	Micronutrients	
Boron (B)	H_2BO_2, $H_2BO_3^-$	6-60 µg/g (ppm)
Iron (Fe)	Fe^{2+}	50-250 µg/g (ppm)
Manganese (Mn)	Mn^{2+}	20-500 µg/g (ppm)
Copper (Cu)	Cu^+, Cu^{2+}	5-20 µg/g (ppm)
Zinc (Zn)	Zn^{2+}	21-150 µg/g (ppm)
Molybdenum (Mo)	MoO_4^{2-}	< 1 µg/g (ppm)
Chlorine (Cl)	Cl^-	0.2 – 2%

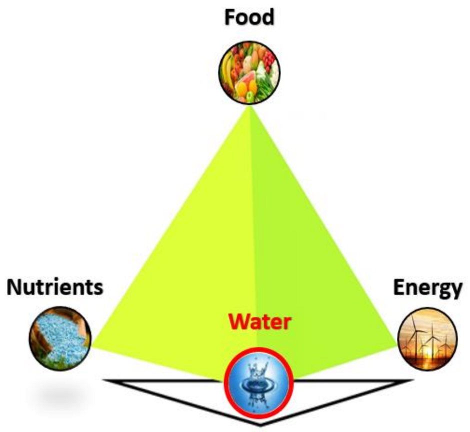
Table 10 Essential plant nutrients, forms taken up and their typical concentration in plants (Data source: Roy et al., 2006)

Because of the nutrient consumption through foodstuffs, faeces and urine contain high concentrations, making sewage a large nutrient stock. Especially phosphorus and potassium flows in cities are dominated by the food sector and consequently by the water and wastewater industries (Villarroel Walker et al., 2014). In order to prevent nutrient deficiencies and to compensate for the loss of potassium, phosphorus and nitrogen through leaching and harvesting crops, soils need to be fertilized (Sardans & Peñuelas, 2015). Fertilizer is therefore another big nutrient stock.

7 Framework of Analysis: Uni-sectoral Flows

Interaction in a nexus are called flows and represent the transportation or conversion of resources from one stock to another. Any flow entering the system from outside the system boundary is called an import while flows exiting are referred to as exports. Flows do not only occur between the resources and end products on the vertices of the WEF nexus pyramid shown in figure 23. Also flows occur within each resource group itself. Those are the so-called uni-sectoral flows and will be described in this chapter.

7.1 Water linkages



The water balance describes all the incoming and outgoing water flows in an outlined area and is relying on the principle of conservation of mass. The inflow of water into the (urban) system equals the outflow of water from said system plus the change in storage capacity within the system. According to Sahely et al. (2003) most metabolism studies show that inflow and outflow of water are relatively equal and little storage takes place. Douglas (1983) put forward an urban water balance for use in urban metabolism studies (equation 3). On the left hand side the inflows into the system are described, whereas the right hand side shows the outflows and difference in storage.

$$P + D + A + W = E + Rs + S \quad \textit{(equation 3)}$$

P	Precipitation
D	Dew and hoar frost
A	Water released from anthropogenic resources
W	Piped water
E	Evaporation
Rs	Natural and piped surface and subsurface flow out of the city
S	Change in water storage

Douglas' water balance describes the interaction of the urban water system with external areas by hydrological processes and engineered water exchange. What happens within the urban system with the water is not described, as the water balance formula represents the urban area as a black box. In general, we can conclude that Douglas' general urban water balance fails to comprise a complete set of water flows in the urban area and is neglecting the internal competition between various water uses in the urban setting. Urban water cycle schemes like the one in figure 24 or metabolism studies are a better tool to look into those internal waterflows.

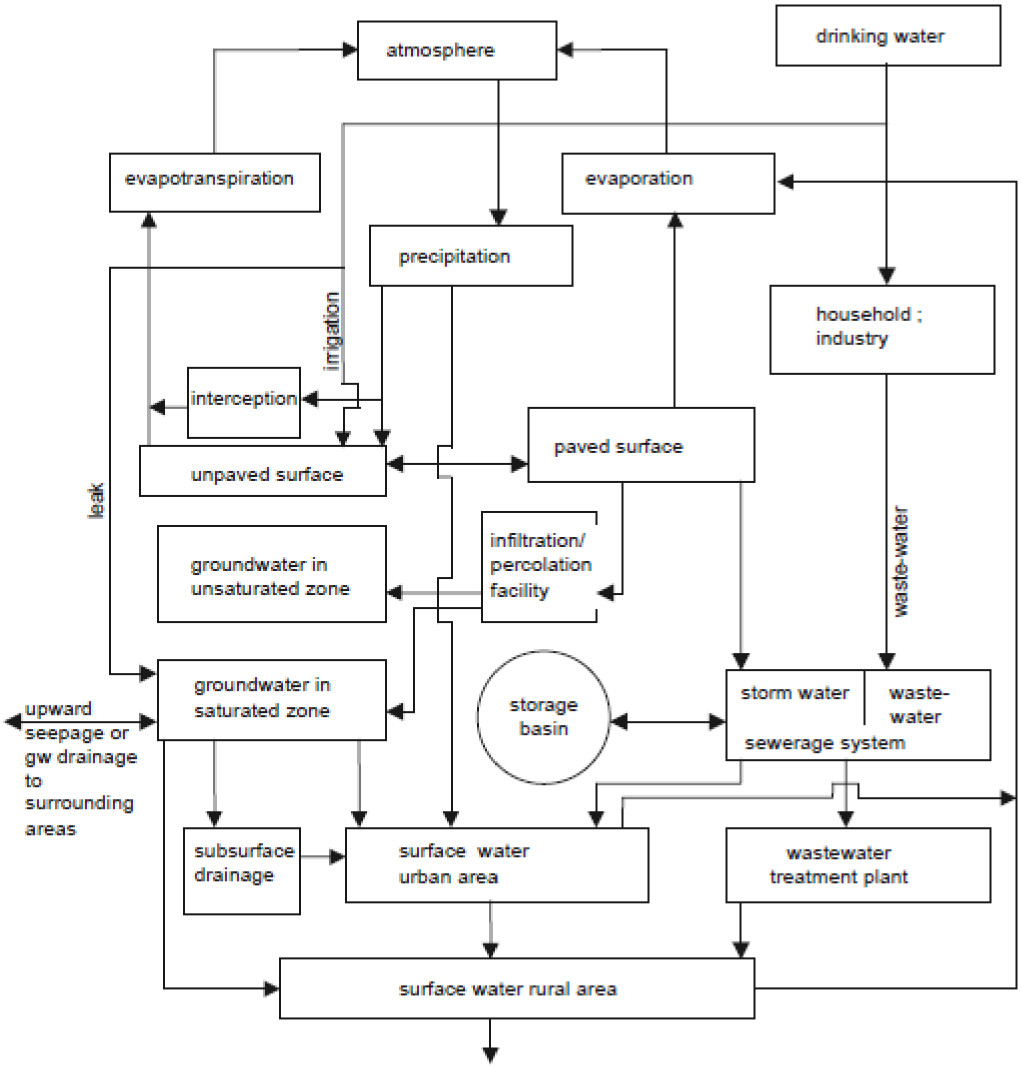


Figure 24 Water flows in an urban area (Source: Van de Ven, 2011)

7.1.1 Surface runoff

Other than directly evaporate, rain can infiltrate into the soil, result in surface runoff and/or can be captured in rainwater storage facilities and sewage systems. The amount of runoff that is generated depends principally on the type of land cover and the rainfall intensity (Butler & Davies, 2010). Table 11 shows what values of runoff coefficient characterize certain urban areas and surface types.

Area description	**Runoff Coefficient**
City centre	0.70-0.95
Suburban business	0.50-0.70
Industrial	0.50-0.90
Residential	0.30-0.70
Parks and gardens	0.05-0.30

Surface Type	**Runoff coefficient**
Asphalt and concrete paving	0.70-0.95
Roofs	0.75-0.95
Lawns	0.05-0.35

Table 11 Typical values of runoff coefficients in urban areas (Source: Butler & Davies, 2010)

Van de Ven & Voortman (1985) gathered even more detailed information. They found that of the total inflow of water (precipitation and seepage combined) in a Dutch residential area generally 20% ended up in the stormwater sewerage.

The quality of the rainwater can be affected by the route that the water travels to its destination. Generally, rainwater contains a low level of pollution and is quite pure, apart from some impurities that are drained from the air. Precipitation falling in urban areas is characterized by ${SO_4}^{2-}$ and ${NO_3}^{-}$ anions and Ca^{2+} cations, which are present in aerosols as a consequence of soil composition and anthropogenic activities like domestic heating, traffic and industries (Sanusi et al., 1996).

Once precipitation reaches the ground, it can pick up all kinds of pollutants form urban surfaces, like garbage, fuel spills and bird droppings. Moreover, some of the urban surfaces themselves, like asphalt and roofing materials can contaminate the rainwater. It is therefore safe to state that the quality of rainwater is generally better than the water quality of overland flow resulting from that same rain event. The quicker precipitation can be captured and the cleaner and more inert the collection surfaces are, the purer the collected runoff will be and the easier it will be to reuse it for other purposes.

Ouyang et al. (2015) found that most of the pollution load was washed from the surface in the first 5 to 10 minutes of a precipitation event, during the so called first flush. Gikas & Tsihrintzis (2012) stated that the implementation of a first-flush diversion system improves the physicochemical quality of collected rainwater, but it cannot avoid microbial contamination of stored rainwater. Its good physicochemical quality, however, makes the roof runoff appropriate for e.g. garden irrigation with no need for on-site treatment.

Roofs are the first candidates for rainwater harvesting in urban areas (Farreny et al., 2011). Therefore, it is important to study the effect of conventional roofing materials (i.e., asphalt shingle, metal, and concrete tile and green roofing) on the quality of harvested rainwater (Mendez et al., 2011). Rainwater harvested from any of these roofing materials would require first-flush diversion, filtration, and disinfection to meet USEPA drinking water standards or non-potable water reuse guidelines.

The concentration of each metal in the rainwater harvested after the first-flush was compared to the appropriate United States Environmental Protection Agency (USEPA) drinking water standards. None of the rain harvested from roof materials mentioned above violated the arsenic, copper, lead and zinc standards after the first-flush. However, all the roofs exceeded acceptable aluminium standards and all but the green roof violated iron standards. Although all tested roofs violate the microbial quality standard as described by the USEPA primary drinking water standards, significant differences were noted. Shingle and green roofs generated water with higher dissolved organic carbon concentrations than rainwater harvested from metal roofs, cool roofs and concrete tiles, which tend to have lower concentrations of faecal indicator bacteria as well. The better microbiological quality indicated that metal, cool and tile roofs are most suitable for rainwater harvesting applications (Mendez et al., 2011).

7.1.2 Water abstractions for drinking water and irrigation

The water balance displayed earlier this chapter does not consider infiltration of precipitation into the groundwater as a loss to the urban water system, presumably because the water remains within the city boundaries. Infiltrated water is however (temporarily) lost for activities and services at the surface, like municipal water supplies and agricultural irrigation.

Similarly, water that is locally abstracted from groundwater reservoirs for irrigation or drinking water supply purposes, are not seen as a gain to the urban water system, and therefore left out of equation 3. Groundwater abstraction does however cause a flow internally of the urban water system, as water is abstracted from one stock and added to another. In the Netherlands about 65% of urban drinking water and 47% of irrigation water originates from groundwater abstractions (CBS, 2019). In the USA this is 38% and 48% respectively (Margat & Van der Gun, 2013; Dieter et al., 2018).

7.1.3 Drinking water production, distribution and consumption

An urban metabolism study by Villarroel Walker et al. (2014) distinguished public water supply for residential and commercial users (56%) and public water supply leakages (11%) as the main water 'usages' in London. Water for human consumption is taken from a multitude of sources, depending on the local availability and water quality of the source. In developed countries, most of the water that is intended as drinking water is collected from the sources and is treated by the water sector before it is distributed through a centralized system for consumption.

Drinking water flows are generally a function of the demands in the system, which are a direct result of consumption patterns, population size and the amount lost through water main leakage (Villarroel Walker et al., 2014). On average the current per capita domestic drinking water use in the Netherlands amounted 129 litres per day in 2016, whereas the American national average total domestic per capita use amounted 310 litres of water in 2015 (CBS, 2019; Dieter et al., 2017).

7.1.3.1 Leakages

Some of the water that has entered the piped water system is lost by leakage, combined sewer overflows and stormwater bypasses following extreme rain events (Sahely et al., 2003). Groundwater infiltration into the sewer through pores and cracks, however, can be seen as a gain to the piped water system. Villarroel Walker et al. (2014) argued that leakage from the water supply system and groundwater infiltration cancel each other out.

Losses in western countries vary significantly. In the Netherlands, losses in drinking water pipelines are estimated to be 3 to 7 % of the distribution input, whereas in United Kingdom and the United States leakage ranges from 10 to 30 %. In developing countries losses can even reach up to 70% of the total water supply (Beuken et al., 2008).

7.1.3.2 Wastewater production

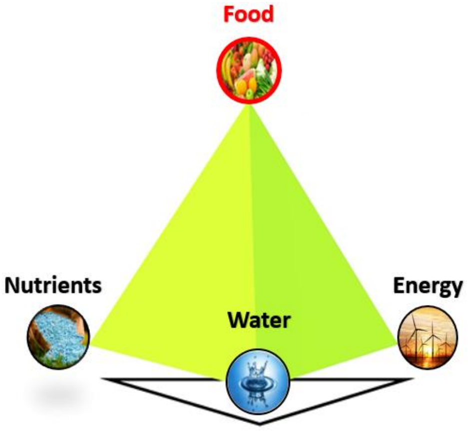
Besides water that is lost from the piped system by for example watering the garden or by domestic leakages, the majority of consumed drinking water turns into wastewater. In developed urban regions, this wastewater is collected and treated by the water sector to reduce the amount of pollutants that are discharged into the environment or to make it available for reuse (Villarroel Walker et al., 2014).

7.1.3.3 Wastewater as irrigation water

Wastewater can substitute for freshwater for irrigation. In the context of increasing wastewater availability due to widespread (urban) population growth on the one hand and irrigation water scarcity and declining soil fertility on the other, 200 million farmers are estimated to use wastewater to irrigate their crops (UNPD 2007; Raschid-Sally and Jayakody 2008; Kurian, 2014).
Wastewater can be applied in various fashions. Untreated urban wastewater from a sewage outlet can be used for cultivation either locally or by farmers downstream of the urban centre. More advanced wastewater irrigation uses wastewater that has undergone treatment before it is applied to the fields (Raschid-Sally and Jayakody, 2008; Kurian, 2014). Because of the preserved nutrient rich nature in combination with an increased pathogenic quality and widespread occurrence, decentralized wastewater treatment enables reuse for irrigation of local (urban) agriculture.
More information on the relation between wastewater reuse and food production will be provided in section 8.1.1.1.

7.2 Food linkages

In this urban nexus, the food sector refers to food produced within the urban boundaries. Nonetheless, food that is imported to or exported from the system is externally influencing the local sector.



7.2.1 Food production

Arable farming can produce crops. Those crops are not always meant for human consumption. Some serve as fodder (food for animals). Indirectly, one type of food (produce) is converted into another type (e.g. meat, dairy or eggs). Livestock production uses large amounts of produce and records the highest loss rate of food for human consumption, with losses of between 81 and 94% of protein, energy and dry mass (Alexander et al., 2017). Animal products are however not the focal point of this thesis' analysis.

7.2.2 Human consumption of food products

Very little is known about the food flow through cities, as estimating the import and consumption of food in cities is difficult due to the diffusivity of the production and delivery system (Decker et al. 2000; Sahely et al., 2003). It is however expected, that the increasing world population and improved living standards, will boost global food consumption by 35% by 2030 (US NIC, 2012). When is assumed that people consume as much food as the national average of food supply per inhabitant, an estimate can be made of local calorie consumption.
It is found that in the US the average food supply per capita per day amounts 3682 kcal. In the Netherlands 3228 kcal of food per capita is supplied on a daily basis (FAO, 2019-2). Not only the amount of calories supplied to each inhabitant differs, also the diets of the people in those two countries deviate as demonstrated in table 12.

	Item	**Food Supply** *(kcal/capita/day)*	
		The Netherlands	**United States of America**
Grand Total	Vegetal Products	2152	2697
	Animal Products	1076	984
Vegetal Products	Cereals – Excluding Beer	706	801
	Vegetables	78	69
	Starchy Roots	169	92
	Vegetable Oils	355	689
	Fruits – Excluding Wine	176	119
	Other	668	927
Animal Products	Meat	412	424
	Eggs	54	56
	Milk products – Excluding Butter	460	368
	Fish, Seafood	48	35
	Other	102	101

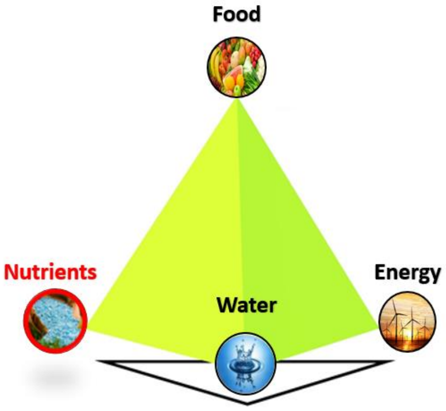
Table 12 Food Supply per capita per day for the Netherlands and the United States of America in 2013 (Source: FAO, 2019-2).

Food consumption in the Netherlands and the USA is likely higher than that in many Asian countries, because of the differences in diet and physical build of the people (Sahely et al., 2003).

7.2.3 Food waste production

Unfortunately, not all the food that is supplied is consumed and a part of it is wasted during multiple stages of the food production and value chain, as well within the postconsumer phase (Sarker et al., 2016). Studies done on the amount of food waste show divergent results. The amount of food that is wasted as percentage of total food grown, was estimated at 18% in Switzerland, 20% in Finland and even 31% in the United States (Betz et al., 2014; Silvennoinen et al., 2015; Buzby et al. 2014). The American study also found that most food waste (61%), occurs in the consumption phase, 17% during the production phase, and the remainder (22%) is lost during other activities such as handling, storage, processing, packaging, distribution, and marketing (Buzby et al. 2014). Wasted food is a high-magnitude, energy- and nutrient-rich waste stream. (Sarker et al., 2016). From a WEF nexus perspective, especially the food waste that is composted or digested for energy production is lucrative as that way the resources are brought back to the WEF system, while incinerated waste or waste disposed in landfills does not.

7.3 Nutrient linkages



Intensive agriculture tends to withdraw nutrients from the land by harvesting and removing crops, not allowing the soil to regenerate as the biomass decomposes. In order to prevent nutrient depletion on croplands fertilizers are added to the soil (McLauchlan, 2006).

7.3.1 Nitrogen

Nitrogen flows though the urban system occur in many different molecular forms. For example, it is released into atmosphere as diatomic nitrogen (N_2) and nitrogen oxides (NO_x) during gas combustion for heating and power generation and is released by traffic (Villarroel Walker et al., 2014). Combustion is however outside the scope of this WEF nexus analysis.

Nitrogen, which is absorbed by plants as NH_4^+ and NO_2, is a crucial nutrient for crops to grow and is often present in soils or added through fertilizers (Roy et al., 2006).

Because of the nitrogen consumption through foodstuffs, faeces and especially urine contain high concentrations of this nutrient, resulting in nitrogen rich sewage flows (fig. 25) (Villarroel Walker et al., 2014). When denitrification techniques with activated sludge are applied during treatment of the sewage, nitrogen is released into the atmosphere as elemental nitrogen (Villarroel Walker et al., 2014). Other treatment methods convert soluble nitrogen ($NH_4{}^+$) together with soluble phosphorus ($PO_4{}^{3-}$) and magnesium (Mg^{2+}) into a solid form, such as struvite ($MgNH_4PO_4 * 6H_2O$), which can serve as a slow-release fertilizer for crop cultivation again (Talboys et al., 2016).

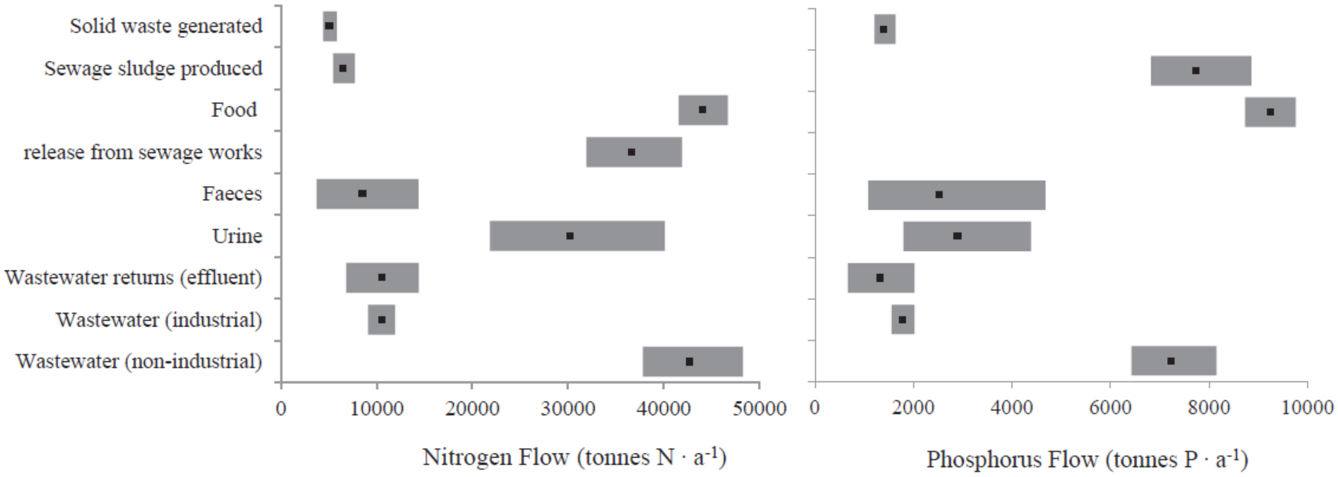


Figure 25 Estimated median values (dots) and 5-95 percentiles (bars) of the main flows in tonnes per year for 2010 in London for nitrogen (left) and phosphorus (right) (Source: Villarroel Walker et al., 2014)

7.3.2 Phosphorus

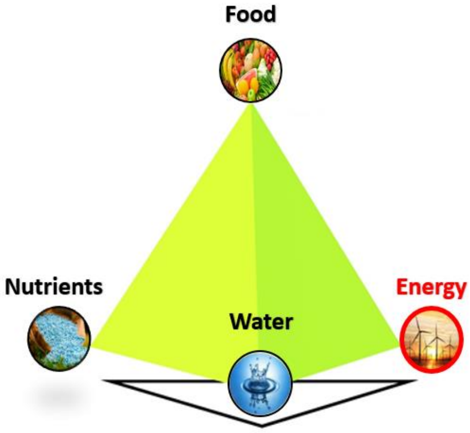
It is estimated that phosphorus flows in cities are dominated by the food sector and consequently by the water and wastewater industries (Villarroel Walker et al., 2014). In the London area, accommodating 7.8 million people, annually, 8,700-9,700 tonnes of phosphorus are carried inside food, and 6,800-8,800 tonnes of phosphorus are transported by sewage sludge (fig. 25). Just like nitrogen, phosphorus can be harvested from sewage and added to crops to serve as a fertilizer.

7.3.3 Potassium

The (urban) potassium cycle is far less complex than the nitrogen and phosphorus cycles, due to the nutrient's limited presence in materials other than soil, (ground)water and food. Nonetheless, potassium is indispensable for many plant functions and as the second most abundant nutrient in plant tissues, it is required in large amounts for growing crops (Sardans & Peñuelas, 2015). However, potassium is more easily leached from the soil than nitrogen or phosphorus (Boxman et al., 1994; Neirynck et al., 1998). Certain activities, among which agricultural practices, decrease soil pH and result in potassium leaching, decreasing the availability for plants (Sharifi et al., 2013). In order to prevent potassium deficiencies and to compensate for the loss of potassium through leaching and harvesting crops, soils need to be fertilized (Sardans & Peñuelas, 2015). In 2013, the global supply of potash fertilizer (K_2O) was estimated at 42 million tonnes (FAO, 2015-1).

Potassium accumulates in plant cells and is transported to urban areas in the form of edible crops and animal protein. After being consumed in the human diet and after excretion, potassium follows the same route as nitrogen and phosphorus through the wastewater collection and treatment system. Information on the potassium content of different urban streams is not available in the same detail as it is for nitrogen and phosphorus. However, Arienzo et al. (2009) found that municipal wastewater in a range of western countries contains between 13 and 20 mg of potassium per litre, but concentrations are likely higher in waters discharged by the food industry.

7.4 Energy linkages



Energy can occur in various forms and is constantly converted into different types, some of which are considered more useful than others (see energy stock section 6.3). The energy balance however, preaches that the total amount of energy present never changes.

Electricity (electrical energy) and primary energy as in fuel (to create thermal energy during combustion) are two of the energy types that are highest in demand (EIA, 2019). Of those two, electricity has the highest value as it can easily be converted into heat. The other way around, turning heat into electricity, is more difficult and results in lower effective energy and higher losses.

Electricity is crucial to drive a wide range of household appliances and industrial machinery, whereas excess thermal energy can be used for heating and a deficiency for cooling.
In agriculture energy is required to provide light to crops. This light can be delivered by sunlight or by electromagnetic radiation created by artificial lighting powered by electricity. Moreover, if

implemented, pumps and air conditioning are connected to the electricity grid. Thermal energy is supplied for heating farm spaces to create optimal climate conditions for the crops.

In 2012, the United States National Intelligence Council (US NIC) estimated that energy demands would increase by 50% by 2030. In Toronto, it was seen that electricity demand and gasoline inputs had more or less increased at the same rate as population growth (Sahely et al., 2003). The exact values and proportions in an energy balance of a specific city obviously depend among others on climate, population size, economic activity and local customs and preferences.

However, according to Villarroel Walker et al. (2014) residential energy use, e.g. building heating-cooling and water heating, are dominating the energy flows. The energy demand is met by converting energy inputs to the system into convenient forms. Among others, fossil fuels, biofuels, renewable energy (e.g. wind, tidal, solar, hydropower) can serve as energy inputs to the urban system and can be converted into electricity and/or heat. Moreover, energy is carried by food.

7.4.1 Losses

Oftentimes, inputs and outflows of (fossil) fuels and electricity in the urban system are investigated and conversion losses (e.g. during electricity production from burning fossil fuels or other organic materials) and transmission losses of energy (e.g. when friction losses occur) throughout the area are not accounted for. However, these losses are estimated to be substantial (Sahely et al., 2003).

8 Framework of analysis: Multi-sectoral fluxes

Each city has many WEF interactions (fig. 22) and provides opportunities for WEF interactions within its boundaries (Ramaswami et al., 2017). The links connecting the different WEF sectors form a complicated and dynamic web, as each of the three sectors does affect one-another at various spatial and temporal scales (USDOE 2014; Hoff, 2011). Major conflicts persist between economic activities like agriculture or energy generation as they are often competing for resources (Peronne and Hornberger 2014; Fabiola & De Rosa, 2016). Moreover, Sherwood et al. (2017) showed the strong correlation between water and food intensity (fig. 26). Relations between food and energy and water and energy are less unambiguous, but existent nonetheless (fig. 26 & fig 27), when outliers caused by high food intensities are corrected for (Sherwood et al., 2017).

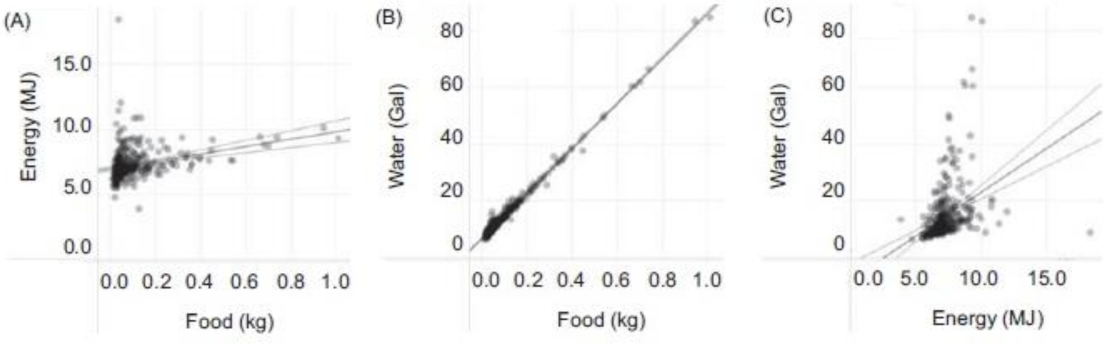


Figure 26 *Scatter plots on the correlations between food, energy and water intensity per dollar of GDP (Source: Sherwood et al., 2017).*

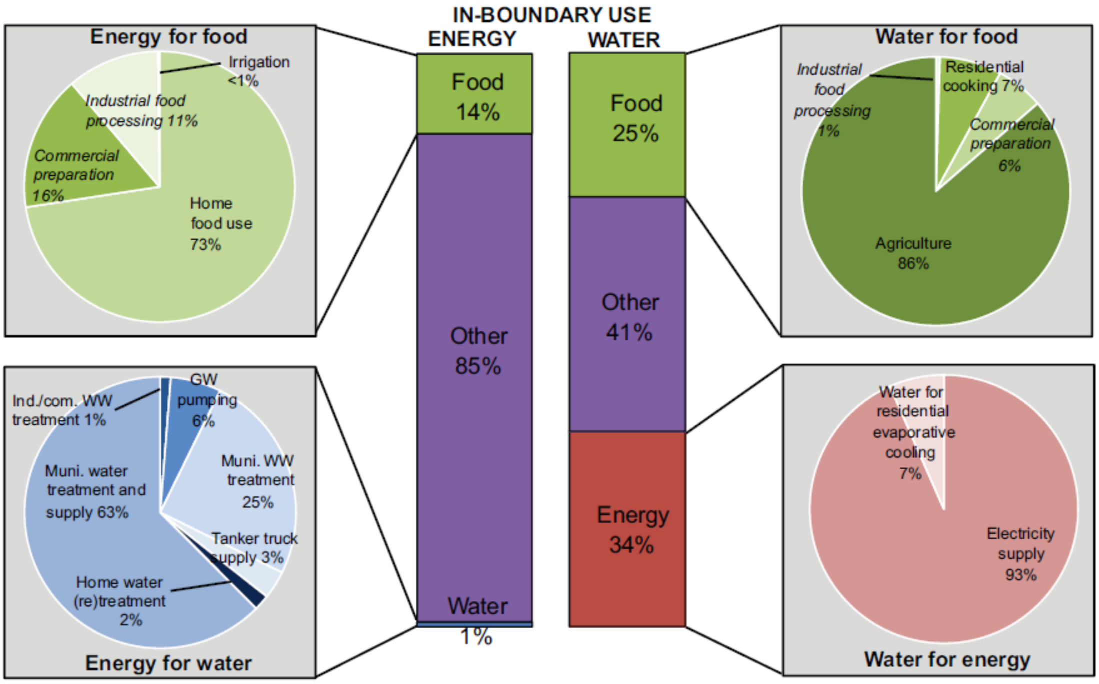
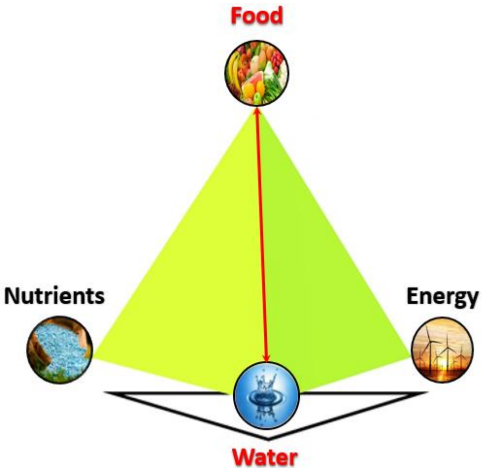


Figure 27 *Bar charts show the total direct community-wide water and energy demand of Delhi, India. The pie charts demonstrate a more detailed view on the direct water and energy demand attributable to FEW related activities (Source: Ramaswami et al., 2017)*

The dynamics between food and water or energy security, as well as potential synergies and antagonyms between land, water and energy management, are not yet entirely understood (Kurian, 2014). However, in this chapter an attempt is made to describe these interlinkages based on existing research. A cross-sectoral perspective could provide more insight in the synergies and trade-offs among the many parts of the urban WEF system and increase the scope for maximizing the benefits of a technology or policy implementation, as it facilitates more integrated and cost-effective solutions (Fabiola & De Rosa, 2016; Smajgl et al., 2016; Villarroel Walker et al., 2014).

8.1 Water-food linkages



8.1.1 Irrigation

Irrigation is an obvious example of the interaction between water and food and agriculture is the world's largest water consumer. Globally, 70% of all the fresh water withdrawals are used by farming (FAO, 2015-2). Plants take up water with their roots. Although they partially embed it in their configuration, they transpire most of the water that is released into the atmosphere again after it has been used by the plant as a transport medium. Different crops have a diverse range of water demands, as is shown in table 13 (Chang et al., 2016; Mekonnen & Hoekstra, 2012). Moreover, it can be concluded that generally animal products require a larger amount of water per unit of produced nutritional energy.

Food Items		**Water Footprint (L/kcal)**	**Water Footprint (m^3/kg)**	**Water Footprint (m^3/kg)**
		Source: Chang et al., 2016	Source: Chang et al., 2016	Source: adapted from Mekonnen & Hoekstra, 2012
Cereal	Rice	1.7	0.5	1.64
	Wheat	1.8	0.7	
	Maize	1.2	0.4	
Other plant-based food	Vegetables	0.2-0.3	1.1-1.6	0.32
	Fruits	0.5-1	1.2-2.4	0.96
	Groundnuts	3.1	1.0	-
	Starchy Roots	-	-	0.39
Animal products	Beef	3.8-23.8	1.9-11.8	15.42
	Pork	4.4-12.1	1.3-3.5	-
	Chicken meat	1.7-6.7	0.9-3.7	4.33
	Eggs	1.3-6.0	0.9-4.1	-
	Milk	0.5-1.3	0.7-1.9	-
Beverages	Wine	1	1.4	-
	Tea	0.12	-	-
	Soft drinks	0.3-0.6	0.7-1.4	-

Table 13 Water Footprint (WF) of food products (Source: Chang et al., 2016)

Approximately 92% of global consumptive water use is devoted to food production. This water does not return to the system, as water in food and water transpired by plants, cannot be reused directly. According to the FAO, on average 50% of the global water withdrawal is "lost" between the source and the destination (FAO, 2014). This is especially alarming, when irrigation water is supplied from water resources that are not sustainable. Of the consumptive water use, about 70% is coming from the root zone of the soil (Allan et al., 2015; Hoff, 2011). 43 percent of global irrigation water comes from groundwater withdrawals, and this number is increasing as groundwater pumping allows for a greater food production, as farmers got more individual control over the timing and quantities of irrigation water. This all comes at the cost of an increasing risk for depletion of groundwater sources (Siebert et al., 2010; Kurian, 2014). The numbers show, however, that on a global scale groundwater is used more efficiently than the green, rootzone water.

Water efficiency and productivity vary from one location to another. The output per unit of water volume consumed depends among others on available technology, knowledge, capital and the water intensity of crops (Mohtar & Daher, 2012). According to Barbosa et al. (2015) conventional agriculture requires 250 L/kg/y, whereas hydroponic systems, using 20 L/kg/y, are much more efficient. Thanks to technological innovation and economic upscaling, the agricultural sector presents an obvious water saving potential. Sprinkler irrigation, micro-irrigation techniques, and low-pressure pipe irrigation become cost-effective, available and therefore more prevalent, saving water during crop production (Zou et al., 2013).

8.1.1.1 Wastewater irrigation

In developed countries, (effluent of) wastewater irrigation at agricultural sites is very uncommon. This is likely due to the fact that in the western world, as Smit & Nasr (1992) state very strikingly: 'Fear of contamination by unclean water has, over time, become institutionalized in law and in a reluctance by many governments. Strict regulations for wastewater reuse could lead to a paradoxical situation where polluted open water bodies are used for irrigation instead of better-quality sewage (Kurian, 2014).

In the 1990's it has been estimated that 10% of the global human population, consumed food produced by the direct application of waste water with or without incomplete treatment (Smit & Nasr, 1992; Lunven, 1992). Studies from the late 00's show that approximately 20 million hectares, 8% of irrigated land world-wide but concentrated in Asia, received raw or treated wastewater as irrigation water (Qadir et al., 2007; Raschid-Sally & Jayakody, 2008; Howell, 2001).

Wastewater is a valuable resource of irrigation water in arid and semi-arid regions (Babayan et al. 2012). Instead of discharging sewage straight into the environment, it could serve as a resource for agricultural production, increases the availability of freshwater for other uses (Smit & Nasr, 1992). When wastewater is applied to stabilisation ponds with aquaculture not only the waste can settle and the air will naturally aerate the organic pollutants, but also fish (which might be polluted) and algae (which can serve as biofertilizer) can be grown (Kurian, 2014). Also, for the cultivation of biofuel crops pathogenic contamination of water is not such a problem as no human consumption of the crops is involved and as long as farmers and workers are protected adequately. A similar argument arises when wastewater is used to cultivate fodder crops for livestock, although it might come at larger risks of human contamination when the livestock gets sick (FAO, 1997). Moreover, wastewater can serve as irritation water for vegetable and fruit production, although this can pose serious pathogenic risks, especially when the parts of the crops that are edible show above the ground surface and have been in direct contact with the sewage.

Attitudes to wastewater reuse are not always positive and cause cultural barriers (Smit & Nasr, 1992). This is a pity, as nutrient-rich wastewater could be viewed as a valuable resource to (urban) farmers seeking a consistent spatially and temporally available source of irrigation water, along with water conservation and groundwater recharge (Van der Hoek et al., 2002; Miller-Robbie et al., 2017; Qadir et al., 2007; Smit & Nasr, 1992). Due to it's nutrient-rich character, it could reduce the consumption of artificial mineral fertilizer and enhance crop yields (Asano, 1998; Corominas et al 2013; Qadir et al 2007; Hanjra et al. 2012). All in all, wastewater agriculture is thought to increase the returns by up to six times because of double cropping and lower expenses incurred on fertilizers (Kurian, 2014).

Drawbacks of wastewater irrigation include health risks, and pollution of the environment with pathogens, metals and micropollutants (Qadir et al., 2007; Ensink et al., 2008). Continuous application of wastewater for example may lead to accumulation of heavy metals in soils (Kurian, 2014). Whether water is fit for agricultural use depends on a range of factors concerning soils, climate and agricultural practices. Also, the susceptibility of crops to contamination varies. The same quality water might be suitable in one situation while being unfit for irrigation in another (Bartone et al., 1985; Kurian, 2014).

When it is decided that wastewater irrigation needs or will be applied, risks of environmental and health hazards must be minimized. One could think about protection of workers against the biohazard, but also about the irrigation method and the types of crops that are produced by applying sewage. Using drop irrigation instead of spraying water over the farmland could already reduce the exposure of crops to sewage, therefore reducing contamination of the crop by pathogens carried by the wastewater. Moreover, wastewater should initially be used for energy crops. Only when no other option for water supply is available, crops meant for human consumption should be grown with wastewater irrigation as they have to comply with the strictest pathogenic safety standards. When sewage is left and green and blue water are scarce, wastewater can be applied to grow fodder crops in order to safe cleaner water sources for crops meant for human consumption (Bartone et al., 1985; Smit & Nasr, 1992).

Treatment of wastewater with UV lights or low-capital intensive methods including exposure to sunlight and biological treatment by algae or duckweed, could eliminate pathogens and improve the water quality (Shuval, et al., 1986).

8.1.2 Food processing and food waste management

Food processing and preparation often require water (Ramaswami et al., 2017). Boiling, adding water as an ingredient, and rinsing vegetables are very common steps during food preparation, but in industrial food processing factories many more activities, like cleaning, cooling and peeling require water supply to facilitate production. However, during processing and preparation activities, organic food waste is created, such as peels, over-ripe crops.

Water can be contaminated with food when after processing or consumption, food waste is dumped into water bodies or grinded into the sewage system through the kitchen sink (Sarker et al., 2016).

Water needs to be added to the grinded food mixture in order to lower the viscosity and to allow for transportation to a wastewater treatment plant (WWTP). At the WWTP, the water needs to be treated to remove carbon and nutrients before it can be discharged in surface waters, to prevent contamination and eutrophication. In developing countries, (food) waste is often disposed in open water streams, without intervention of a wastewater treatment facility, which can lead to an adverse food-related impact on urban water quality (Ramaswami et al., 2017).

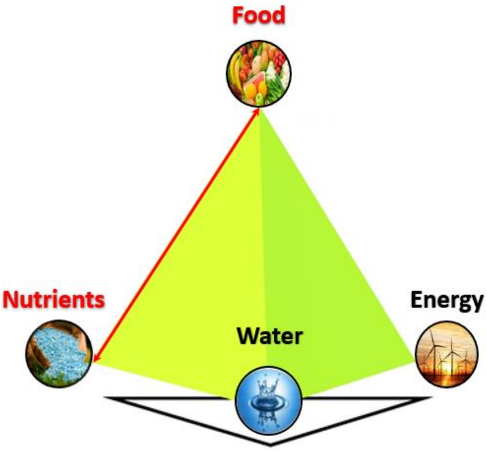
Not only can water be used for transport of food waste, during the crop cultivation process water is embedded in food. The typical water content of wasted food is around 70% (Sarker et al., 2016). When food disintegrates, it breaks apart into several molecules, including water.

8.1.3 Trading in agricultural products

Trading in food implies trading in water embedded in these products (Mohtar & Daher, 2012). The water needed to grow agricultural products is referred to as virtual water. This concept can be applied to examine the quantities of water that are indirectly imported by an urban area through their food supply and can reveal the effect of urban consumption on the water balance in the source area of the food (Qadir et al., 2007; Endo et al., 2017).

8.2 Food – Nutrients

Food and nutrients are linked through various interactions, which are on their turn embedded deeper into the WEF nexus. This section will discuss nutrient use in food production and nutrient harvesting from food waste handling.



8.2.1 Fertilizer addition in the agricultural sector

Crops need nutrients to grow. In traditional open field agriculture, the soil is the natural supplier of nutrients to vegetation. Every soil type has a different pallet of nutrients available for root uptake. The more organic matter and clay minerals a soil has, the higher the cation exchange capacity (CEC) of the soil and the better the soil can attract, hold and exchange positively charged ions like ammonium (NH_4^+) and potassium (K^+) (Sparks, 2003).

The anion exchange capacity, which determines if phosphorus is released from the soil, depends on the presence of clay minerals and metal oxides, since phosphorus is absorbed by plants as the negatively charged phosphoric acids dihydrogen phosphate ($H_2PO_4^-$) and hydrogen phosphate (HPO_4^{2-}) (Roy et al., 2006; Sparks, 2003).

To prevent nutrient depletion in agricultural soils, fertilizers are added. In the past, human excreta and livestock manure served as natural nutrient supply. Nowadays, synthetic fertilizers are widely used. In the year 2014, globally the demand for nitrogen (N), phosphate (as P_2O_5) and potassium (as K_2O) to enhance soil fertility was 113, 43 and 31 million tonnes respectively (FAO, 2015-1).

On their turn, crops can also be used to clear water from excessive nutrient concentrations. This principle is used in aquaponic farming, which involves a combination of raising fish and plants. Nutrients from the fish tank wastewater are recycled and used as nutrient input for the crops. Aquaponic farming is described in more detail in section 2.4.2.4.

8.2.2 Nutrients from food (waste)

A case study in the London area, where 7.8 million people live, showed that phosphorus flows carried inside food annually amount to between 8.7 and 9.7 kilotons of which between 6.8 and 8.8 kilotons of phosphorus ended up in sewage sludge (Villarroel Walker et al., 2014).

Human nutrient intake in the form of food can be estimated by knowing the food intake per person and the average content of this food, multiplied by the population size. In the case of nitrogen this could be done by looking into meat and cereals consumption as those nutrition types represent the largest intake of nitrogen. Altogether, 7.8 million Londoners are estimated to consume between 68% and 85% of the total 42 -47 kilotons of nitrogen per year in food products though those foods (Villarroel Walker et al., 2014).

Between 22 and 40 kilotons of consumed nitrogen end up in urine in London each year and consequently, water, typically used as a waste handling medium, becomes a carrier of the nitrogen. However, between 32 and 42 kilotons of nitrogen in the London sewage is lost to the atmosphere as nitrogen gas during the denitrification stage in the activated sludge process (Villarroel Walker et al., 2014). When instead of losing this amount of nitrogen as elemental nitrogen gas it would be recovered it can potentially supply 32% to 46% of the demand for nitrogen for producing the food consumed in London. A study done on Paris in 1913 showed a similar result, as 40% of Parisian dietary nitrogen consumption was recycled for food production (Barles, 2007-1, 2007-2).

Not only food, but also food waste forms a link in the nutrient cycle. From the moment the food is wasted, several pathways can be walked in order to get rid of it. The majority of food waste is processed as landfill disposal (USEPA, 2014). This method of uncontrolled degradation wastes all valuable components that reside in food waste. Moreover, in the US it nationally releases 34% of all emissions of the strong biogas methane. In 2013, approximately 2.1% of wasted food generated in the United States was anaerobically digested, resulting in biogas and an effluent high in nutrients (EREF, 2015). Another way to deal with food waste is to thermally convert it, releasing energy captured in the organic material as heat. The last method to deal with food waste is by composting (Sarker et al., 2016). During some of the waste management methods mentioned, nutrients are lost for the system, whereas in others they are available to be recycled. Anaerobic digestion (section 8.3.3) and composting (section 8.2.2.1) are the two methods that conserve and even concentrate nutrients so that it can be harvested.

8.2.2.1 Composting

Composting facilities generally require a smaller investment than anaerobic digestors, and might therefore be more viable for local small-scale operation, reducing the energy footprint of transport (Hochman et al., 2015). When air, moisture and temperature are adequately maintained, composting is a viable process to recover nutrients from food left-overs, enhancing a circular economy (Sarker et al., 2016).

Compost contributes to food production as fertilizer as it has beneficial impacts on soil quality (Schwalb et al. 2011). When applying compost (from local sources), (urban) agriculture can play a significant role in the recycling of organic wastes (Smit & Nasr, 1992). However, on a yearly basis, less than three percent of the wasted food in the US is recovered through composting (USEPA, 2014).

Composting is a biological oxidative process driven by aerobic micro-organisms that convert bio-degradable organic constituents primarily into carbon dioxide (CO_2), water, mineral ions and humus (Oluchukwu et al., 2018). During the process, pathogens are destroyed, and nitrogen is converted from volatile ammonia to stable organic forms.

Compost has a wide range of possible moisture contents; when 80% or less of its weight consists of water it is called dry compost and when it has a water content of 85% or more it is considered wet compost. Both dry and wet composting produce gaseous emissions. The largest part of these emissions is composed of carbon dioxide, but also the potent greenhouse gas nitrous oxide is emitted, resulting in loss of nitrogen resources from the urban system into the atmosphere, while contributing to global warming (Sarker et al., 2016).

When food waste and yard waste are mixed, dry composting is accomplished. The wet composting system requires additional liquids for organics to be pumped and mixed with waste and microorganisms during composting. Therefore, from the nexus point of view, wet composting is less desirable, as it recycles nutrients at the cost of energy and water resources.

The chemical composition of compost, and the ratio of the weight that consists of nutrients for the plants and crops, varies as it is dependent on the maturity of the compost and on the raw materials that were composted to start with. Given the fact that this thesis is considering the composting process in a WEF nexus frame, it makes sense to analyse the composition of compost types that are at least partially composed of food waste compost. A paper by Oluchukwu et al. (2018) studied exactly that. They mixed 25 kg of sawdust and 15 kg of food waste. The chemical composition of these input products is shown in table 14. By combining sawdust and food waste, micro-organisms that are crucial in the composting process but are unable to survive in pure sawdust due to the high C/N ratio and consequent lack of nitrogen, are fed with high nitrogen supplies from the food waste and can continue composting the organic material. On the other hand, the addition of sawdust to food waste results in less nuisance by bad odour, since the high C/N ratio in sawdust reduces the amount of excess nitrogen from the nitrogen rich food substrate that can be converted into ammonia (Oluchukwu et al., 2018).

Compost composition	**Moisture Content (%)**	**Organic Matter (%)**	**Total Carbon (%)**	**N (%)**	**P (%)**	**K (%)**	**pH**	**C/N**
Sawdust	45	44	38.5	0.38			5.9	101.3
Food waste	57	67	47.8	4.43			6.4	10.8
Sawdust (63%) & food wastes (33%)	19.2	89	66.6	2.82	6.2	7.4	5.7	23.6

Table 14 Chemical composition of the raw materials sawdust and food waste compared to the composition of a mixture with sawdust (63%) and food wastes (33%) before composting (Data source: Oluchukwu et al., 2018).

Unfortunately, the data on the composition of the mature compost were not provided in this study. It is very likely though, that the ratios of the nutrients in the mature compost slightly differ from the ratios in the initial compost mixture. Lin (2008) showed that nitrogen, phosphorus and potassium concentrations increased during the composting process. This trend was attributed to the fact that during the composting process, organic carbon is decomposed into methane (CH_4) or carbon dioxide (CO_2), which leaves the mixture at a higher rate than that of nitrogen, phosphorus and potassium, causing the concentration effect (table 15).

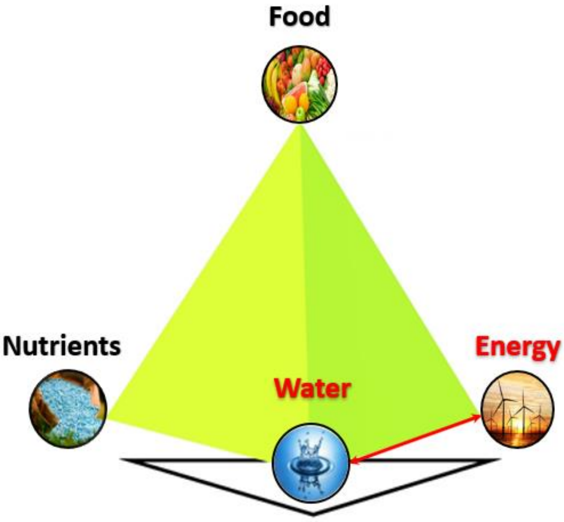
Another study executed by Mladenov (2018) showed values in the same order of magnitude for different compost mixtures. A blend between grass and hardwood resulted in a compost containing 0.45% nitrogen, 0.057% phosphorus and 0.12% potassium. A mixture of food and park-wood wastes consisted of 1.23% nitrogen, 0.092% phosphorus and 0.53% potassium after the composting process ended.

	Ratio in initial compost mixture	**Moisture Content (%)**	**N (%)**	**P (%)**	**K (%)**	**pH**	**C/N**
Food wastes	64	85	1.1	0.6	1.2	4.57	36
Mature compost	16	35	1.6	0.3	1.1	7.46	23
Sawdust	20	12	0.8	0.1	0.3	4.20	58
Mixture before composting (day 0)		63	1.2	0.5	1.1	5.20	32
Mixture during composting (day 30)			1.5	0.5	1.3		
Mature composted mixture (day 60)			1.6	0.6	1.4		

Table 15 Chemical composition of initial input products (food waste, mature compost and sawdust) and of the mixture between the input products during a composting time of 0, 30 and 60 days. (Source: Lin, 2008)

8.3 Water-Energy linkages

Long international supply chains in which water and energy are embedded form the basis of modern urban economies (Allan et al., 2015). Water and energy are intertwined driving the urban system from the suppliers to end users (Wang et al., 2017). They are also very much related to the food sector. A hybrid flow analysis from Beijing shows that the agricultural sector accounts for the largest water related energy consumption which comes as no surprise as it is also the largest water consuming sector. The transportation sector is the largest contributor to energy–related water consumption (Wang et al., 2017).



Water is needed in the energy supply chain, e.g. for the extraction of (fossil) fuels, during cultivation of biofuels and for power generation. On the other hand, the water supply chain requires energy too, during extraction, conveyance and treatment stages and for water heating and cooling. Based on these facts, it can be argued that saving water can lower pressure on energy resources and increasing energy efficiency can reduce the amount of consumed water and increase sustainability (Dai et al., 2018). The co–existence of energy and water and competition between the two resources will be depicted in this section.

The energy that is utilized for the water sector and water consumption related activities can be categorized by utilization stage. First of all, there is the energy that is required for water provision. Moreover, energy is used during the usage stage and during wastewater disposal (Wang et al., 2017).

8.3.1 Water heating

The US experience is that water heating, which is predominantly residential, is a larger energy consuming business than water supply and treatment. Heating water is consuming 14% of electricity and 31% of natural gas in the state of California (DOE, 2006).
With 4.18 $Jg^{-1}K^{-1}$ water has a relatively high heat capacity (Verkerk et al., 2008). This means that for every kilogram of water that is heated by one degree Celsius 4.18 kJ of energy is required. Cooling water down, on the other hand, releases the same amount of thermal energy.

In a WEF nexus setting, this fact can predict energy needs when heating irrigation water for delicate crops or energy supplies of recovery through heat exchangers in sewage drains. Depending on local customs, climate and season, the temperature difference between incoming (drinking) water and outflowing wastewater can be significant, which signals that in domestic wastewater a lot of thermal energy is stored. Thermal energy recovered from warm sewage can be reused in order to heat indoor farms during colder periods or to process food.

Warm sewage can also be used for heating shower water using heat switches. Cold water from recently withdrawn groundwater can be used for cooling of overheated greenhouses or indoor farms in order to reduce the need for air conditioning (Ramaswami et al., 2017).

By recovering heat from the sewer at the wastewater source, heat loss during transport to a treatment facility is reduced due to the smaller temperature differences between the sewage and its environment. A negative side effect of recovering thermal energy at the sewage source is that the water that is entering the treatment plant has a lower temperature than without heat recovery. This could result in a slowed down wastewater treatment process, or in the need for heating at the plant, as higher temperatures accelerate (bio-)chemical water treatment processes (Ahsan et al., 2005).

Excess thermal energy does not have to be used immediately, as it can be stored too, for example in geothermal heat pump installations. In summer these installations store excess heat underground, while pumping up colder water from the reservoir for cooling purposes. In winter warm water is brought up to the surface for heating purposes, whereas cold water is collected to refill the cold-water reservoir.

8.3.2 Energy required for drinking water and wastewater treatment

According to Villarroel Walker et al. (2014), the water sector is not a significant player in the total urban energy sector, even though energy is the largest operational cost in the water sector. Nevertheless, wastewater treatment is a crucial process in reducing the environmental footprint of urban areas. Wang et al. (2017) found out that, 10% of the total energy in the urban water cycle is used for the pumping and treatment of water utilities.

Wastewater needs to be cleaned in compliance with acceptable standards before it is discharged in the environment or used for drinking water. Purification of blue (runoff, stream flow, ground) water to make water potable and conversion of grey (waste) water into green water that can be safely discharged into the environment simply requires energy (Kurian, 2014).

Basic sewage treatment aims at removing oxygen consuming substances in order not to suffocate aquatic life. Treatment can be expanded by removing nutrients like nitrogen and phosphate to prevent eutrophication in surface waters that receive the treated sewage. Advanced treatment systems could also remove pathogens, micropollutants and heavy metals. However, those steps are rather expensive and generally only considered feasible when direct reuse of wastewater for human consumption is intended.

Although many treatment steps could be completed naturally and without supplies of artificial energy, water treatment plants often use energy input to accelerate their (bio)chemical processes in order to be able to treat larger volumes of water in the same time period, as mentioned in section 8.3.1. However, when transported over long distances, the water tends to cool down and reaches the treatment facility in a cooler state than when it just left the dwelling.

In figure 28 energy requirements of some widely applied treatment methods are depicted.
Pumping is the largest energy consuming unit process for drinking water production from surface water. Mixing is a distant second.
In wastewater treatment plants, aeration, whether by trickling filters or bubble diffusers, and digestion are the biggest energy consuming activities. Digestion uses energy as digestors need to be kept at the constant temperature of 54–55 °C at which microbes operate. Smaller digestors lose their heat more easily due to their relatively large outer surface, hence the larger energy requirement for small-scale installations (Plappally, 2012). Digestion, however, does not only consume energy, it also delivers energy in the form of biogas, making it a net energy supplier instead of a consumer.

8.3.2.1 Desalination

Desalination is a water treatment process that requires large amounts of energy to create the high pressure which is needed to pump the salted water through the small pores of reverse osmosis membranes. For every cubic meter of desalinated water, 4-6kWh is used (Semiat, 2008). Therefore, this technique is only viable in areas where water is scarce and energy abundant.

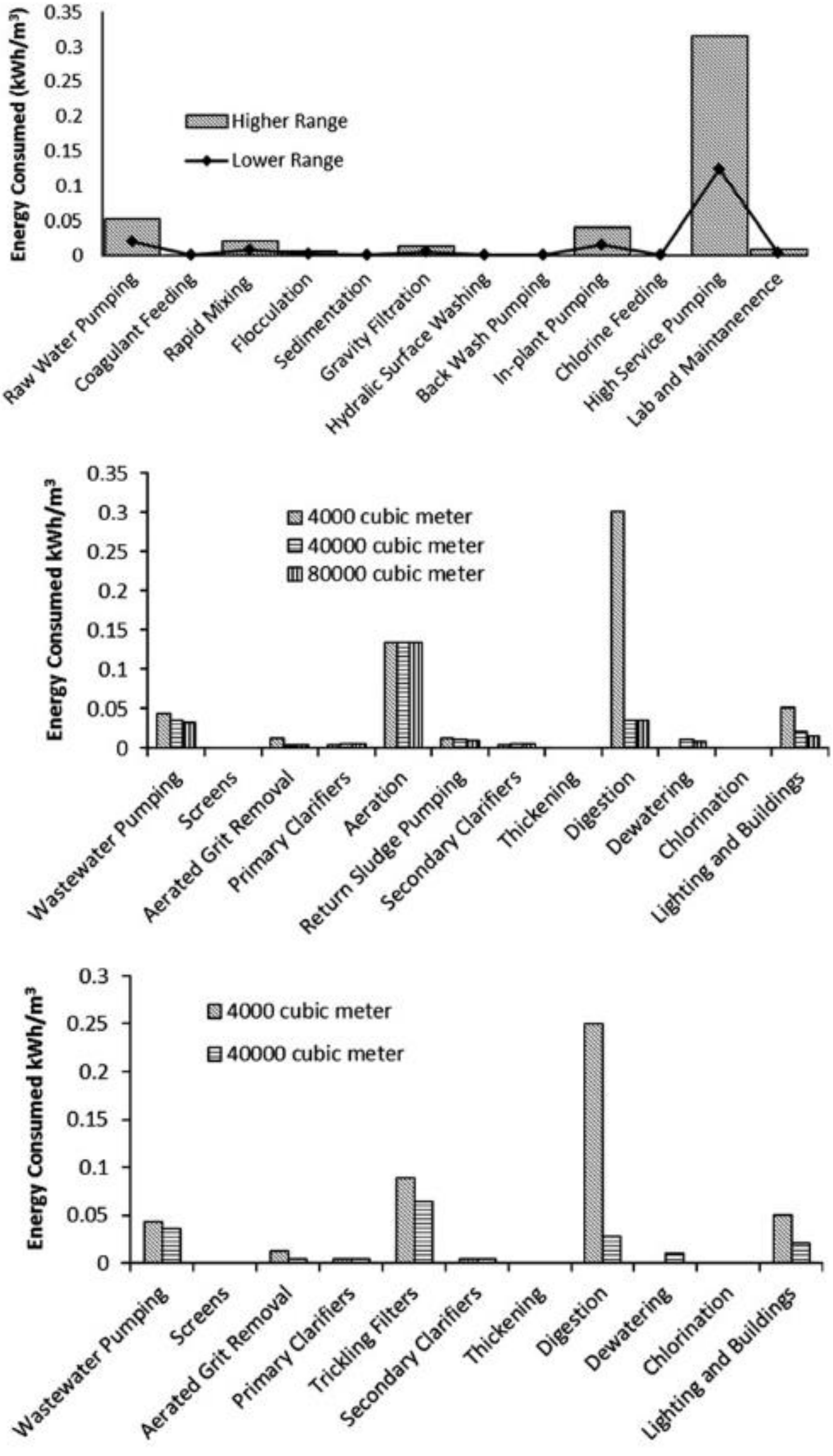


Figure 28 *Energy consumption of unit processes:*

Top: *during drinking water production in surface water treatment plants in the United States (Source: WEF, 2010)*

Middle: *for activated sludge wastewater plants (Source: Murty et al., 2011)*

Bottom: *for trickling filter wastewater plants (Source: WEF, 2010)*

8.3.3 Energy produced/released during water treatment

Along the entire sanitation chain energy is consumed. In Munich (Germany) it was estimated that saving the water used for flushing the toilet can result in energy savings up to 5.5 kWh per capita per year (Schönfelder et al., 2013). Also, conventional wastewater treatment is a large energy consumer. However, there are also opportunities for energy recovery from sewage. Theoretically, a significant part of the energy required for wastewater treatment could be provided by the energy content in wastewater (Hall et al., 2012; Heidrich et al., 2011). Heidrich et al. (2011) stated that wastewater has energy content that varies between 5.6 and 16.8 kJ per litre (1.6-4.7 kWh per m^3). This was further specified by Villarroel Walker et al. (2014), who estimated that the energy content in predominantly residential wastewater varies from 6.8 to 7.2 kJ per litre (1.9-2.0 kWh per m^3).

Two types of energy can be recovered from wastewater: thermal energy and biogas. Thermal energy recovery occurs through the inverse process of water heating, which was described in section 8.3.1. Besides, biogas can be harvested from the organic compounds present in wastewater. During biomass production energy is chemically stored by the endothermal reaction shown by equation 4.

$$nCO_2 + \frac{1}{2}(a-3d)H_2O + dNH_3 \rightarrow C_nH_aO_bN_d + \frac{1}{4}(4n+a-2b-3d)O_2 \qquad (eq.4)$$

During the aerobic decomposition of biomass this formula occurs in counter direction and oxygen is needed in order to dismantle complex organic molecules. However, when biomass ($C_nH_aO_bN_d$) is digested anaerobically, biogas (CH_4) is produced as explained by equation 5 (Van Lier, 2016; Kwietniewska & Tys, 2014).

$$\begin{aligned} C_nH_aO_bN_d &+ \frac{1}{4}(4n-a-2b+3d)\,H_2O \\ &\rightarrow \frac{1}{8}(4n-a+2b+3d)\,CO_2 + \frac{1}{8}(4n+a-2b-3d)\,CH_4 + dNH_3 \qquad (eq.5) \end{aligned}$$

Kwietniewska & Tys (2014) state that if the composition of the organic matter is known and all organic material is converted to biogas, the theoretical methane yield potential can be calculated using the Buswell equation (eq. 6)

$$\frac{litre\ CH_4}{gram\ COD} = \frac{\left(\frac{n}{2}+\frac{a}{8}-\frac{b}{4}\right)*22.4}{12n+a+16b} \qquad (eq.6)$$

However, the composition of the biomass is not always known. In those cases, the potential methane yield could be derived theoretically from the chemical oxygen demand (COD) of the substrate. In order to oxidize the products of anaerobic digestion, all methane (CH_4) in the solution needs to be converted into carbon dioxide (CO_2) (equation 7).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (eq.7)$$

For every mole of CH_4 produced the oxygen demand is reduced by two moles. Given a standard molar volume of 22.4 l/mole and a molar weight of oxygen of 16 g/mole, this means that for every litre of biogas produced 2.86 grams of COD is removed from the solution (similarly: 1 gram COD removal equals 0.35 litres of biogas (CH_4) production at most).

The calorific value of methane biogas amounts 35.8 MJ/m^3 (Verkerk et al., 2008). Consequently, the maximum theoretical energy content of a solution is 12.5 MJ/kg COD, which equals 3.47 kWh/kg COD. However, the conversion of biogas into electricity requires biogas motors, which generally have an efficiency of around 35% (Van Lier, 2016).

Besides large-scale wastewater treatment plants, small-scale local treatment facilities could be used to treat sewage and harvest biogas. An example from practice in Hamburg (Germany) shows that blackwater with sludge from greywater and organic waste of 2000 persons is used to generate 340,000m^3 of biogas on an annual basis, using a fermenter and a sludge thickening process. The entire installation to generate energy from sewage costed €935,000 with a cogeneration plant included (Schönfelder et al., 2013).

8.3.4 Transportation of wastewater & drinking & irrigation water

Depending on research boundaries and applied technologies, the provision of 1 m^3 of ground water requires around 0.5 kilowatt-hours of energy (Belfer Center, 2010). This value however varies per groundwater reservoir. Moreover, it is estimated that supply from surface water requires 30% less energy due to lower requirements for raw water pumping (Belfer Center, 2010).

The energy footprint of water provision significantly varies among different water sources, although they have one thing in common. The required energy is needed to overcome friction losses and height differences. Following the Darcy-Weisbach equation (eq. 8), which describes the head loss or pressure loss (ΔH) in pipelines, transporting water in sewage systems or drinking water supply systems requires energy.

$$\Delta H = \frac{\lambda L}{D}\frac{u^2}{2g} \quad (equation\ 8)$$

The Darcy-Weisbach equation shows that the larger the velocity (u) at which the fluid travels, the rougher the transport pipelines are (described by the friction coefficient λ), the longer the length (L) of the transport pipelines that is covered, and the smaller their diameter (D), the larger the friction losses are that need to be compensated (Elger et al., 2014).

Boosters and pumps are often added to sewer and drinking water systems in order to transport the water either towards the outlet at the treatment station or the consumer outlets (Kooij, 2015). Of course, operating these devices to compensate for friction and height differences that need to be overcome consumes energy (from the grid). Moreover, engines and pumps only have a limited efficiency and therefore water transport requires more energy than the Darcy-Weisbach equation makes us believe.

On the other hand, the kinetic energy that is remaining when the water is entering the treatment facility or consumer outlets could be captured, using turbines. This could increase the energy efficiency of the transport operation.

8.3.5 Electricity production

Energy is consumed in many ways in our modern-day society. Some systems run directly on fossil fuels, whereas others are propelled by electricity, which can be generated by renewable as well as non-renewable sources. Non-renewable energy sources (coal, oil, and natural gas), need to be mined from the earth, which consumes water (see section 8.3.5.1). Since renewable sources, such as solar radiation, tidal energy, and geothermal energy, biomass, do not require an extraction step, they are generally less water intensive.

8.3.5.1 Resource extraction

Most conventional power generation facilities run on fossil energy. Fossil fuels (such as coal, crude oil, and natural gas) and raw materials for nuclear energy, need to be extracted from the earth, before they can be converted in energy forms that can be used by society. This resource extraction requires water consumption. The extent of this consumption depends on geographical features, geological conditions, and extraction technologies. The extraction of different types of non-renewable energy resources is paired with different water consumptions for dust suppression, cooling drilling equipment and removal of impurities (McMahon & Price, 2011).

In the United States, the ratio of water consumption to oil production ranges from 6.3:1 to 9.5:1 (Wu et al., 2008). The extraction of natural gas is way less water intensive than crude oil and coal production. Shale gas extraction, however, are the exception, as this method relies on hydraulic fracturing of the geological formations in the sub-soil (Chang et al., 2016). In table 16 the water consumption for the extraction of different energy resources and the water needs of their corresponding processing paths are displayed.

Energy Type		**Extraction & Processing (m^3/GWh)**	**Cradle-to-wire (m^3/GWh)**	**Cradle-to-liquid (m^3/GJ)**
Coal	Surface mining	23 - 220	160 - 5,160	0.12 - 0.29
	Underground mining	64 - 870	200 - 5,800	0 - 0.01
Natural Gas	Conventional natural gas	4 - 100	4 - 4,530	0.04 - 0.06
	Shale gas	8 - 800	8 - 5,230	0.03 - 0.05
Nuclear	Uranium	50 - 1250	430 - 4,450	-
Solar	Photovoltaic	20 - 800	20 - 810	-
	Concentrated Solar Power	300 - 640	400 - 4,800	
Wind	Onshore	0 - 35	4 - 42	-
	Offshore	0 - 35	0 - 38	
Hydropower		1 - 60	5,400 - 68,200	-
Geothermal		8 - 7600	26 - 2,730	-
Tidal	Ocean	60 - 220	60 - 220	-
Oil	Conventional Oil	-	-	0.01 - 0.02
	Enhanced Oil Recovery			0.02 - 2.52
Biofuel	Sugarcane (ethanol)	-	-	25 - 108
	Maize (ethanol)			9 - 200
	Sugar beets (ethanol)			13 - 23
	Rapeseed (biodiesel)			400 - 574
	Soybean (biodiesel)			50 - 394

Table 16 Water consumption of different energy technologies (Source: Chang et al., 2016)

8.3.5.2 Power generation and fuel/energy demand water abstractions

In 2010, a total of 583 billion cubic meters (bcm) of water was withdrawn for energy production, which accounts for 15% of the world's total water retraction. Approximately 11 % of the total energy withdrawn for energy production was consumed, and therefore not available anymore for other purposes afterwards (IEA, 2012).

Power is generated in many ways. A few of the most common traditional and renewable power production methods and their water needs are depicted in the following section.

8.3.5.2.1 Thermoelectric power plant

Thermoelectric power plants, mainly due to their need for cooling, have a tremendous dependency on water resources (Chang et al., 2016). These power plants still accounts for 70% of today's electricity and in the US, about 90% of electricity is produced thermoelectrically (Chang et al., 2016; Zhang & Vesselinov, 2017).

Nuclear energy is the thermoelectric technology with the highest water demand per unit of produced energy, because of the large water consumption for both extraction and processing (50-1250 m^3/GWh) and cooling. This results in a cradle to nuclear power water consumption between 750 and 3000 m^3/GWh (Belfer Center, 2010) or between 430 and 4450 m^3/GWh (Chang et al., 2016).

Zhang & Vesselinov (2017) estimated that coal-fired power plants require 'only' 1,200 m^3/GWh, whereas natural gas-fired plants demand 1,600 m^3/GWh of electricity. This is all within the ranges that are provided in table 16 by Chang et al. (2016).

The water footprint can vary depending on which cooling systems a power plant adopts (IEA, 2012). Once-through cooling systems generally have a higher water withdrawal, but lower water consumption, than closed-loop cooling system, which often have a lower water withdrawal, but a higher water consumption due to the brine that is created (Walker et al., 2013; Whittemore, 1995). With once through cooling systems, approximately 0.075 litres of water per kWh are consumed by evaporation from the surface of the receiving body. A closed loop power plant with cooling towers requires 1.5–1.9 litres per kWh for evaporation (Hightower, 2011).
Alternative cooling technologies like dry cooling with air are available, but are more expensive in acquisition and operation and are less effective than water for cooling, reducing power generation by 1% to 7% (EPA, 2009; Qin et al, 2015).

8.3.5.2.2 Renewable energy

Renewable energy is generating power or collecting heat without drawing from finite sources after the installations have been completed. In 2015 only 16.6 % and 8.7% of the energy that is consumed in the European Union and the United States respectively is generated sustainably (Worldbank, 2019). However, in the context of the current energy transition the market share of renewable energy is expected to expand because of its sustainable nature. Even though conventional power generation techniques generally record a higher water consumption than renewables do, many types of renewable energy still need water (Chang et al., 2016).

8.3.5.2.2.1 Bioenergy

Biofuels are derived from biological sources and are one of the most water-intensive fuel sources, consuming more than 3.5 litre/MJ on average. This is approximately two orders of magnitude greater than that of other fuel sources (CSS, 2010). The biomass originates from plants such as sugarcane, maize, and soybean which store carbon, and therefore holds great promise for greenhouse gas mitigation (McKendry, 2002). In 2008, 10% of the world's energy (50.3 EJ) was supplied by biomass, and projections predict doubling or even six-folding of that number by 2050, as the world has begun to move toward bioenergy (IPCC, 2012). At the same time, the International Energy Agency (IEA, 2012) projects that water needs for energy production will grow at twice the rate of the energy demand, largely due to the continued development of biofuel production.

Irrigation is essential for plant cultivation. Therefore, the water demand for production of bioenergy is significantly higher than that of fossil fuels. However, it varies per energy crop, irrigation method and region. For example, maize, a common biodiesel feedstock, has a different water consumption per unit energy in the Netherlands (9 m^3/GJ) than in the United Sates (18 m^3/GJ) (Gerbens-Leenes et al., 2009). The water footprint of several common biofuel crops are shown in table 17.

Crop	**Water footprint (m^3/GJ)**			
	Brazil	**The Netherlands**	**USA**	**Zimbabwe**
Cassava	30	-	-	205
Coconut	49	-	-	203
Cotton	96	-	135	356
Groundnuts	51	-	58	254
Maize	39	9	18	200
Miscanthus	49	20	37	64
Palm oil	75	-	-	-
Poplar	55	22	42	72
Potatoes	31	21	32	65
Soybeans	61	-	99	138
Sugar beets	-	13	23	-
Sugarcane	25	-	30	31
Sunflower	54	27	61	146
Wheat	83	9	84	69
Rapeseed	214	67	113	-
Average	62	24	57	142

Table 17

Water footprint for different types of biofuel crops in four different countries

(Source: Kurian, 2014)

8.3.5.2.2.2 Hydropower & tidal energy

Even though the extraction and processing of building materials for hydropower facilities requires only 1 to 60 m^3/GWh, the cradle-to-wire water use is enormous with 5,400 to 68,200 m^3/GWh (Chang et al., 2016), although Gerbens-Leenes et al. (2009) estimated a slightly smaller water use of 22m^3/GJ (79,200 m^3/GWh). This large difference in water use between the extraction phase and the total energy production process is mainly because hydropower requires water to propel the turbines. Fortunately, the water use mostly concerns once-through flow and the water is not really consumed but released into the environment again after it has lost some of its potential energy. The dependency of tidal energy on water is similar. Without a water flow, no current is created to drive the turbine blades. However, in a tidal setting, the same volume of water can move back and forth past the turbines and as a result the water volume required for harvesting one unit of energy is only fraction of the water requirement for hydropower. Chang et al. (2016) estimated that for each GWh of tidal energy only 60-220 m^3 of water is needed.

8.3.5.2.2.3 Wind energy

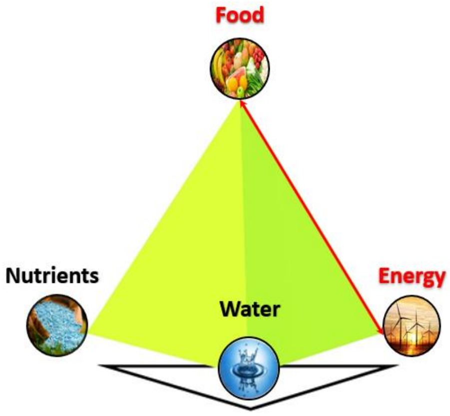
The water footprint for wind energy is negligible (Gerbens-Leenes et al., 2009). The small difference between the extraction and processing phase (0-35 m^3/GWh) and the cradle to wire water use (0-42 m^3/GWh) shows that maintenance of wind turbines requires very little water (Chang et al., 2016).

8.3.5.2.2.4 Solar energy

Gerbens-Leenes et al. (2009) stated that 0.3 m^3/GJ (1080 m^3/GWh) of water is needed to produce solar energy. In the solar energy industry, the difference in water consumption between extraction and processing of the structures (20-800 m^3/GWh) and the total water consumption for solar power production (20-4800 m^3/GWh), indicates larger water requirements for maintenance activities (Chang et al.,2016). This corresponds to the fact that water is needed for cleaning solar panels and mirrors to make sure dust does not prevent them from using their full potential.

8.4 <u>Food- Energy linkages</u>

Food and energy are two components of the WEF nexus that are intensively linked. Their relation is apparent when the correlation between food and energy prices is studied, as shown in figure 29 (Ringler et al., 2013). From 2006 to 2008, when the among others, petroleum prices rose, prices of common crops like wheat and rice, respectively doubled and even tripled (Steinberg, 2008).



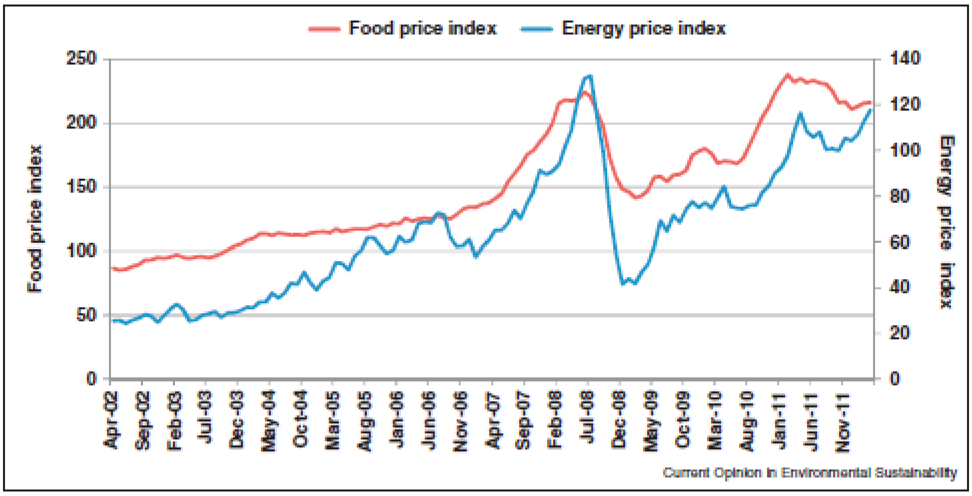


Figure 29 The relation between food prices and energy prices (Source: Ringler et al., 2013)

8.4.1 Food production/consumption line

Food production and supply account for approximately 30% of the global energy consumptions (FAO, 2011). A highly complex chain of energy consuming activities is required to convert raw resources into crops and eventually into the actual product on a consumer's plate. All these steps are depicted and quantified in the sections below.

8.4.1.1 Energy stored in crops

Plants produce glucose in their leaves during the process of photosynthesis and are able to store it on the long-term as starch (Atkinson, 1977). Once the plant is in need of energy, for example during the flowering season, it can take energy from this storage and release it for its internal processes. The formation of glucose during photosynthesis is described by equation 9 (Grace, 2001). Right below the chemical reaction (9.1) the standard thermodynamic quantities (ΔH_f) are provided in equation 9.2 and 9.3 for all molecules at 25°C in kJ/mol (CRC, 2003).

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O \quad (eq\ 9.1)$$

$$6*(-393.5)+12*(-285.8) \rightarrow (-1273.3)+6*(\ 0\ )+6*(-285.8) \quad (eq\ 9.2)$$

$$\Delta H_R = (1*-1273.3+6*0+6*-285.8)-(6*-393.5+12*-285.8\ ) = 2802.5\frac{kJ}{mol} \quad (eq\ 9.3)$$

This outcome indicates that energy is stored during food production inside the crops, as energy is required to drive the reaction towards the side of glucose formation. When a crop dies, or is being composted, the reaction is reversed, and this energy is released again, as micro-organisms break down the organic matter into water and carbon dioxide again.

8.4.1.2 Energy consumption of agricultural practises

Agriculture has become a very energy intensive sector because of the increased use of fertilizers, machinery and groundwater pumping (Ringler et al., 2013). Currently, 30% of world's available energy is consumed by food production systems (FAO, 2012). The consumption of energy at farms, that is required for primary production of crops and cattle, accounts for only 6.6% of the total energy the food sector consumes (Vanham, 2015). These data imply that indirect energy consumption embodied in the production of machinery, farm equipment, fertilizers, pesticides and food processing activities such as packaging, account for the majority of the sector's energy needs. Ringler et al. (2013) stated that petroleum-based fertilizers and mechanization consume most energy in conventional agricultural production in the United States, each using about one-third of the 1 m^3 of fossil oil per hectare. Belgian wheat cultivation was found to consume approximately 3,400 MJ/hectare. Operations relying upon machinery that runs on gasoline and diesel fuel, like agricultural vehicles, are large energy consumers. Ploughing (800 MJ/hectare), combine harvesting (650 MJ/hectare) and sowing and injecting/spreading manure (400–500 MJ/hectare), are dominating the energy requirement on-site. On-site wheat transport, spraying and baling straw were way less energy intensive (Van Linden & Herman, 2014).

8.4.1.3 Energy requirements for food processing and storage

Most of the food produced today is highly processed (Ramaswami et al., 2017). Where in the past food was washed, peeled, sliced and cooked by hand, electrically driven equipment for food preparation has become increasingly popular both in the industry and at home. Without a doubt, this trend has increased the energy footprint. Moreover, heavily packaging and refrigerated storage have become the norm for many foodstuffs and both require significant energy inputs.

8.4.1.4 Energy requirements for transport of food and resources

Global food systems are the main source of foodstuff for urban populations (Barthel & Isendahl, 2013). These large international supply chains have great benefits when they function as a system with reliable vendors, transportation and high connectivity. This could decrease a cities' vulnerability to food shortages (Ernstson et al., 2010).

Transport of foodstuffs and their resources, however, require significant energy inputs. Food in American supermarkets has on average, travelled 2000 kilometres (1,300 miles), so-called food miles, before it ends up on the consumer's plate (Smit & Nasr, 1992). A more recent study by Xureb (2005) found that a selection of 58 commonly eaten foods travelled on average 4,497 kilometres (2,811 miles) to the shop. This number didn't even include the distance consumers travel to shop or the distance that waste food travels to be disposed of.

Pirog et al. (2001) found that food sourced from the conventional system had travelled around 35 times more than locally sourced food and consequently required a much higher fossil fuel input (table 18). Local food production could result in cost and energy savings in transport, but also in storage and handling (Smit & Nasr, 1992; Fabiola & De Rosa, 2016). Table 19 shows how much energy different transport modes consume per kilometre.

Since the travel distance partly concerns refrigerated transport, the transport operation is even more expensive and energy consuming than the mere number of miles travelled makes us believe (Qadir et al., 2008).

Crop	**WASD locally grown (miles)**	**WASD Conventional Source (miles)**
Apples	61	1726
Beans	65	1313
Broccoli	20	1846
Cabbage	50	719
Carrots	27	1838
Corn	20	1426
Garlic	31	1811
Lettuce	43	1823
Onions	35	1759
Peppers	44	1589
Potatoes	75	1155
Pumpkins	41	311
Spinach	36	1815
Squash	52	1277
Strawberries	56	1830
Tomatoes	60	1569

Table 18

The Weighted Average Source Distance (WASD) in miles for locally versus conventionally sourced produce (Data source: Pirog et al., 2001)

	Rail	**Water**	**Road**	**Air**
Energy consumption *(kJ/tonne/km)*	677	423	2,890	15,839

Table 19

Estimated primary energy consumption for four different freight transport modes (Data source: Hill, 2008)

8.4.2 Biofuel production

The agricultural sector is however not only consuming energy. More and more often, crops are cultivated for biofuel production. The energy embedded in the structure of the biomass, can be used for electricity generation or biogas production. However, given the high energy intensive agricultural production methods that are currently applied (see section 8.4.1.2), the energy used for crop cultivation outweighs the energy harvested (Gerbens-Leenes et al., 2009). One additional concern about bioenergy is that its land use requirement impinges on cropland. More on the competition over land between food and energy production can be found in section 8.7.1.

8.4.3 Food consumption and conversion of food waste into biogas

As we all intrinsically know, food contains energy. It keeps our human engine burning.
In 2009, the population of London, an estimated 7.8 million people, consumed food with a total energy value of about 11,500 GWh per year, which is 1,475 kWh/person/year (3,475 kcal/person/day) (Villarroel Walker et al., 2014). It is said that an average Dutch adult man requires to eat about 2500 Kcal/day. Given these data, we can either conclude that people tend to overeat, or that a large part of the food that is produced and supplied to the population is wasted. Each day the average American wastes food that represents 1520 Kcal out of the available 3976 Kcal/per capita/per day grown globally (WRI, 2013; Buzby et al., 2014; Sarker et al., 2016). It must be noted that individuals that adhere to an organic diet, are cutting on their indirect energy use, as organic food has an energy footprint that is typically 20%–70% smaller than that of conventional food (Pimentel & Berardi, 1983; Pimentel & Patzek, 2005; Flessa et al., 2002). This is mainly because organic agriculture abstains from synthetic fertilizers and pesticides, which require fossil energy for their production process.

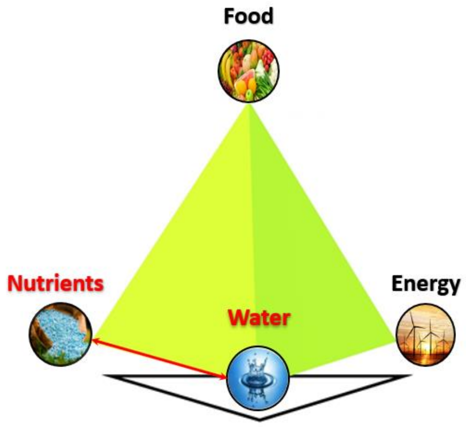
8.4.3.1 Biogas production from organic matter through anaerobic digestion

If food waste would be left untouched, the organically stored energy would dissipate as it perishes. However, the energy embedded in wasted food could also be captured. A part of the 'waste' is combusted in waste-to-energy facilities and an unknown quantity of food waste enters sewage systems for treatment where biogas can be harvested (Sarker et al., 2016).

Wastewater treatment plants that apply anaerobic digestion methods, can recover both energy and nutrients from organic waste stream, such as sewage (enriched with food waste).
During anaerobic digestion of organic matter, organic polymers are being converted into methane gas (CH_4) and carbon dioxide (CO_2) in four key stages; hydrolysis, acidogenesis, acetogenesis and finally methanogenesis (Sarker et al., 2016). As described in section 8.3.3 this process releases 0.35 litres of biogas (CH_4) per gram of COD removal and is an exothermal reaction, which means it can happen spontaneously.

8.5 Water – nutrients

8.5.1 Eutrofication



When excessive amounts of fertilizer are applied or when surface runoff is generated from cropland and grazing lands receiving manure, soluble nutrients can be transported to streams and other downstream surface waterbodies. High concentrations of nutrients in the water affect the quality of the water negatively and can result in eutrophication and deterioration of aquatic life which can have a negative effect on the fishery industry (Endo et al., 2017; Seitzinger, 2010; Kurian, 2014; Palhares et al. 2012).

8.5.2 Water as a transport medium

As explained in section 8.1.2 water is often used as a transport medium to carry food waste and sanitary waste towards a centralized treatment plant. Mixing grinded food waste with sewage to transport organic material to a wastewater treatment plant is quite common in the US. This method, however, requires large quantities of water and potentially extra energy-intensive boosters in the sewer system (Sarker et al., 2016). Transportation of organic waste to centralized digestors by vehicles, is expected to have a smaller water footprint, but is no less energy intensive.

8.5.3 Struvite harvesting

Nutrients, water and energy found in domestic wastewater are valuable and can be reutilized in agriculture (Miller-Robbie et al., 2017). When wastewater is treated anaerobically undegradable solids remain. When those solids are dewatered and thickened a liquid supernatant is produced that is rich in nutrients (Sarker et al., 2016; Campos et al., 2019). This supernatant waste stream must be treated prior to discharge to prevent eutrophication, but due to its high nutrient concentrations it could serve as a nutrient source for mineral struvite production, or as duckweed and algae feed which can be used as organic fertilizers. Harvesting nutrients from the effluent, for example by struvite ($MgNH_4PO_4 * 6H_2O$) formation (equation 10) kills multiple birds with one stone. It improves the water quality and recovers fertilizer, while saving energy that would otherwise be used for conventional aerobic treatment to get rid of nutrients.

Struvite, chemically known as magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4$) is a hydrate crystal containing an equal molar amount of magnesium, ammonium and phosphate, and is formed by the following reaction (STOWA, 2012; Rahaman et al., 2008):

$$Mg^{2+} + NH_4{}^{+} + PO_4{}^{3-} + 6H_2O \leftrightarrow MgNH_4PO_4 * 6H_2O \ (eq.10)$$

In recycle lines of anaerobic reactors, struvite precipitation is a common problem. After the anaerobic digestion process, whereby biogas can be produced, the supernatant contains high concentrations of phosphate and nitrogen in the form of ammonium. This is however favourable for nutrient recovery. When a magnesium ammonium phosphate crystallizer with a fluidized bed is placed after the digestor, an effective recovery of phosphorus (80–90%) can be obtained from the anaerobic digester supernatant (Adnan et al. 2003).

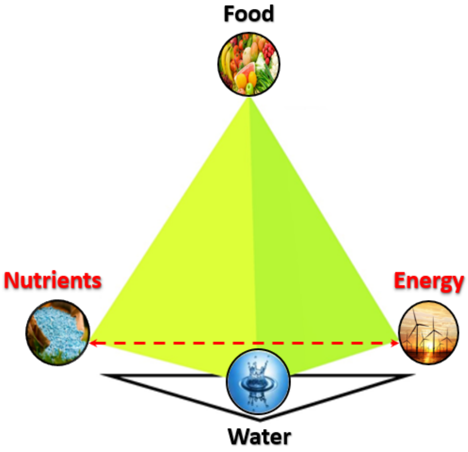
Struvite is highly soluble in acid solution, but precipitates in neutral and basic environments (STOWA, 2012). This characteristic provides the suitability of struvite as slow release fertilizer. Chemical modelling found that the optimum conditions for precipitation of struvite, occur at a pH of 9.0 (Miles & Ellis, 2001). At this pH dosing with magnesium, till at least a molar magnesium to phosphorus ratio of 1.05:1, results in up to 97% phosphorus removal as struvite (Jaffer et al., 2002).

Most domestic wastewaters do not contain the concentration of magnesium ions required to fulfil the stoichiometric requirements for struvite formation (Rahaman et al., 2008). Although struvite can be formed at any Mg:P ratio, for intentional struvite crystallization the Mg:P ratio should be at least be unity. When magnesium and phosphate were added in order to achieve an ammonium:magnesium:phosphate molar ratio of 1:1.25:1, the maximum ammonia removal of 88% was achieved at a pH of 9.5 (Miles & Ellis, 2001).

8.6 Energy – nutrients

In London, a case study pointed out that power generation by natural gas combustion is amounting to an annual nitrogen flow between 18 and 56 kilotons. Residential, industrial, and commercial natural gas consumption is releasing 62 -190 kilotons of nitrogen per year into the atmosphere (Villarroel Walker et al., 2014).

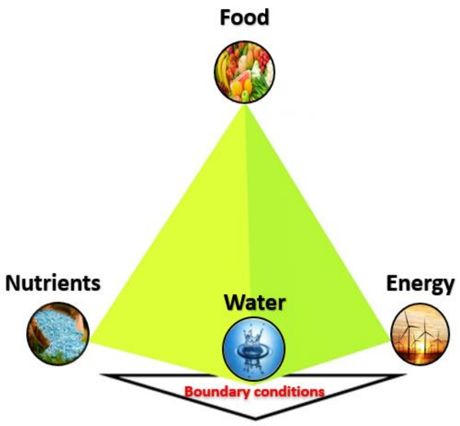
Although it must be noted that power generation and combustion of natural gas are responsible for large flows of nitrogen, in the context of the WEF nexus in relation to agriculture, the energy-nutrient relation is dominated by the energy required for fertilizer production (Villarroel Walker et al., 2014).



Fertilizer production requires energy. Together with the production of chemical pesticides and herbicides, it is the largest energy consuming activity in the agricultural sector at 30% to 50% of its total consumption (Fabiola & De Rosa, 2016; AGREE, 2015). The production of one kilogram of nitrogen fertilizer consumes 34 MJ. The energy consumption for the same amount of phosphate and potassium fertilizer is significantly lower at 8 MJ and 6 MJ respectively (Gellings & Parmenter, 2004).

Ronteltap et al. (2007) found that the enthalpy of a common fertilizer production reaction from urine, struvite formation, accounts for 22.6 (+/-1.1) kJ/mol. Since the value is positive this means that struvite formation is an endothermic reaction and that energy is absorbed inside the molecular structure when struvite is formed. On the other hand, the same amount of energy will be released when struvite molecules are being decomposed.

8.7 Boundary conditions



Although the land use dimension is not included in most existing nexus frameworks, land is another important determinant of global food security (Ringler et al., 2013; Kurian, 2014).

When land is viewed in the sense of space and is seen separately from its resource providing function, it becomes clear that it is, just like labour and capital, a boundary condition for activities in the WEF nexus. No flows of those finite commodities are taking place inside the nexus, however, their input is crucial for (economic) activity and (engineered) links in the WEF web to take place. Land needs to be available to accommodate the stocks and both labour and space are required for carrying out activities to accomplish certain links between or within stocks.

This relation between the boundary conditions with the rest of the WEF nexus has been visualized in the scheme in figure 23 as a separate base layer.

8.7.1 Landuse and the urban WEF nexus

Since this entire framework is talking about the WEF nexus in an urban setting, it only makes sense to shortly address the possibilities for integrating WEF solutions and typical urban challenges in spatial planning. Potential synergies between urban challenges and WEF solutions could not only result in a higher water and energy efficiency, but also in more efficient land management (Gondhalekar & Ramsauer, 2017).

Especially, climate change adaptation measures could well be combined with WEF solutions. Climate change leaves cities, compared to rural areas, increasingly vulnerable to heavy peak rains and excessive heat. Their high levels of built density and impermeable surfaces are resulting in pluvial flooding and the urban heat island effect (EEA, 2012; Kuttler, 2010). Urban farms could serve as a connecting activity that can defy different urban challenges, while supporting WEF circularity. Co-design of stormwater catchments and irrigation basins for farms could simultaneously reduce water nuisance and unsustainable water abstractions for agriculture. Moreover, a connection between the agricultural system and water management could reduce the demand for space, as less facilities have to be made compared to when an uncoordinated approach is applied.

In the same way, urban farms, as growers of edible green, can serve to restrict the heat island effect, while leaving space for recreational and/or economic activity (BMUB, 2015). Besides retaining rainwater and cooling of the microclimate, agriculture on green roofs can even combine even more co-benefits, as it supports the energy efficiency of buildings due to its insulating effect (Future Cities, 2013).

8.7.1.1 Competition over land between water, energy and food production

Abundance or shortage of land can influence decisions on and possibilities of connections between the different components in the WEF web. Land rearrangements and relocation of economic activities may reduce transportation distances for both inputs and outputs of agricultural activities, making the whole process a lot more energy-efficient.

The different dimensions in the nexus compete for land, as it is required not only to produce food or to live, but also to produce energy (e.g. for solar panel parks or to grow crops for biofuels) and to store water (Ringler et al., 2013). Not only above ground, also in the subsoil this competition continues, as in areas where shale gas is extracted, aquifers are at risk of contamination and water (and crops) grown in these regions are better not be used for human consumption.

Another important competition that exists in the tension field between food and energy is related to the space trade-off between food and biofuel crop cultivation. Given the land competition and the dependency of agricultural production on energy supplies, increased biofuel production can lead to both positive and negative effects on food security and water security (HLPE, 2013; Gerbens-Leenes et al., 2012; Scarlat et al., 2013).

Worldwide, approximately 38 % of the Earth's terrestrial surface (5.6 billion hectares), is used for crop cultivation (Kurian, 2014). The FAO (2015-2) estimated that the land area used for biofuels would increase by 775% between 2000 and 2020 to 35 Mha, accounting for less than 1% of the total amount of land currently used by agrosystems. It is predicted that biofuel production would account for more than 6% of the total cultivation area of wheat, maize, sugar cane and oilseeds in 2020 (OECD-FAO, 2007) and Bloomberg (2008) argued that about one-third of U.S. corn will be devoted to ethanol production by then. To protect food cultivation and security, it has been suggested that bioenergy production should be limited to land of marginal productivity (Zhuang et al, 2011; Campbell et al., 2008). However, it is possible that market mechanisms prove this solution unfeasible.

Economic drivers push farmers towards more efficient production methods. One way to accomplish a more efficient cultivation of crops, initially, is to create monocultures. The increase in efficiency that is accomplished by this uniformity of production, comes at the cost of an increased risk of crop disease and decline in biodiversity. Moreover, the phenomenon of increasing monocultures largely concerns energy crops and expels food production and emerges as a central interlinkage between the WEF nexus's sectors (Smajgl et al., 2016).

Hydropower is yet another form of energy production controversial for the trade-off between power generation and the availability of space for agricultural practices (Ringler et al., 2013). Large reservoir lakes replace land, potentially reducing crop production. On the other hand, besides generating power, hydropower dams could improve water availability downstream by serving as a storage basin for irrigation and flood control. Other forms of renewable energy production pose much less of a problem space-wise. Solar panels and wind turbines for example allow multipurpose land use enabling co-production of energy and food, due to their distributed nature (IRENA, 2015).

9 The position of urban agriculture in the WEF nexus

All agricultural production requires water, nutrients and energy (see chapter 8). For crops grown traditionally rain, irrigation, soil and solar radiation provide these resources. However, since a fair amount of agricultural manifestations in urban settings does not or cannot make use of the naturally delivered resources they have to be administered differently.
Fact is that these resources are abundant in urban environments, be it in currently unconventional forms, which can be harvested nevertheless. This chapter will look into the opportunities for resource harvesting in the urban realm, while solving other issues in that especially pose difficulties in urban areas.

9.1 Urban water & urban agriculture

Urban agriculture and urban water are two sectors in the urban economy that have the potential to complement each other. Heavy rain showers can cause damage in both rural and urban areas. However, in cities, the smaller infiltration capacity of abundant paved surfaces and the higher density of economic assets result in larger risks of water nuisance than in rural areas where water can infiltrate more easily and where the economic value per unit area is generally lower (Markovič, 2014). Therefore, many cities drain excess rainwater artificially and discharge (treated) wastewater inside natural streams traversing the area. All in all, urban areas are generally trying to get rid of water, whereas farms need water as an input. Rainwater harvesting, on built surfaces or through a stormwater sewer, cannot only fill the water storage for agricultural purposes, and thereby help farms to cover dry periods, it also has the ability to reduce the impact of heavy rain storms by decreasing the amount of runoff.

Water in conventional agriculture, is delivered to the crops as rain or by irrigation from (nearby) surface or groundwater sources. An additional advantage of farming in developed urban areas compared to conventional rural farming is that cities are generally connected to extensive (drinking)water supply systems which can often supply water to the population and crops in times of local drought. As a result of this luxury, many of the farming initiatives in urban areas can tap into the city’s water supply system and are not solely dependent on water supplied by rain or groundwater.

Moreover, in cities a vast amount of domestic wastewater is created by the human population. As a result, there is always a relatively constant base flow of omnipresent sewage that could be used for irrigation in times of drought.

9.2 Urban nutrient cycle & urban agriculture

Nutrients are another vital resource for crop cultivation and can be harvested from (domestic) wastewater streams as struvite which can serve as a slow-release fertilizer in agricultural initiatives. Wastewater is generally abundant in places where many people live together, and it contains substantial excreta and food waste that are nutrient-rich. Especially in urban areas in the western world there is even a collection system (the sewer) in place for these wastewater streams.

An alternative for struvite harvesting after anaerobic digestion, would be to compost organic materials found in food, garden and sanitary ‘waste’. During this natural process, the ‘waste’ is transformed into fertile soil which could be added to the soil-profile of open field and other soil culture farms.

Natural fertilizer based (urban) agriculture could reduce or eliminate the need for artificial fertilizer, and consequently reduce the energy and unsustainable mining that is associated with the production of synthetic fertilizer.

9.3 Urban energy & urban agriculture

Cities are generally big consumers of energy. However, this consumption does not only take place within city boundaries. Also, supply chains for resources and food require significant amounts of (fossil) fuels. Urban food production could reduce the energy footprint of a city by decreasing the number of road miles travelled by both inputs and outputs of the food industry, reducing the negative impact on the environment (Leung Pah Hang et al., 2016). By growing fresh food close to consumers, urban farming reduces or even eliminates the energy required for transportation, cooling and processing, while reducing traffic, a common problem in urban areas (Garnett et al., 2000).

Moreover, tapping into local urban waters to meet the water and nutrient demand of city-grown crops could potentially result in smaller energy needs for groundwater pumping and/or irrigation water transport in the agricultural sector. Besides, decentralized wastewater treatment at urban farms to ensure a steady supply of nutrients and energy (and potentially water) would reduce the need for wastewater transport, what would result in energy savings (Hanjra et al. 2012).

Furthermore, urban agriculture initiatives are generally quite small-scale, resulting in the application of less tillage machinery compared to conventional open field culture. Consequently, energy use for activities like ploughing is significantly reduced or even absent.

However, growing food inside cities consumes energy too. Moving food production into urban areas could increase the energy requirement of a city. Depending on the cultivation method, the energy demand for urban farms differs from the energy consumption in traditional open field agriculture.

When crops are grown in indoor facilities a whole new set of energy expenses is tapped into. When non-greenhouse indoor culture is the production method of choice, plants cannot make use of natural sunlight and the light source must be powered artificially.

Another factor that is often manipulated in indoor (urban) farms is the temperature. To ensure optimal climate and growing conditions for the crops (year-round), temperature regulation is often applied. Whether heat is added (in cold months/regions) or withdrawn by air conditioning (in warm periods/regions), artificial temperature regulation consumes energy.

Moreover, (indoor) hydroponic growing methods do require water to be circulated through a system with height differences. Besides, in multi-story farms water needs an extra lift from ground level to reach the crops. The height differences that need to be overcome require pumps to transport the water towards the plants. Along with the need for lighting and temperature control, this makes indoor culture a more energy-intensive activity than the mainly gravity driven, sunlight dependent growing operation in rural areas.

Depending on the farming system that is applied, additional energy needs to be imported or generated in the city itself to sustain urban agriculture. Fortunately, there happen to be plenty of possibilities to generate that energy, for example by extracting waste heat from industries or sewage or through anaerobic wastewater treatment, which results in biogas production. This gas can be burned to either create electricity or to heat (farm) dwellings.

9.4 Indirect relations with urban farming within the WEF nexus

Urban systems offer many opportunities for the realisation of sustainable agriculture in cities, as waste management and farming could mutually reinforce each other. Although the rise of widespread urban farming could increase competition over water, energy and nutrients in the city, it also helps to get rid of inconvenient abundances of the aforementioned resources.

Due to the intense interconnectedness between and within stocks in the WEF nexus, not only direct links between urban farming and the WEF nexus as described in this chapter exist. Developments elsewhere in the nexus can indirectly influence the availability of and demand for resources required in (urban) agriculture. Second and higher degree relations with urban farming can be derived from figure 22 in the framework.

10 Results & Discussion: Physical system

Boston

Boston is home to two of the three case study sites: community garden Eastie Farm and Corner Stalk container farm. The resource demand and availability near each site will be discussed separately. However, because the rainfall depth at both sites is considered the same, as the farms are located in the same neighbourhood, precipitation data are discussed first in a general sense. Site-specific rainfall volume data are discussed in the site-specific sections of this chapter.

Precipitation

Boston has a continental climate with warm and humid summers and cold and snowy winters. Annual rainfall measured at Boston Logan Airport in East Boston over the last 20 years amounts 1100 mm on average, with a minimum of 780 mm (in 2001) and a maximum of 1383 mm (in 2008). Precipitation falls year-round (fig. 30) with a relatively small variability throughout the year. The amount of rainwater falling in a certain month, however, is highly variable, with standard deviations up to 74 mm/month (March) during the 20-year measurement period that was taken into consideration. Monthly averaging points out that the wettest month is June (106 mm) and the driest August (79 mm). Extremes in monthly precipitation occurred in June 1999 when it did not rain for an entire month, resulting in a dry spell of 37 days and in March 2010 when a total of 378 mm was recorded.

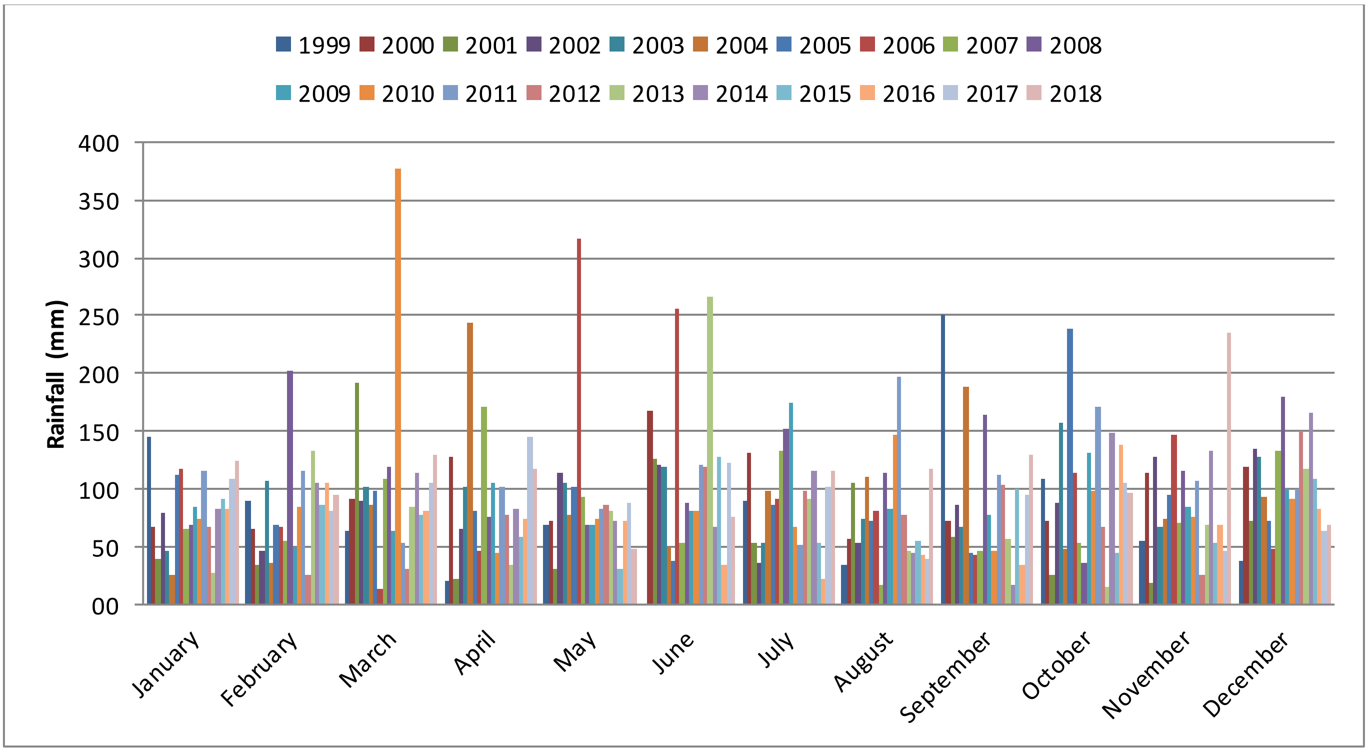


Figure 30 Monthly Rainfall in Boston

For open field culture the growing season starts at April 7 and finishes at November 7 and lasts for 214 days. The amount of rainfall during that period varied between 391 mm (2016) and 945 mm (2006) and averaged at 631 mm per season.

However, since Corner Stalk container farm is growing crops year-round, an analysis was made on the total amount of rainfall which would fall during a growing season of 214 days, starting every month (fig. 31). On average, those seasons had 644 mm of rain in store, with growing cycles starting in December being the wettest (670 mm) and those commencing in July being the driest (617 mm). This shows that the relatively long duration of growing seasons combined with the relatively constant rainfall during the year seems to level out seasonal variation in precipitation.

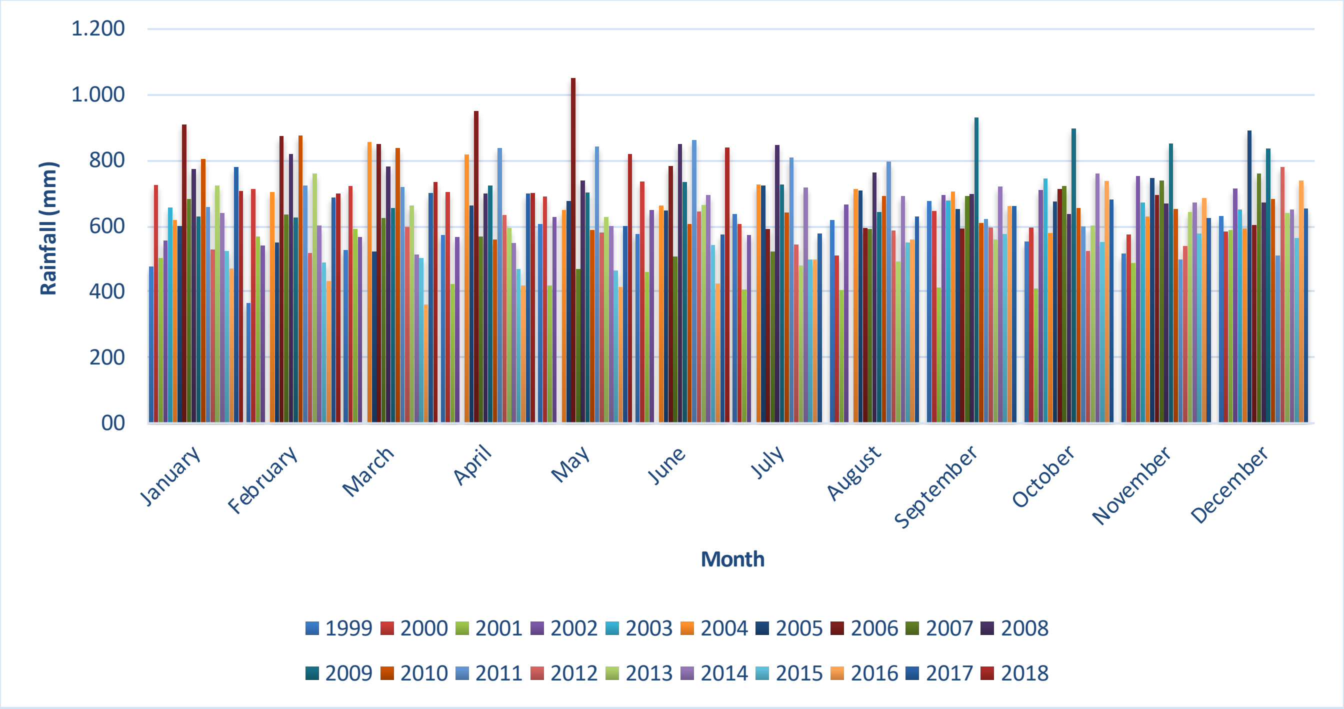


Figure 31 Rainfall in Boston during a period of 214 days starting every month

10.1 Eastie Farm

Open field community garden Eastie Farm in East-Boston had many systems in place to facilitate sustainable food production. This section will describe the farm's resource consumption as well as the resource availability in the farm's vicinity.

10.1.1 Required resources

At Eastie Farm several water meters were installed, which were read by farm volunteers on a regular basis. Moreover, they kept track of compost additions to the farm. Eastie Farm did not make use of any electrical equipment and therefore has no artificial energy requirements.

10.1.1.1 Water

Eastie Farm's water is supplied by precipitation falling on the fields and by manual irrigation of water captured on neighbouring rooftops (fig. 32).

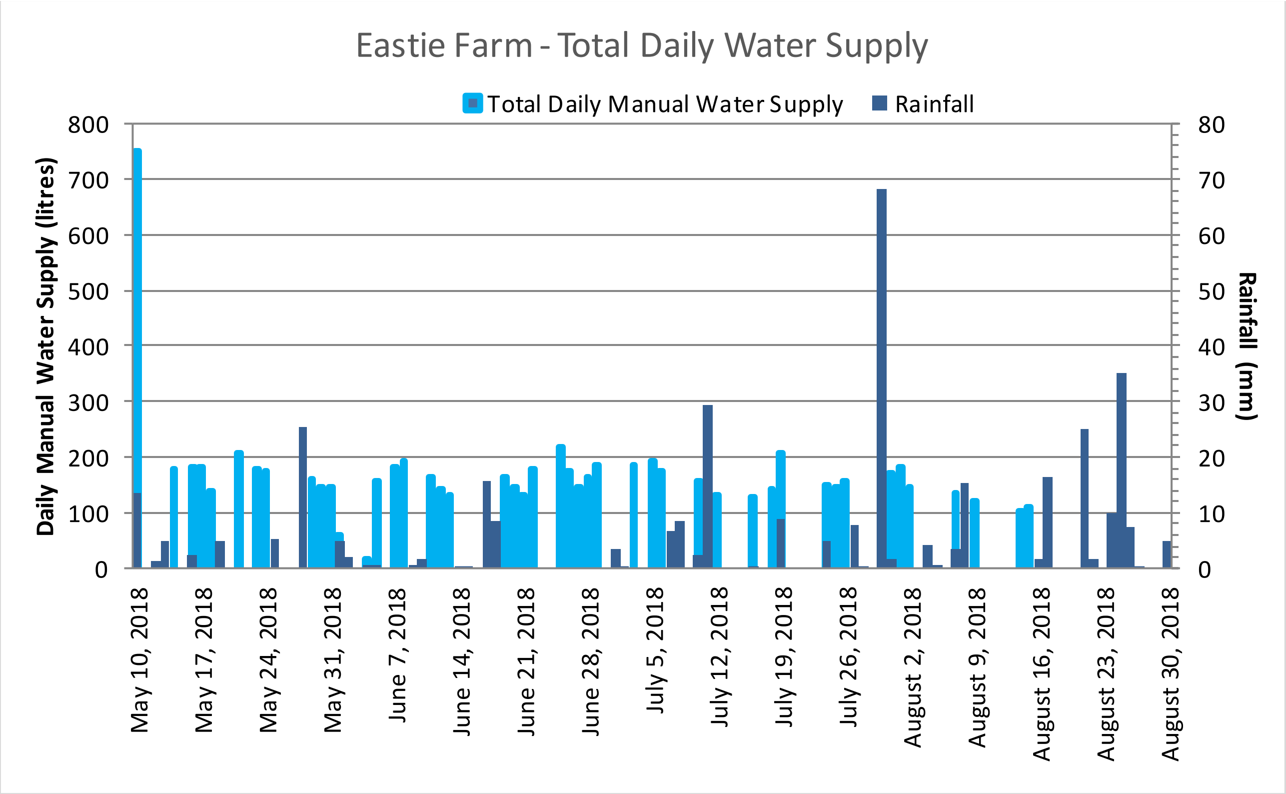


Figure 32 Rainfall and manual water supply to Eastie Farm during the 2018 data collection period

During the complete data collection period from April 28 till August 17 - a timeline that does not cover the entire growing season - in total 10,312 litres of precipitation watered the beds and 7,920 litres of water were supplied manually. The 750 litres peak in daily irrigation at the start of the season was recorded during the day that the majority of the seeds were sowed and included water needed for sheet mulching. During the remainder of the season, water was supplied manually with great regularity to sustain the crops. On days that water was added to the garden, manual water supply was on average 150 litres a day, the kick-of day not included.

It's clear that during extended periods of drought, like from mid-June till mid-July, the farm is dependent on stored water. During this period, the manual watering frequency was higher than during times with regular and sufficient rainfall. Surprisingly, there does not seem to be a correlation between the number of days since the garden last received rain and the amount of water that was added during a watering session. In this sense, watering seems to be a matter of routine rather than am activity synchronized with the weather situation.

As this research didn't collect demand data year-round, but aimed to simulate the potential storage over a multi-year timespan, the average water demand of the measurements taken during the summer were used as water demand input for days outside the measurement period. This required the assumption that the same crops were grown, in the same ratios, during the entire growing season, under the exact same climatic circumstances as during the study period. However, Eastie Farm is an open field farm and weather conditions have a great impact on crop water needs. In times of lower outside temperatures and less daylight hours than during the study period, plants transpire less. Since the average water demand measured during the summer was used as a water demand input for spring and fall, the water consumption during those seasons is likely overestimated.

10.1.1.2 Nutrients

Compost was added only during three occasions during the data collection period, totalling 25 gallons, among which 591 grams of nitrogen, 222 grams of phosphorus and 517 grams of potassium. On average, this is 5, 2 and 5 grams of nitrogen, phosphorus and potassium respectively during the entire data study period, whereas the maximum daily compost supply consisted of 355 grams of nitrogen, 133 grams of phosphorus and 310 grams of potassium.

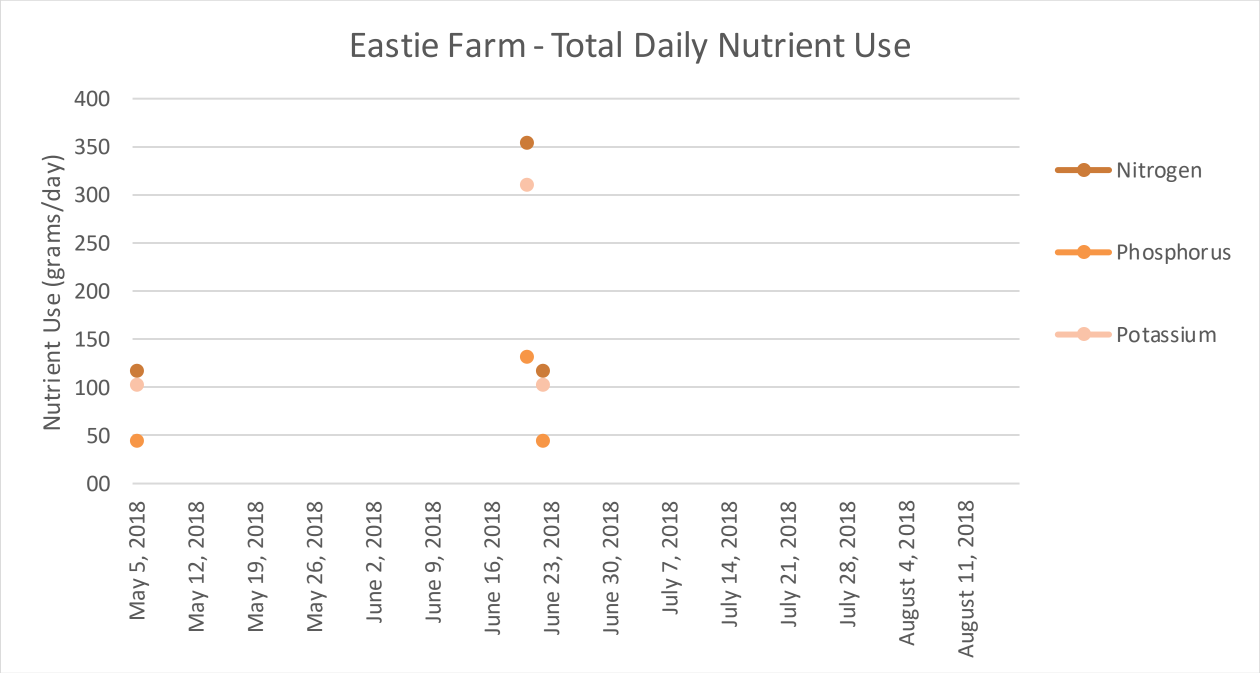


Figure 33 Nutrient additions in the form of compost at Eastie Farm

10.1.2 Available resources

Both nearby sewage flows and local precipitation patterns were studied to find out more about the local availability of resources. However, the difference in water quality made rainwater the preferred source for irrigation water, whereas sewage would only be used to meet nutrient demands.

10.1.2.1 Precipitation

Rainwater could be used to meet water requirements of Eastie Farm. It can be harvested from stormwater sewers, but since those are located a block away from the farm, nearby collection surfaces are considered a less complicated and cheaper option for rainwater collection. Table 20 and fig. 34 show the total surface area within Eastie Farm's housing block deemed suitable for rainwater collection.

	Rainwater catchment areas in the same block					
	Adjacent parcels	**<25 m**	**< 50 m**	**50-100 m**	**< 100 m**	**Farm**
Pitched roof (m^2)	50	91	300	700	1000	
Flat roof (m^2)	230	267	1392	2098	3490	
Raised beds (m^2)						29.7
Total catchment surface (m^2**)**	**280**	**358**	**1692**	**2798**	**4490**	**29.7**

Table 20 Surfaces suitable for rainwater collection within Eastie Farm's housing block

Figure 34 Flat (purple) and pitched (turquoise) roof surfaces within a 50-meter radius (inner circle) and a 100-meter radius around the farm and within Eastie Farm's housing block.

Not all water falling on these surfaces will be available for harvesting. Rooftop areas under investigation were multiplied by a runoff coefficient, depending on their slope (0.8 for flat roofs and 0.9 for pitched roofs). Subsequently, this effective surface was multiplied by the daily rainfall depth in order to determine the daily available rainfall volume.

The total available rainwater volume depends on the rooftop area at the farm's disposal, which on its turn should be in relation to the water needs of the community garden Due to this interdependence, water availability is discussed in section 10.1.3.1, in the assessment on the match between water demand and availability.

10.1.2.2 Sewage

Sewage will be analysed to see if it can meet the fertilizer demand of the community farm. Hence, this section will first look into the available wastewater quantity. Subsequently the sewage quality will be described.

10.1.2.2.1 Wastewater quantity

The volume of wastewater flowing past the farm was determined using the maps provided by the Boston Water and Sewer Commission (BWSC). These maps showed the outline of the sewer in the vicinity of the farm, but did not show the direction of the flow, nor the quantified volume.

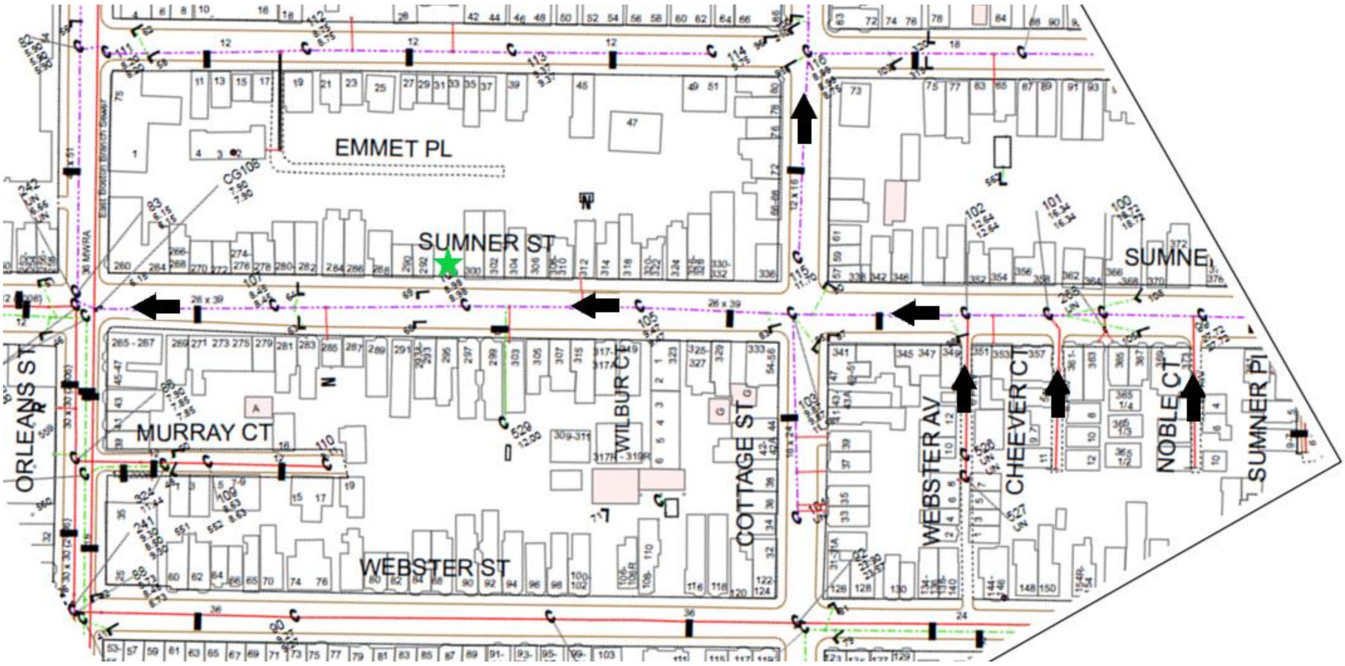


Figure 35 Sewer layout near Eastie Farm (green star) with arrows indicating flow direction from upstream sanitary sewers (red lines) and combined sewers (purple dotted line).

Flow direction, however, was derived looking at the layout of the sewer system. Collection systems start as a branched network. Branches are later united in increasingly bigger and more centralized pipelines. This means that the branched side of the system is the most upstream part. Sewage flowing in front of Eastie Farm thus originates from the east side of the neighbourhood, more specifically from Noble Court, Cheever Court, Webster Avenue, Cottage Street and the eastern part of Sumner Street (fig. 35).

The number of upstream housing connections to the sewer was determined by simply counting the number of houses in those streets on the BWSC map. Consequently, this number was multiplied by 2.36 persons per household, which is the average household size in Boston (Census, 2018). Local drinking water consumption amounts on average 41 gallon (155 litres) per capita per day (MWRA, 2016), resulting in a total daily dry weather flow of 42.8 m^3 in the sewer pipe in front of Eastie Farm (table 21).

Street	**Number of upstream connections**	**Estimated number of inhabitants**	**Estimated daily dry weather flow (litres)**	**Type of sewer**
Noble Court	5	12	1,829	Sanitary
Cheever Court	6	14	2,195	Sanitary
Webster	11	26	4,024	Sanitary
Cottage Street	21	50	7,682	Combined
Sumner Street	74	175	27,069	Combined
	Total	**Total**	**Total**	
	117	276	42,799	

Table 21 Origin and quantification of the dry weather flow in the sewer nearest to Eastie Farm

10.1.2.2.2 *Wastewater quality*

Wastewater from East Boston enters the Dear Island Treatment plant through the North System headworks (MWRA, 2017). A table containing data on the sewage quality in this system is shown in appendix 3b and shows that the wastewater influent contains on average 21.6 mg/L of ammonium, 0.25 mg/L of nitrate and 2 mg/L of dissolvable orthophosphates. Unfortunately, no data were provided on potassium presence in the sewage. The average chemical oxygen demand (COD) amounts 399 mg/L.

Pollutant	**Load (gram/day)**	
Ammonium – nitrogen	Minimum	261
	Average	924
	Maximum	1374
Nitrates	Minimum	0
	Average	11
	Maximum	142

Pollutant	**Load (gram/day)**	
Orthophosphates	Minimum	21
	Average	86
	Maximum	137

Table 22 The total load of several 'pollutants' in a wastewater flow of 43 m^3 *per day in Boston, based on minimum, average and maximum daily concentrations*

Table 22 shows the total load of several 'pollutants' in a wastewater flow of 43 m^3 per day, based on minimum, average and maximum daily concentrations of the constituents. Nitrate loads are two orders of magnitude smaller than ammonium loads, and therefore considered negligible. Average daily nutrient loads amount 924 and 86 grams for ammonium and orthophosphates respectively, equalling 718 grams of nitrogen and 28 grams of elemental phosphorus, given their mass ratio as expressed in equation 11.

$$Mass\ ratio\ of\ phosphorus\ in\ orthophosphate\ (PO_4{}^{3-}) = \frac{30.97}{30.97 + 4 * 16.00} = 0.326\ (eq.11.1)$$

$$Mass\ ratio\ of\ nitrogen\ in\ ammonium\ \left(NH_4{}^{+}\right) = \frac{14.01}{14.01 + 4 * 1.008} = 0.777\ (eq.11.2)$$

10.1.3 Match resource requirements and resource availability

In this section the resource demand and availability in the area will be compared in order to find out if sufficient water, energy and nutrients are present in the urban waters surrounding the case study site.

10.1.3.1 Water

The dimensioning of the area that was required to match water demand and supply was approached by minimizing the difference between collected rainwater and water use at the farm. It was assumed that water demand took place between April 27 (first day water demand was recorded) till November 7 (the last day of the frost-free growing season), whereas rainwater was harvested year-round. The rainwater availability was calculated for a wide range of surface areas. Subsequently, the water needs for the case study farm were subtracted.

The surface area of the water catchment which could meet the water demand year-round in all the 20 years for which rainfall data were analysed is called the break-even surface. If 100% of the rain falling on that surface is captured, the water demands for the farm could be met during all 20 seasons under investigation. This method assumes no evaporation from the surface and no water remaining on the roof. The break-even surface for Eastie Farm is 154 m^2.

As shown in fig. 36, rainwater could already have been caught before the start of the growing season in each of the 20 years under investigation. Even in 2001, the year with least rainfall at the beginning of the season, a rainwater catchment area of 154 m^2 would have captured 2,855 litres of water before farming activities had kicked off and would have ensured the availability of enough rainwater for the farm to fulfil its needs.

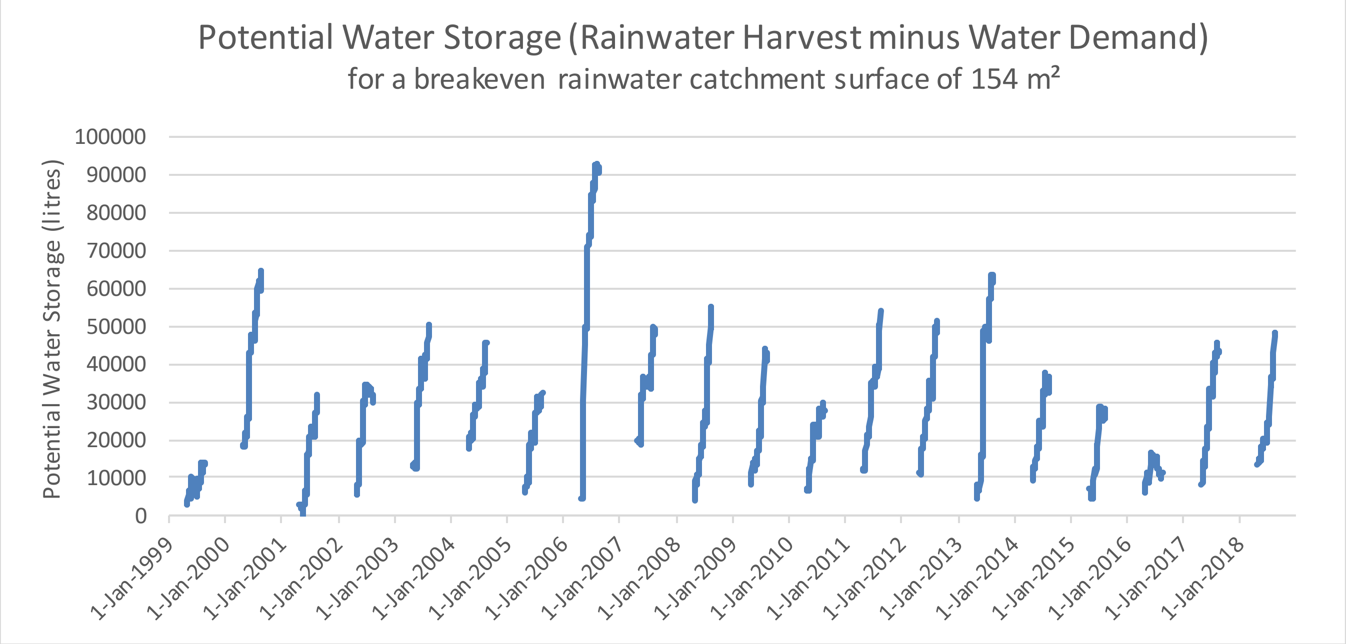


Figure 36 Potential rainwater harvest with a break-even surface of 154m^2 for rainwater collection that would have met water demand at Eastie Farm from 1999 till 2018. Data run from April 28 (when water demand starts) till August 17 (when water demand data end) every year. The offset of each line represents the potential storage build up since April 7 (when the frost-free season starts).

Larger catchment areas (if connected to sufficient storage capacity) increase the rainwater availability throughout the growing season (fig. 37). Smaller areas, like the raised beds themselves, are not able to provide enough water for the farm.

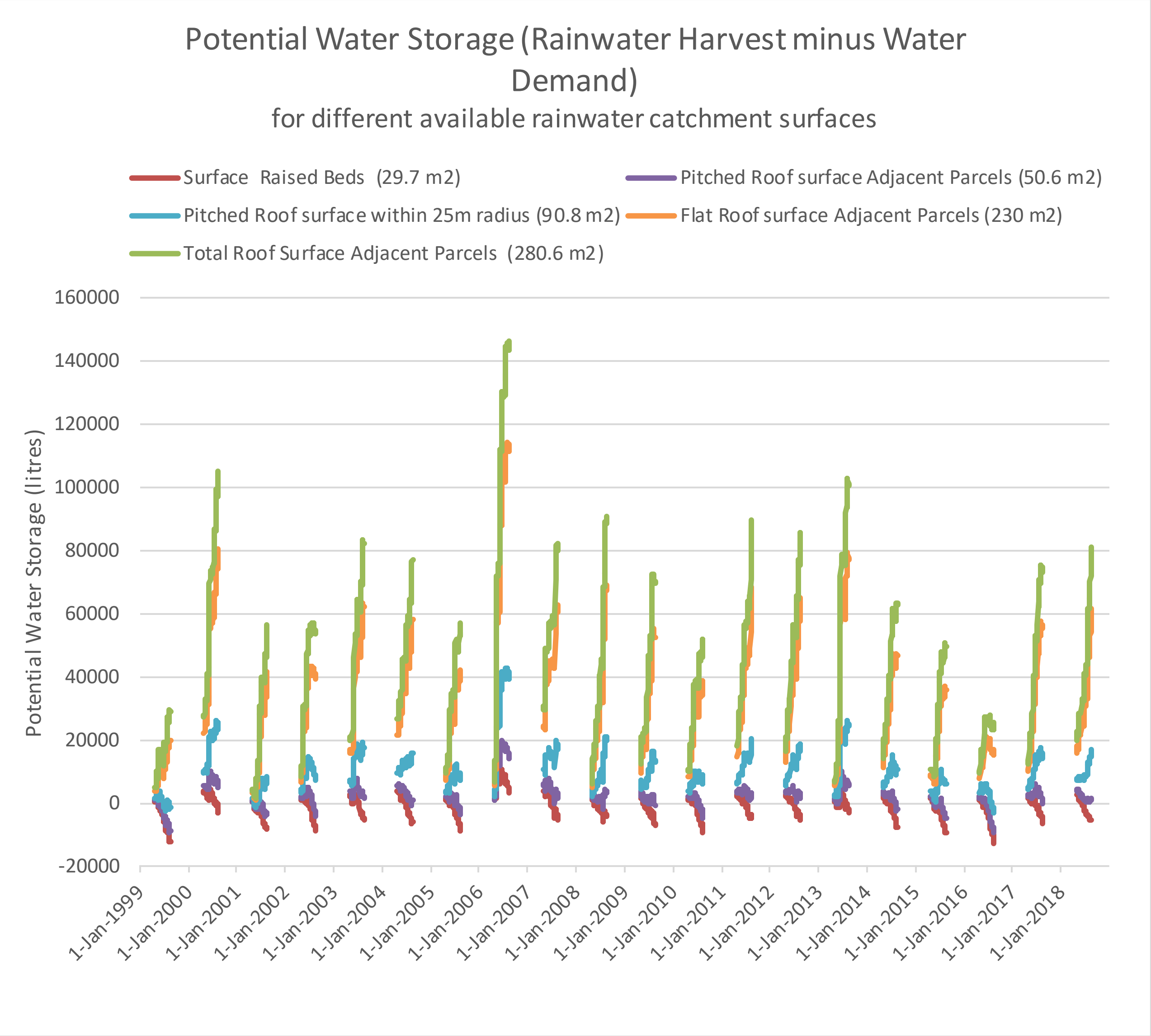


Figure 37 Potential storage of rainwater for different rainwater collection surfaces at Eastie Farm from April 28 (when water demand starts) till August 17 (when water demand data end) every year. The offset of each line represents the potential storage build up since April 7

Figure 37 shows that generally the water volume that can be stored keeps building up during a growing season (when a sufficiently large catchment surface is connected to the storage). Consequently, most seasons end with significantly more water in store than they had at the start of the season, as rainwater availability exceeds water demand when connected to the breakeven water collection surface. Moreover, in the previous figures, the potential storage build-up during the post-season is not even included. Altogether, this shows that not all water reserves which could be created are used and consequently, that not the entire rainfall harvesting capacity needs to be stored to sustain crops during dry periods.

10.1.3.1.1 Storage requirements

When a continuous simulation is made for the storage during the year, including both the growing season and the post-/pre-season, it becomes evident that the storage capacity required to overcome the largest decline in potential storage, which occurred in 2016, amounts 6,812 litres of water (equalling 33 55-gallon barrels), using the breakeven water collection surface of 154 m^2 (see fig. 38). Allowing a water shortage once every 20 years would result in a significantly smaller storage requirement of 5,729 litres. This amount of storage would be sufficient to cope with a dry period like the one in 2007, but would result in a water shortage of 1,083 litres in 2016. Since the frost-free growing season started before the farm started to water the crops, water reserves started to build at the beginning of the first growing season of the rainfall records (fig. 38). In following years, a reoccurring pattern of water abstraction during the growing season and water refill in the post-season can be noticed

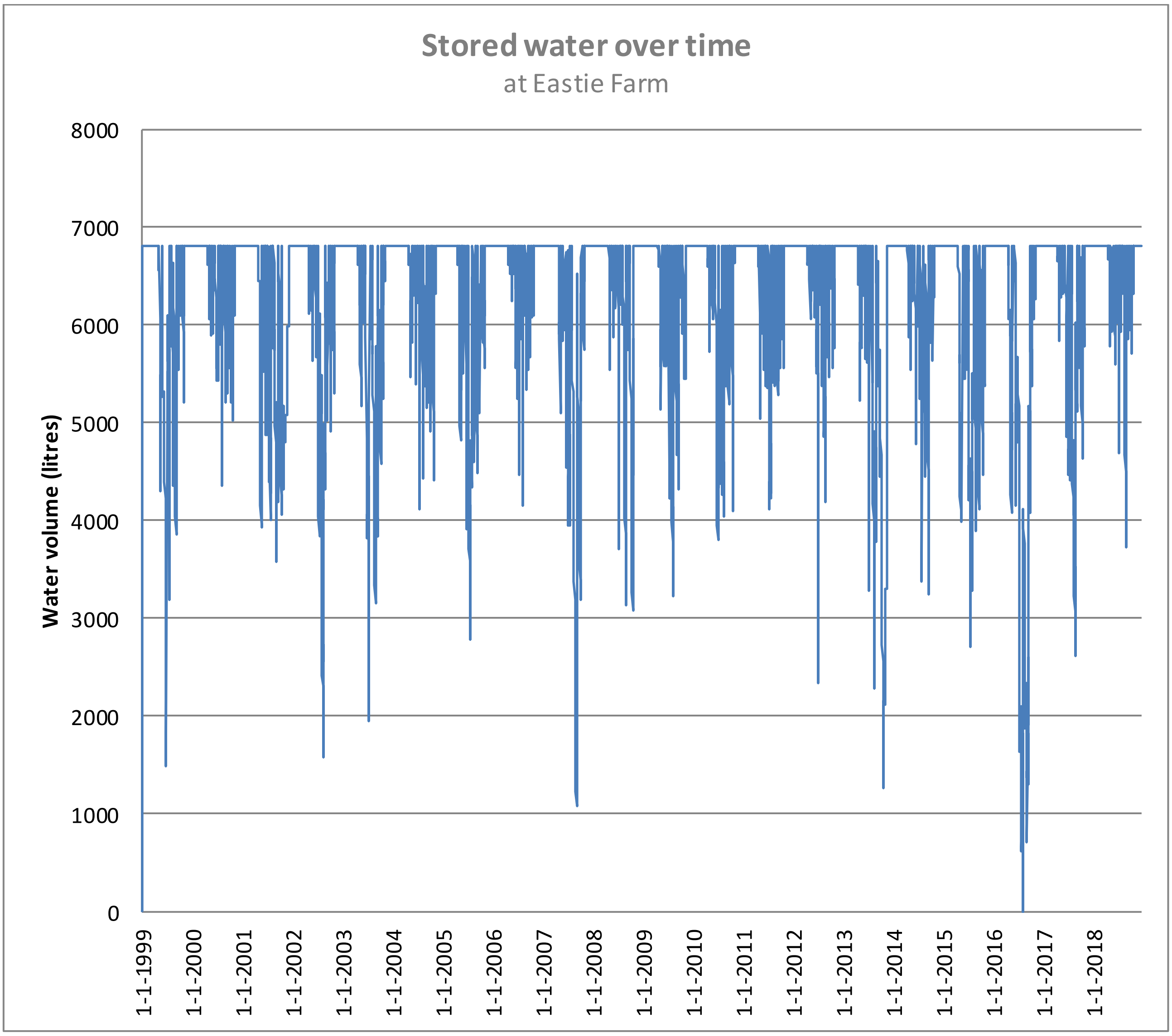


Figure 38 Stored water over time, based on a catchment surface of 154m^2 and maximum storage volume of 6,811,5 litres

10.1.3.1.2 Storage solutions

In short, Eastie Farm needs a significant expansion of the storage capacity to avoid water shortages. If the captured water is stored where it is caught - at a higher altitude than the raised beds - gravitational flow could transport the water to its destination, reducing the need for artificially generated energy. However, common rooftop storage options, like storage on roofs or even the creation of a green roof sporting a layer of sponge or gravel substrate with root canvas and crops on top, are not considered feasible. Buildings in the area seemed too weak to carry the extra pressure created by stored water in combination with the dead load for the construction.

Underground water storage could be an option too, although it needs to be realised in a closed tank to avoid contact with the polluted soil in the area. Moreover, underground storage would require pumps to transport the water back up to ground level for watering crops. However, from a WEF nexus perspective, this set-up is preferably avoided as it would improve water security at the expense of draining the energy stock. On the other hand, underground storage could work, when use is made of a manually operated pump.

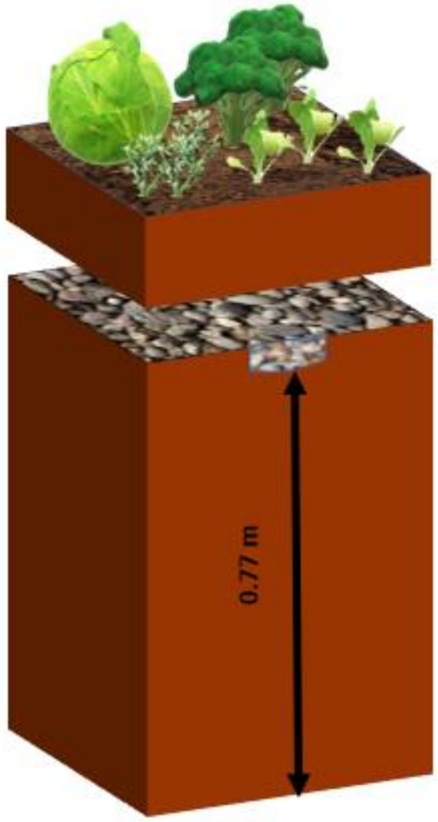


Figure 39

Suggested storage solution at Eastie Farm: a gravel filled basin of 77 cm high underneath the soil bed in which crops are sowed.

A less costly storage solution could be realised on ground level, for example by installing more water barrels like the ones that are already in use. The question is, however, where to put a total of 28 to 33 of those barrels (depending on whether a water shortage is allowed once every 20 years or if deficiencies are completely avoided). The farm's premises are already crammed with raised beds, pots, footpaths and compost containers and no public open or green spaces, except for a small parking lot, are present in the densely built block surrounding the farm.

When a connection can be made between the neighbour's flat roof (230 m^2), the total required storage volume (6.8 m^3) could be created in or underneath the crop cultivation beds, which extend over 29.7 m^2. If empty tanks were to be installed underneath the raised beds to store this amount of water, technically the tank would need to be able to hold a total water depth of 0.23 m. To make it easier for plant roots to reach water reserves in times when the water level in the storage is low, the tanks need to be filled with a soil medium. When choosing a soil material, soils with a high porosity, like gravel (~30%) are preferred. A gravel filling would result in a final height requirement of 0.77 m for the water storage tank (fig. 39). Above this height an overflow spill needs to be created in the tank to avoid the crops in the bed above from drowning.

10.1.3.2 Nutrients

Sewage can ensure an ample supply of nitrogen and phosphorus to Eastie Farm's community garden (no data were known about potassium availability). The average sewage concentrations show that wastewater can supply a daily nutrient load of 718 grams of nitrogen and 28 grams of elemental phosphorus. This can not only provide for the average daily demand of 5 grams of nitrogen and 2 grams of phosphorus, but could also provide enough nutrients to meet extreme daily demands of 355 grams of nitrogen. Peak demands of 133 grams of phosphorus fertilizer, however, cannot be met by the wastewater stream.

As the wastewater influent at the central treatment plant contains on average 0.7 mg/L of phosphorus and 16.8 mg/L of nitrogen in several molecular configurations, the average daily nitrogen demand can be met by recovering nutrients from 298 litres of sewage. Sufficient phosphorus recovery requires treatment of 2,857 litres of wastewater (if 100% recovery can be assured), where 43,000 litres are available.

Nevertheless, it must be noted that this analysis makes use of average concentrations in the wastewater at the inlet of the wastewater treatment plant. During rain events concentrations in the combined sewer are likely to be significantly lower (minimum values of 6.1 mg/L of ammonium and 0.5 mg/L of orthophosphate are recorded). A local treatment facility with a 2,857 litre treatment capacity will therefore not be able to supply the average fertilizer demand load during rainy periods. In order to always be able to provide average demands, 10,551 litres and 12,270 litres are needed for the recovery of nitrogen and phosphorus respectively.

The question is, however, if a steady daily supply to meet the average demand is needed. Currently, the farm runs perfectly fine with discontinuous peak additions of compost to accommodate nutrient needs as compost is a slow release fertilizer. Although a steady, continuous supply would decrease the risk of nutrient leaching from the soil, a fluctuating nutrient provision depending on the concentration in the sewage was considered sufficient and more financially attractive. Therefore, a treatment facility able to treat 2,857 litres of sewage (or an equivalent of that depending on the nutrient recovery efficiency) was deemed adequate.

10.1.4 Yield and water efficiency

Eastie Farm cultivates various edible crops ranging from fruits to vegetables and even herbs. In total 350 kg (770 lbs) of fresh produce was harvested. In appendix 4b the itemized seasonal yield is shown.

In order to calculate the theoretical resource requirement of the farm, crop factors for different growing stages of each of the harvested crops were searched for. However, this information could not be found for garlic, beets, kale, herbs, cherries, berries, pears, sprouts and cauliflower. Nonetheless, the efficiency analysis was executed for the remaining crops. Although the remaining crops hold the majority of the yield weight (61%) it must be kept in mind that the outcome of this analysis would largely underestimate the efficiency of the farm, due to this assumption.

Assuming crops were sowed on April 7 (immediately at the start of the frost-free growing season), the total theoretical (evapo-)transpiration depth, calculated using the Blaney-Criddle method described in the methods, ranged between 395 mm for spinach and 619 mm for dry onions (table 23).

	Carrots	**Peas**	**Spinach**	**Onions**	**Greens**	**Cabbage**	**Squash**	**Tomatoes**	**Cauliflower**
Transpiration depth (mm)	608.5	470.5	395.0	618.9	493.3	607.3	441.1	594.2	
Theoretical surface requirement (m^2) (based on FAO yield density data)	3.8	9.0	5.9	1.4	15.9	1.9	21.0	6.3	4.8
Approximated cultivated surface area (m^2) (Theoretical surface requirement scaled back based on available space)	1.2	3.0	1.9	0.4	5.2	0.6	6.8	2.1	1.6
Transpiration volume (L)	746.4	1388.3	757.0	274.7	2560.5	378.7	3020.1	1221.9	

Table 23 Total theoretical transpiration depth and volume per crop during the measuring period from April 28 till August 17

To convert this transpiration depth into a transpiration volume, the cultivation surface for each crop had to be known. According to the FAO's yield density data 91 m^2 of growing area is required to produce the garlic, cauliflower, carrot, pea, spinach, onion, lettuce, cabbage, squash and tomato harvest that Eastie Farm recorded (FAOSTAT, 2017). This area exceeds the 29.7 m^2 of raised beds present at the farm, even though the area needed to grow beets, kale, herbs and sprouts is excluded because of the lack of FAO data. Therefore, it is safe to say that the crop density in the raised beds at Eastie Farm must have been higher than the average crop density of American agriculture.

Since only 29.7 m^2 was available for crop cultivation at the community farm, it was decided to proportionally scale down the theoretical surface requirement per crop by a factor 29.7/91 in order to approximate the true cultivation surface per crop. Using the scaled down surface areas a total water need of 10,348 liters was computed by this theoretical approach.

During the same time period, on-site measurements showed that 7,921 liters of water were supplied manually by volunteers. Moreover, 10,312 liters of rain fell on the raised beds, which means that in total 18,233 liters of water were in fact supplied to the crops during the measurement period. All things considered, these data suggest a water efficiency of 57%, which should be a considerable underestimation given all the assumptions made.

An average water use of 52 L/kg of produce was recorded, which is way more efficient than the modelled conventional water use of 250 L/kg that Barbosa et al. (2015) suggest. All in all, the water supply at Eastie farm seems to be highly efficient for an open field farm. In fact, the water efficiency is so high, that one starts to doubt the records on manual water supply. Given the community operated nature of this farm, resulting in a vast number of volunteers helping to sustain the crops, it would also come as no surprise when not all water additions were registered.

10.2 Corner Stalk Farm

Corner Stalk Farm in East-Boston makes use of many high-tech techniques to facilitate optimal food production year-round. As an indoor farm, Corner Stalk had to make use of a range of artificial resources. This section will describe the container farm's resource consumption as well as the resource availability in the farm's vicinity.

10.2.1 Required resources

Water, energy and nutrients were all added to the crops to make them thrive.

10.2.1.1 Water

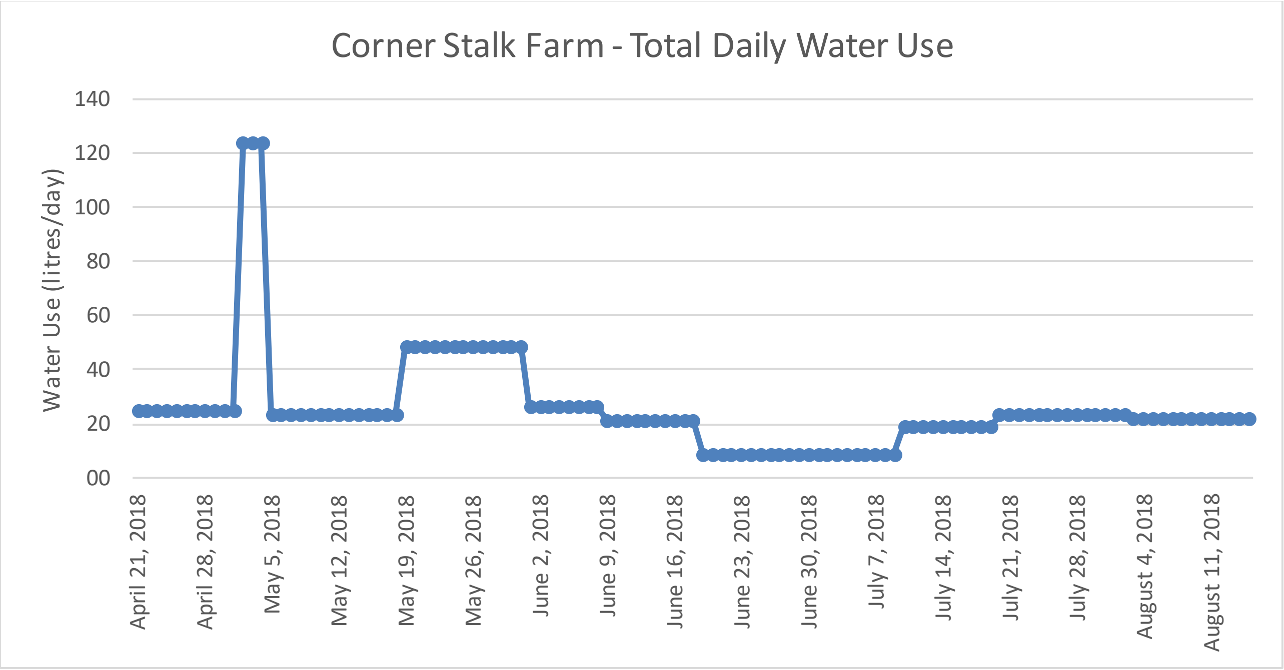


Figure 40 (Averaged) daily water use at Corner Stalk Farm

During the 117 days between April 21 and August 15, a total water consumption of 2,974 litres of water was recorded at Corner Stalk Farm, resulting in a daily average of 25 L/d. Generally, the daily water consumption varied between 8.5 and 48.4 L/d, with outliers of 124 L/d during 3 days at the start of May (fig. 40). This peak period in water demand coincides with some warm days. Therefore, the high temperatures might have resulted in higher transpiration rates and consequently in a higher water loss to the system.

Surprisingly though, summer months June and July, which are generally warmer than May, record a lower average daily water use than May. Hence, a higher transpiration rate probably only explains a part of the peak demand in May. A leakage or a water system flush seems more likely.

Moreover, it was bore in mind that there is a possibility that during the summer months, after the researcher had left the area, water use was registered less consistently. This could have resulted in an overestimation of the time between consecutive water replenishments, underestimating of the total and average daily water use over the summer.

As this study did not collect demand data year-round, but aimed to simulate the potential storage over a multi-year timespan, the average water demand of the measurements taken during the summer were used as water demand input for mid-August till late April. This required the assumption that the same crops are being grown, in the same ratios, during the entire year, under the exact same climatic circumstances as during the study period. The vast amount of LED lights at Corner Stalk Farm provided enough heat to grow crops even during the coldest months and since no use of natural sunlight was made, the reduction in daylight hours during winter did not affect crop production either. Therefore, the water demand during months that no measurements were taken were considered to follow the same pattern as during the study period (late April till mid-August). Consequently, these assumptions seem reasonable.

10.2.1.2 Energy

During the 113 days that electricity use was measured at Corner Stalk Farm a single container consumed a total of 14,958 kWh. Over the course of the study period, the energy demand rose from 95 to 142 kWh/d, resulting in an average daily energy consumption of 131 kWh per container (fig. 41). Only at the start of May a small peak in daily energy consumption was noticed. Both this peak and the relatively high energy consumption during the last data stretch coincide with some very warm spring days with temperatures as high as 34° (93F) and the generally warmer summer months respectively. This observation, combined with empirical knowledge of the farmer in the past, raise the suspicion that the increase of energy consumption during the season can be attributed to a larger electricity need for air conditioning. Moreover, the water consumption during these times was higher than average, resulting in higher energy needs for operating pumps to circulate the water through the farm.

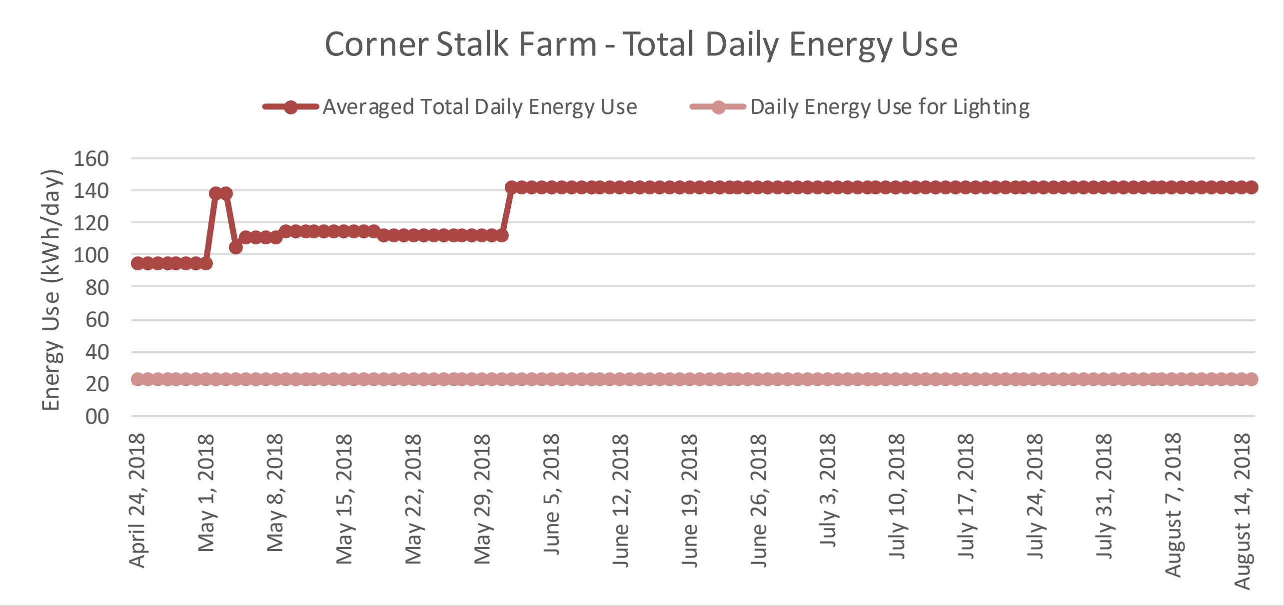


Figure 41 (Averaged) daily energy use at Corner Stalk Farm

Energy requirements for lighting were assumed to be fairly constant as the LED lights are switched on 24/7. LED lights in one half of a container drew 2 amperes and the electrical circuit at the farm ran at 240 V. By simply multiplying the current and the voltage operating the lights, a daily energy consumption of 23 kWh for the lighting at each (whole) container was calculated.

10.2.1.3 Nutrients

Nutrients are added to the system by automated dispensers. Data on the daily release of these dispensers were not available. However, data on the replenishment of the dispensers were recorded, allowing to calculate the average daily nutrient supply in the time period between each refill. During the data collection period, more than 2 kg of fertilizer were added to the container under investigation. Due to the fixed composition of the nutrient powders and the consistently equal supply of the resulting solutions, the ratio between the three analysed nutrients was assumed to always remain constant, resulting in a total addition of 214 grams of nitrogen, 40 grams of phosphorus and 361 grams of potassium. The mean daily consumption of nitrogen, phosphorus and potassium amounted 1.8, 0.3 and 3.1 grams respectively, with maximum daily demand values of 7.9, 1.5 and 13.4 g/d (fig. 42). These peak demands coincide with the peak demand in water consumption, as described in section 10.2.1.1. This overlap is hardly surprising, as the EC of added tap water needs to be increased to comply with the desired value for optimal crop production.

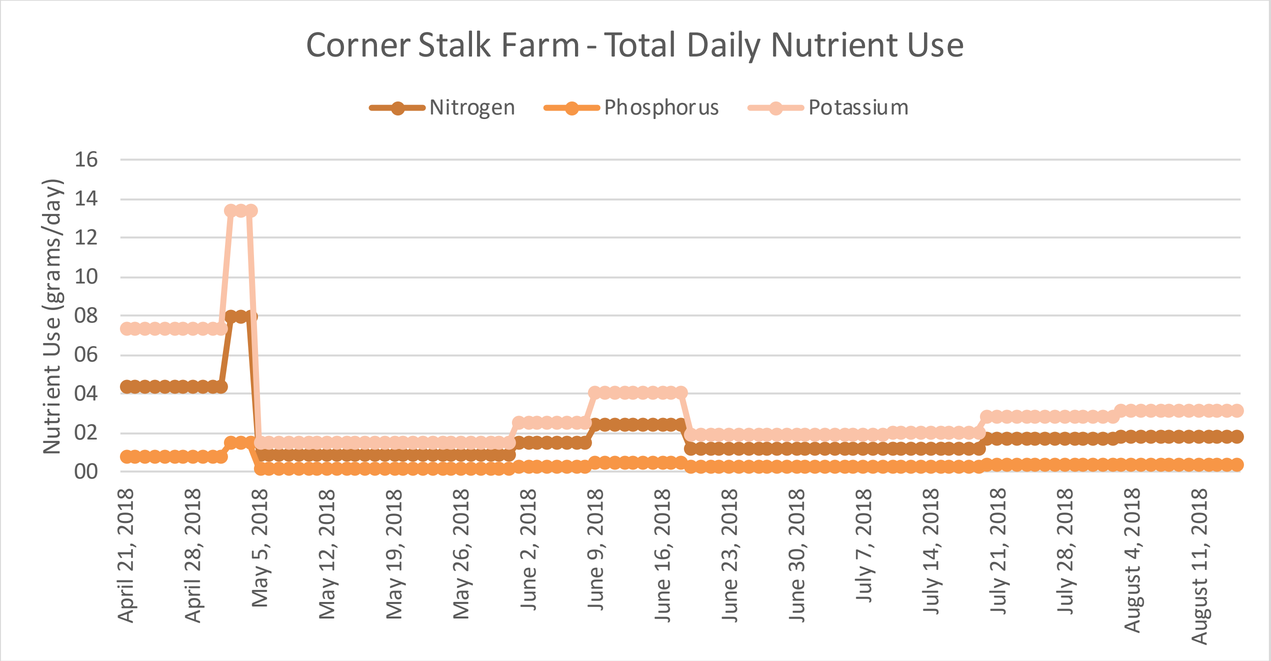


Figure 42 (Averaged) daily nutrient use at Corner Stalk Farm

10.2.2 Available resources

Even though resource needs per unit crop are way smaller at the container farm than in conventional open field agriculture, they need to be supplied nonetheless. Two main sources of water, nutrients and energy were studied in the area surrounding Corner Stalk Farm: rainwater and sewage.

Both precipitation and (sanitary) wastewater could be used to meet agricultural water needs. However, because of its less polluted nature, the better water quality of rainwater made it the preferred source for irrigation. As will turn out in the following section, precipitation can provide enough water to the farm to accommodate the water demand. Therefore, water in the form of wastewater will only be analysed as a source of energy and nutrients, but will be left out of consideration during the water availability discussion.

10.2.2.1 Precipitation

As Corner Stalk Farm is situated in a densely built area, the possibilities for rainwater harvesting on rooftops are plentiful (figure 43 & table 24).

However, unlike Eastie Farm, Corner Stalk Farm is a commercial farm, which might affect the willingness of nearby property owners to outsource the rooftop of their dwelling for rainwater collection for crop production. Anyway, to avoid any dependencies, it is best to arrange a water supply system which doesn't rely on third parties. Catching water on the rooftop of the containers themselves (35m^2 per container) and creating water storage facilities on the farm's premises would do exactly that.

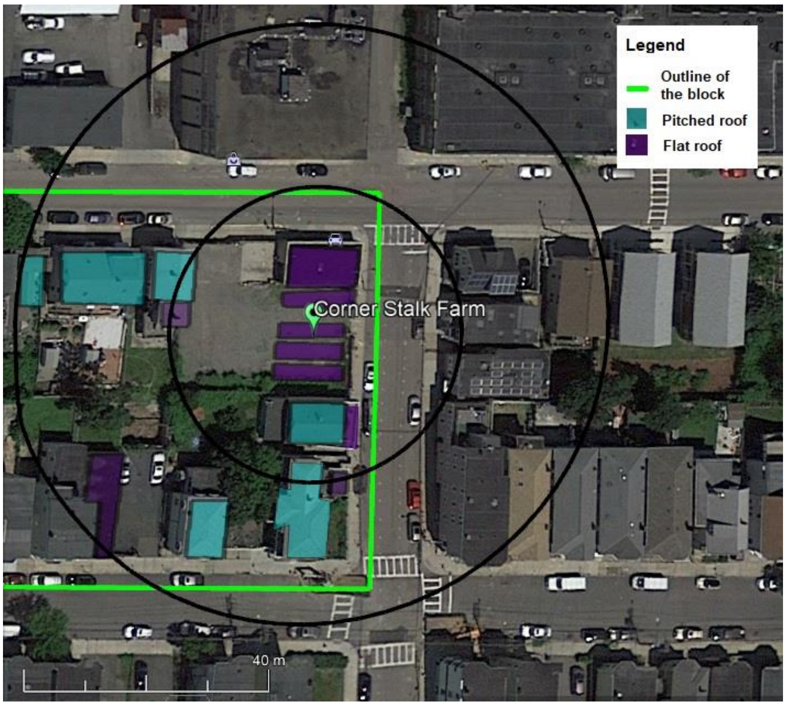


Figure 43 Flat (purple) and pitched (turquoise) roof surfaces within a 25-meter radius (inner circle) and a 50-meter radius around the farm, within Corner Stalk Farm's housing block

	Rainwater catchment areas (m^2)			
	Farm	**Adjacent parcels**	**< 25 m**	**< 50 m**
Pitched roof (m^2)	0	120	64	451
Flat roof (m^2)	140	111.3	233.7	326.4
Total area (m^2)	140	231.3	297.7	777.4

Table 24

Quantification of surfaces suitable for rainwater collection within Corner Stalk Farm's housing block

10.2.2.1.1 Water availability from precipitation

At the beginning of chapter 10 rainfall patterns for East Boston are depicted. These patterns multiplied by the 35 m^2 flat container roof surface that served as rainwater catchment area, represent the water availability for each container unit. More information about the availability of rainwater in relation to the water demand at Corner Stalk Farm is provided in section 10.2.3.

10.2.2.2 Sewage

The quantity of sewage present in the area was studied to get a grasp on the energy and nutrient availability. The sewer system near Corner Stalk Farm has a complicated layout, as during the data analysis period both combined and separated sewer pipelines are present. Because of the more concentrated sewage solution and the more constant flow, which are both practical features for treatment and resource recovery purposes, the sanitary sewer was considered the best 'waste' stream to tap into for energy and nutrients.

10.2.2.2.1 Sewage Quantity

The volume of separated sanitary wastewater flowing past the farm was determined using the maps provided by the Boston Water and Sewer Commission (BWSC). These maps showed the outline of the sewer in the vicinity of the farm, but did not show the direction of the flow, nor the quantified volume. Flow direction was derived looking at the layout of the sewer system. At the intersection between Condor St. and Brooks St. a sanitary sewer pipeline merges with a combined sewer pipeline. Since a sanitary sewer is generally not constructed to deal with the highly fluctuating flows of a combined sewer, from this information was derived that the upstream direction was eastward. The sanitary sewage in front of Corner Stalk Farm thus originates from Putnam Street and the eastern part of Condor Street (fig. 44).

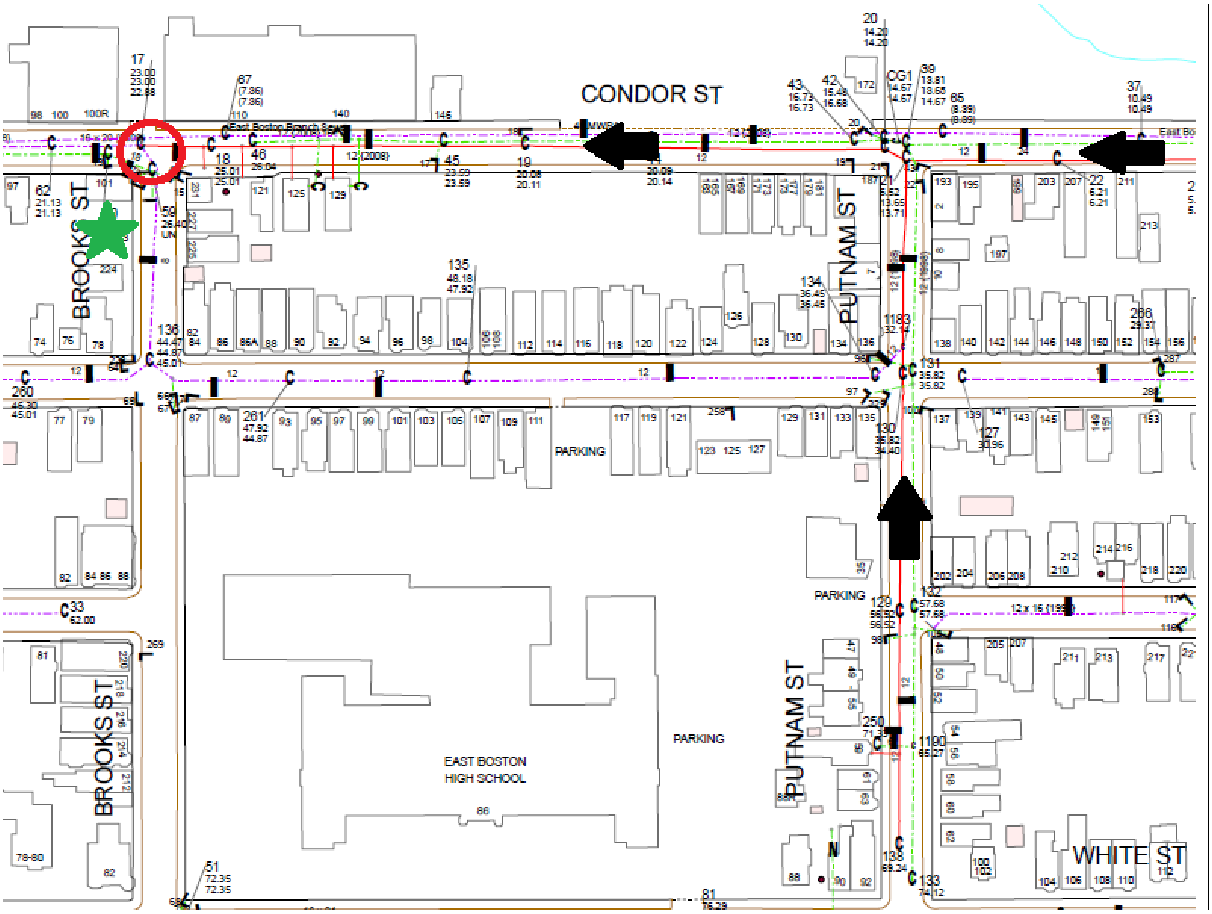


Figure 44 Sewer layout near Corner Stalk Farm (green star) with arrows indicating flow direction from upstream sanitary sewers (red lines) and combined sewers (purple dotted line). The location where the sanitary sewer discharges into the combined sewer pipeline is indicated with the red circle.

The number of upstream housing connections to the sewer was determined by simply counting the number of houses in the source streets on the BWSC map. Consequently, this number was multiplied by 2.36 persons per household, which is the average household size in Boston (Census, 2018). Local drinking water consumption amounts on average 41 gallon (155 litres) per capita per day (MWRA, 2016), resulting in a total dry weather flow of 16 m^3/day in the sewer pipe in right across the intersection near Corner Stalk Farm (table 25).

Street	**Connected dwellings (upstream of Corner Stalk Farm)**	**Estimated number of inhabitants in connected dwellings**	**Estimated daily dry weather flow (litres)**	**Type of sewer**
Putnam Street	20	47	7316	Sanitary
Condor Street	24	57	8779	Sanitary
	Total	**Total**	**Total**	
	44	104	16095	

Table 25 Computation of dry weather flow in sewer near Corner Stalk Farm

10.2.2.2.2 Sewage quality

Just like the wastewater flowing past Eastie Farm, wastewater flowing past Corner Stalk Farm enters the Dear Island Treatment plant through the North System headworks (MWRA, 2017). The wastewater quality of this influent is displayed in appendix 3b. On average influent contains 21.6 mg/L of ammonium, 0.25 mg nitrate/L and 2 mg/L of dissolvable orthophosphates. Nitrate concentrations are two orders of magnitude smaller than ammonium concentrations and therefore considered negligible. Unfortunately, no data were provided on potassium presence in the sewage. The average chemical oxygen demand (COD) amounts 399 mg/L.

However, since the computed wastewater quantity consists of sanitary waste, whereas the influent of the wastewater treatment plant also contains effluent from combined sewers, these centralized data were very likely to present an underestimation of the pollutant concentrations in the target pipeline. However, since the presented wastewater quality data were the only water quality data available, they were used for the resource availability analysis.

Pollutant	**Load (gram/day)**	
Ammonium – nitrogen	Minimum	98
	Average	348
	Maximum	517
Nitrates	Minimum	0
	Average	4
	Maximum	53

Pollutant	**Load (gram/day)**	
Orthophosphates	Minimum	8
	Average	32
	Maximum	52
COD	Minimum	2,028
	Average	6,422
	Maximum	18,831

Table 26 The total load of several 'pollutants' in a wastewater flow of 16 m^3 per day in Boston, based on minimum, average and maximum daily concentrations

10.2.2.2.3 Nutrient availability in sewage

Table 26 shows the total load of several 'pollutants' in a wastewater flow of 16 m^3 per day - which is the computed flow near Corner Stalk Farm - based on minimum, average and maximum daily concentrations of the constituents. Average daily nutrient loads amount 348 and 32 grams for ammonium and orthophosphates respectively, equalling 270 grams of nitrogen and 9 grams of elemental phosphorus, given the mass ratios calculated in equation 11 (section 10.1.2.2.2).

10.2.2.2.4 *Energy availability in sewage*

As described in the framework (section 8.3.3), for every gram of COD that is digested anaerobically 0.35 litres of biogas (CH_4) can be produced. Given the average daily COD load of 6,422 grams (table 26) present in wastewater flowing past the farm, the potential daily biogas yield amounts 2.2 m^3 of methane, which equals 80 MJ.

10.2.3 Match resource requirements and resource availability

In this section the resource demand and availability in the area will be compared in order to find out if sufficient water, energy and nutrients are present in the urban waters surrounding Corner Stalk Farm.

10.2.3.1 Water

The assessment on harvestable water at Corner Stalk Farm is a lot less complicated than the same analysis for Eastie Farm, as at the container farm only one collection surface was investigated. Only the 35 m^2 container rooftop was used as catchment area when creating a continuous storage model for this case study site.

By subtracting the daily water demand from the daily rainfall, the daily change of storage was calculated. Real-time water demand data for all days between April 21 and August 15 (when they were recorded in 2018) were used and copied for all years under investigation. Outside that time frame, the average water use of 25.4 L/day was used to be able to simulate fluctuations in available storage volume year-round.

Not all water that could be captured on the container rooftop throughout the year had to be kept in stock though. By calculating the largest decline in potential storage that occurred during the assessment period, it was demonstrated that a storage volume of 1,177 litres (311 gallon) was sufficient to overcome the greatest drought in the 20-year study period. The outcome of the continuous storage simulation is shown in figure 45.

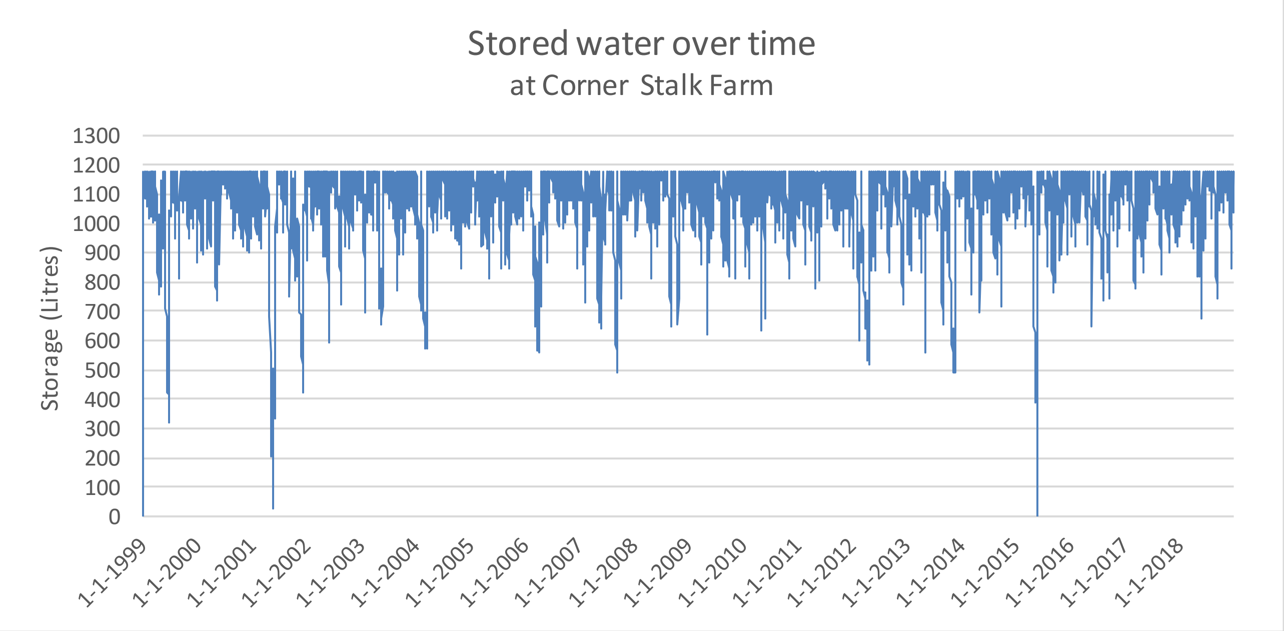


Figure 45 Stored water over time, based on a catchment surface of 35 m^2 and maximum storage volume of 1,177 litres

The required storage volume of 1,177 litres equals 5.6 barrels of 55 gallon each. Six of those barrels are already installed inside the container, suggesting that no additional storage space is needed at Corner Stalk container farm. Quantity-wise, all that is needed to fulfil the farms water demand is a simple connection between the storage barrels and the container rooftop for rainwater refills. Apart from the first two days of the 20-year assessment period (when the storage capacity still needed to be filled), water demand could have been met at all times during the last 20 years and there would even have been water left in the tanks to prevent cavitation of the pumps.

As stated in section 10.2.1.1, the water demand data used during this assessment are questionable. Therefore, the analysis on the match between water availability and water use might be affected adversely too. Although these data show that the required water volume can be captured on a small rooftop surface and stored in a minor storage facility, it is plausible that both need to be larger than calculated here.

10.2.3.2 Energy

If all COD present in the wastewater flow – of which the volume is likely generously underestimated as a result of lacking sewer layout data – a total of 2.2 m^3 of methane can be produced, which equals 80 MJ. Corner Stalk Farm gets all its energy delivered through electricity and therefore a typical biogas generator efficiency of 35% to transform the gas into electric power needs to be taken into account. All things considered, the sewage near Corner Stalk Farm has the potential to generate 7.8 kWh per day for the farm to use.

One of the four containers on the farm's premises already uses far more than that (131 kWh/d on average). Therefore, it can be concluded that the wastewater stream as analysed in this study cannot provide enough energy to operate one – let alone four – container farm unit.

10.2.3.3 Nutrients

Fertilizer use at Corner Stalk Farm is relatively constant due to the dispenser system steadily releasing nutrients. The average daily consumption of nitrogen and phosphorus amounted 1.8 and 0.3 grams respectively, and the maximum daily demand values are 7.9 and 1.5 g/d respectively. This demand can easily be met by the average daily nutrient load of 270 grams of nitrogen and 9 grams of elemental phosphorus in sewer pipelines which run past the farm.

This load is likely to be a considerable underestimation, as it was estimated using an underestimated flow as well as average concentrations of pollutants in the influent of the centralized wastewater treatment plant. Besides sanitary waste, this plant also receives rainwater. The wastewater stream that is suggested to be tapped into for nutrient abstraction for Corner Stalk Farm, however, concerns pure sanitary waste, which generally contains higher concentrations of nutrients than combined wastewater.

Like the demand, the availability of nutrients for the farm was considered relatively steady due to the sanitary nature of the wastewater flow. Because of this constant nutrient supply, the average phosphorus and nitrogen concentration in the sewage were used to calculate the required treatment capacity of a local nutrient recovery facility. Given the modest fertilizer additions in the container farm, per container, only 107 litres of wastewater need to be treated daily (at a 100% efficiency) to recover sufficient nitrogen, whereas 461 litres of sewage are required to supply enough phosphorus to meet a single container's demand.

10.2.4 Harvest & resource efficiency

Corner Stalk Farm grows more than twenty varieties of lettuces and a variety of herbs and other leafy greens (see appendix 4c). The farm records a harvest equivalent to 600 to 1000 heads of lettuce per container per week depending on the size of the heads. Seedlings are grown in horizontal fashion for 3 weeks. Afterwards they are relocated and spend 3 to 5 weeks in vertically positioned towers before they can be harvested. This means that the growing cycle lasts between 6 and 8 weeks (42 -56 days), which is shorter than the 75 to 140 days growing period of lettuce that the FAO indicated (FAO, 2019-3).

Although this discrepancy in growing period could very well be caused by the difference in lettuce species that are cultivated inside the container, it was assumed that the crops were just fully grown after this time shorter time period because of the constant light supply.

10.2.4.1 Water Efficiency

Filling out the equations described in the methods (section 4.3.3) resulted in a total theoretical (evapo-)transpiration depth of 1364 mm over the entire measurement period. Given the growing surface of 78 m^2 per container, subsequently, a water need of 106,400 liters was computed.

Although the application of the Blaney-Criddle method could have overestimated the transpiration rates and/or the lettuce types grown at Corner Stalk Farm could have been less water intensive than the generalized FAO data suggest, it is believed that this outcome provides a reliable view on the theoretical water needs of the container farm.

During the same time frame the farm only consumed 2,974 liters of water, which would mean that 2.8% of the transpired water escaped from the container system and 97.2% of the transpired water vapor was captured by the air conditioning and fed back to the crops.

Moreover, these data do suggest an average water use of 0.7 L/kg of lettuce. This is way more efficient than the hydroponic water use of 20 L/kg Barbosa et al. (2015) computed or the average global water footprint for lettuce of 237 L/kg for that matter (Mekonnen & Hoekstra, 2011). All in all, the water supply and circulation at Corner Stalk Farm seems to be highly efficient.

It is however presumed that the water demand data registered during this thesis' data collection campaign paint a picture which is rosier than reality, as water abstracted from the system by harvesting crops, exceeds the total registered water consumption. Baras (2018) stated that hydroponic lettuce heads rarely weigh over 0.3 kg (10 ounces). Assuming an average weekly harvest of 800 heads of lettuce – yields varied between 600 and 1000 heads per week – about 240 kg of lettuce could have been harvested every week. Over the entire period of 117 days (16.7 weeks) that water measurements were conducted, this would result in a maximum production of 4,000 kg of lettuce heads. Given the typical water content of lettuce of 94%, this would mean that about 3,768 litres of water could have been removed from the system by harvesting the crops (Canet, 1988). The registered water consumption during this time was however no more than 2,974 litres. Although it is possible that lighter heads were harvested, these findings raised again suspicion that not all water additions were recorded.

Amsterdam

10.3 QO Hotel

The rooftop greenhouse on top of the QO hotel in Amsterdam makes use of many high-tech techniques to facilitate optimal crop growth for the restaurant's kitchen. It makes use of a combination of natural, organic and artificial resources. This section will describe the greenhouse's resource consumption as well as the resource availability in the farm's vicinity.

10.3.1 Required resources

In the QO Hotel in Amsterdam measurements were done on all three resources under investigation. Water use was measured indirectly and energy and nutrient data were recorded by the computer operated system.

10.3.1.1 Water

After a start-up period to get all systems in the greenhouse up and running following the grand opening of the hotel, the greenhouse shows a fairly constant daily water demand. An average of 0.48 m^3 of water is consumed per day (with a standard deviation of $0.11m^3/d$), assuming a 95% efficiency of the water circulation system. A slight increase in water demand at the end of July is noted when a fourth subsystem was employed to expend the horticultural production (fig. 46). The highest daily demand during the measurement period from the 6th of July till the 23rd of August was 810 litres and in total more than 22 m^3 of water was consumed during these 43 days.

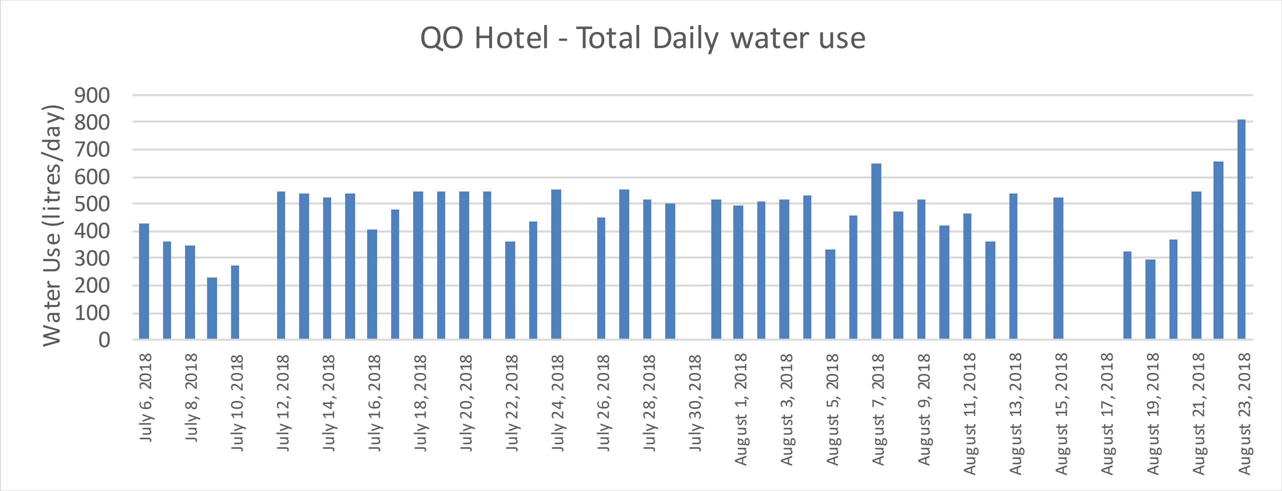


Figure 46 Daily water use in the QO hotel during the measurement period

Outdoor weather conditions have a greater impact on the crop production in the QO hotel greenhouse than in the container farm. Lower outside temperatures and less daylight hours inevitably result in less transpiration and less water demand. Although the QO hotel aimed to produce year-round and the greenhouse had its own heating system and LED lights to (partially) compensate for the seasonal change, the absence of data on continuity of crop production during winter resulted in the assumption that a winter hiatus was intercalated from November up till March/April. During this time period perennial crops would be kept alive, but no yield would be produced. For the sake of simplicity and because of the shortfall of data the water demand during this period is assumed to be non-existent, so that storage could be built.

10.3.1.2 Energy

The computer system that was monitoring greenhouse functions was able to distinguish several types of energy use and could record energy data on different temporal scales. For this study, the time interval was set at 5 minutes, the highest temporal resolution possible. Within those 5 minutes the heat delivery and power consumption could have fluctuated, however, the assumption was made that variances would level out over time.

Solar radiation is by far the biggest supplier of energy to the greenhouse with peaks up to 1,880 kWh/d. Even on the darkest, cloudiest day recorded, solar radiation provided 214 kWh and outnumbered all other energy sources. The energy provided by the sun is however not completely consumed by the crops as plants only absorb light traveling at specific wavelengths. The electrical power for lighting, however, was tuned to the crops' needs and only consumed 105 kWh/day on average (with a peak demand of 135 kWh/day). Average daily heat delivery from April till August amounted 31 kWh. Contrary to the energy consumed by lighting, the heat supply was highly variable, ranging between 0 and 170 kWh per day. During warm summer days, it was completely switched of and cooling was in large demand (fig. 47).

Using information on the elevation of the rooftop and the water demand in the greenhouse the potential energy requirement to transport water from the basement of the building to the rooftop 76 meters above street level was estimated, as no data on this local WEF were recorded. Theoretically, potential energy demands would range anywhere from 0.05 to 0.17 kWh per day, but in reality, considering booster pump efficiencies, this is a considerable underestimation.

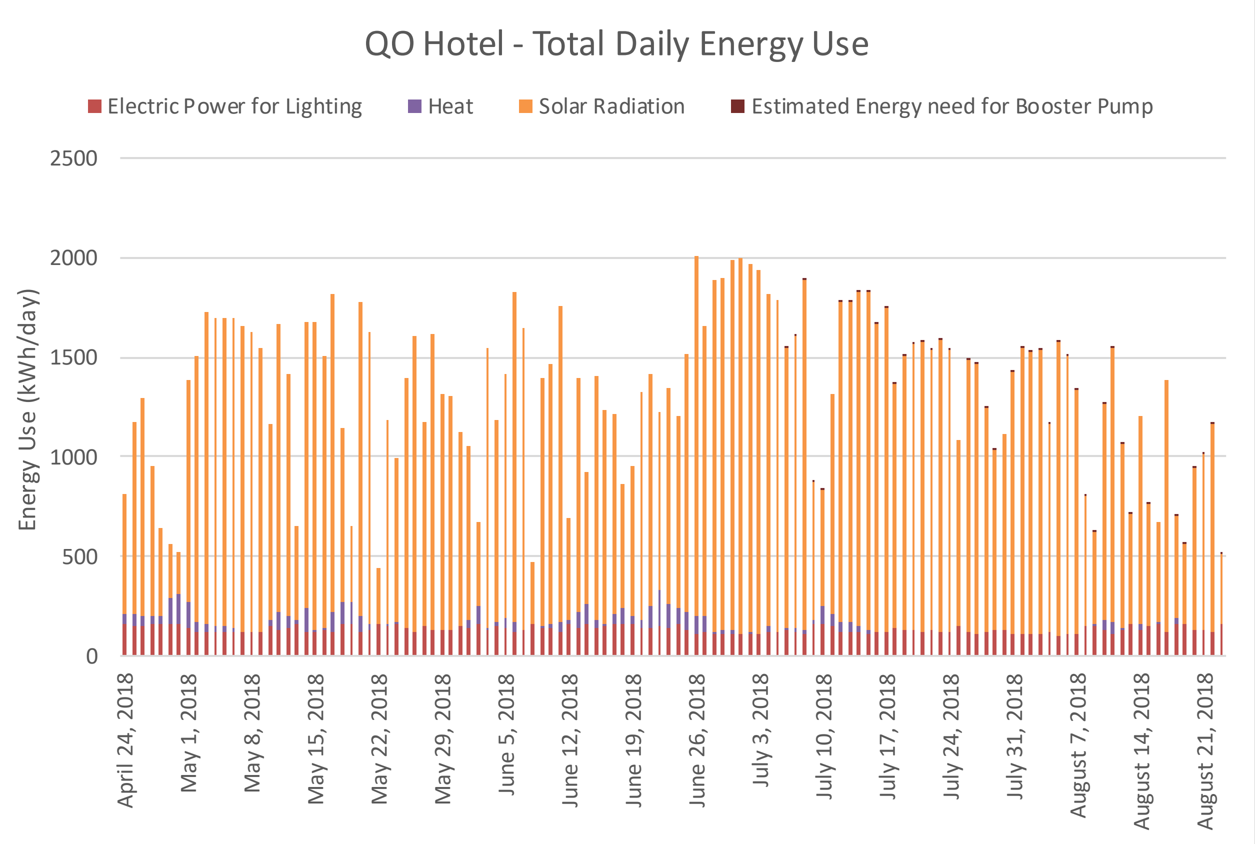


Figure 47 Daily energy use in the QO hotel during the measurement period

10.3.1.3 Nutrients

During the measurement period of 54 days in total 2,935 grams of nitrogen, 3,265 grams of potassium and 513 grams of phosphorus were added to the greenhouse, either in the form of artificial fertilizer or through an organic nutrient solution.

The artificial fertilizer was the sole nutrient supply to the crops for the first 5 days of the study. During this time 41 grams of nitrogen, 45 grams of potassium and 10 grams of phosphorus were added. A gradual transition of 21 days took place during which both artificial and organic fertilizer were supplied to the water circulation system. Oddly enough, it was during this time that the highest daily artificial fertilizer feed of 12 grams of nitrogen, 13 grams of potassium and 3 grams of phosphorus was recorded.

In total 2,894 grams of nitrogen, 504 grams of potassium and 3,219 grams of phosphorus were added through the organic fertilizer solution. This solution was poured over from jerrycans into the water manually. Since the added volume over 50 supply days (of which 21 transition days and 29 days as exclusive supply) was only read out once, this research is only acquainted with the average daily organic fertilizer use of 58 grams of nitrogen, 10 grams of phosphorus and 64 grams of potassium and not with the peak demands.

Given the available information and its temporal resolution, the best estimate of the highest possible daily demand was made by adding the calculated average daily organic fertilizer consumption and the recorded maximum daily artificial fertilizer supply, since the occurrence has most likely taken place during the transition period, when both variants were added. This resulted in a daily peak demand of 70 grams of nitrogen, 13 grams of phosphorus and 77 grams of potassium.

10.3.2 Available resources

Just like in the Bostonian case studies, precipitation can provide enough rainwater to the Amsterdam rooftop farm to accommodate the irrigation demand. Therefore, water in the form of wastewater will only be analysed as a source of energy and nutrients, but will be left out of consideration during the water availability discussion.

10.3.2.1 Precipitation

The Netherlands boasts a temperate maritime climate with mild summers and winters that are cold but not freezing. Annual rainfall amounted 860 mm on average the last 20 years, with 2018 being the driest year (559 mm) and 2000 being the wettest (1054 mm).
Rainfall quantities vary considerably during the year (fig. 48). On average, spring is the driest season and April is the driest month of the year (40 mm). In 2007, the largest dry spell in the data series under investigation was recorded, lasting 44 days from March till May. Summer and fall are considerably wetter. August is the month which generally receives most rainfall (112 mm), with extremes up to 266 mm (in 2006).

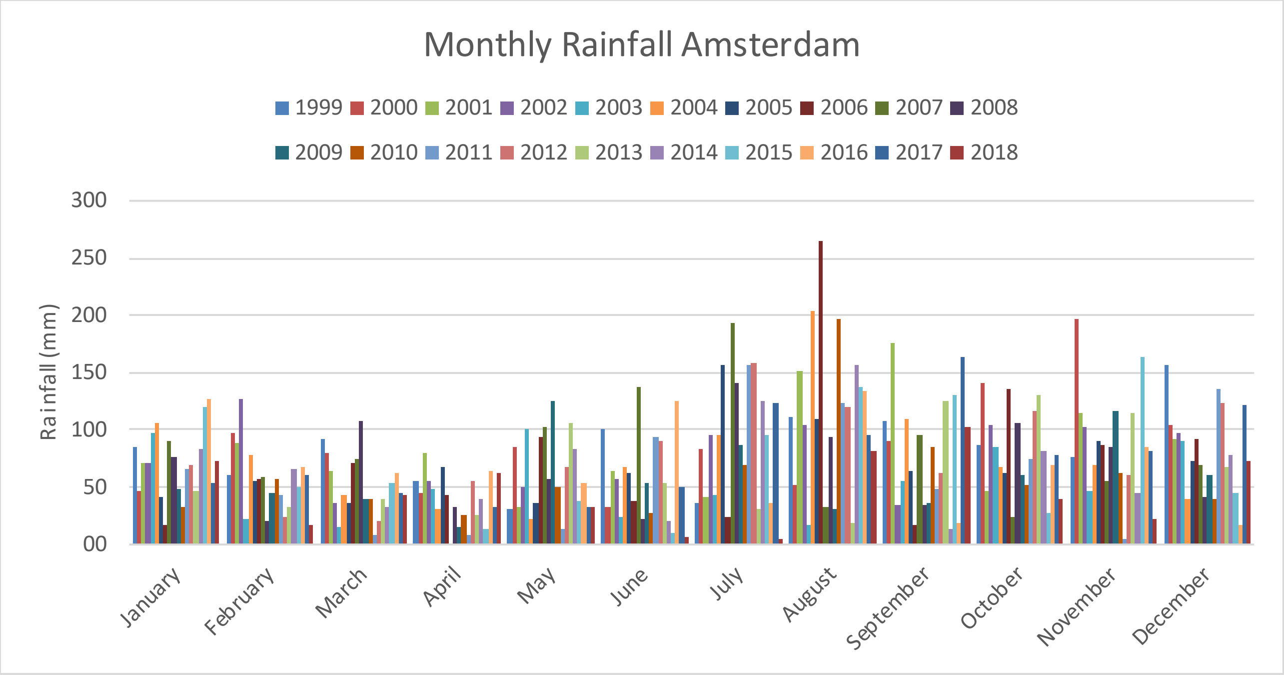


Figure 48 Monthly rainfall in Amsterdam

The outdoor growing season in the Netherlands lasts for 183 days between the 1st of April and the 30th of September. The amount of rainfall during that period varies between 288 mm (2003) and 561 mm (2007) and averaged at 438 mm per season.

However, the greenhouse on top of the QO hotel allows to grow crops during a larger part of the year. Therefore, the total amount of rainfall which would fall during a growing season of 183 days, starting every month, was computed. This averaged at 431 mm. Growing cycles starting in July are the wettest (523 mm) and those commencing in January are the driest (339 mm).

10.3.2.1.1 Water availability through precipitation

Because of this thesis's perspective at resource demand and availability through a WEF nexus lens, it was decided to consider the greenhouse rooftop itself (230 m^2) as the only rainwater catchment area in the rainwater availability analysis. Although plenty of potential rainwater catchment surfaces are present nearby the hotel (fig 49), they were neglected during the analysis process, in order to avoid the need for energy to operate powerful pumps transporting the water to a rooftop on the 21st floor of a building, 76 meters above street level.

The water availability assessment showed that on the glass roof surface of the greenhouse, yearly, an average rainfall volume of 178,000 litres can be caught.

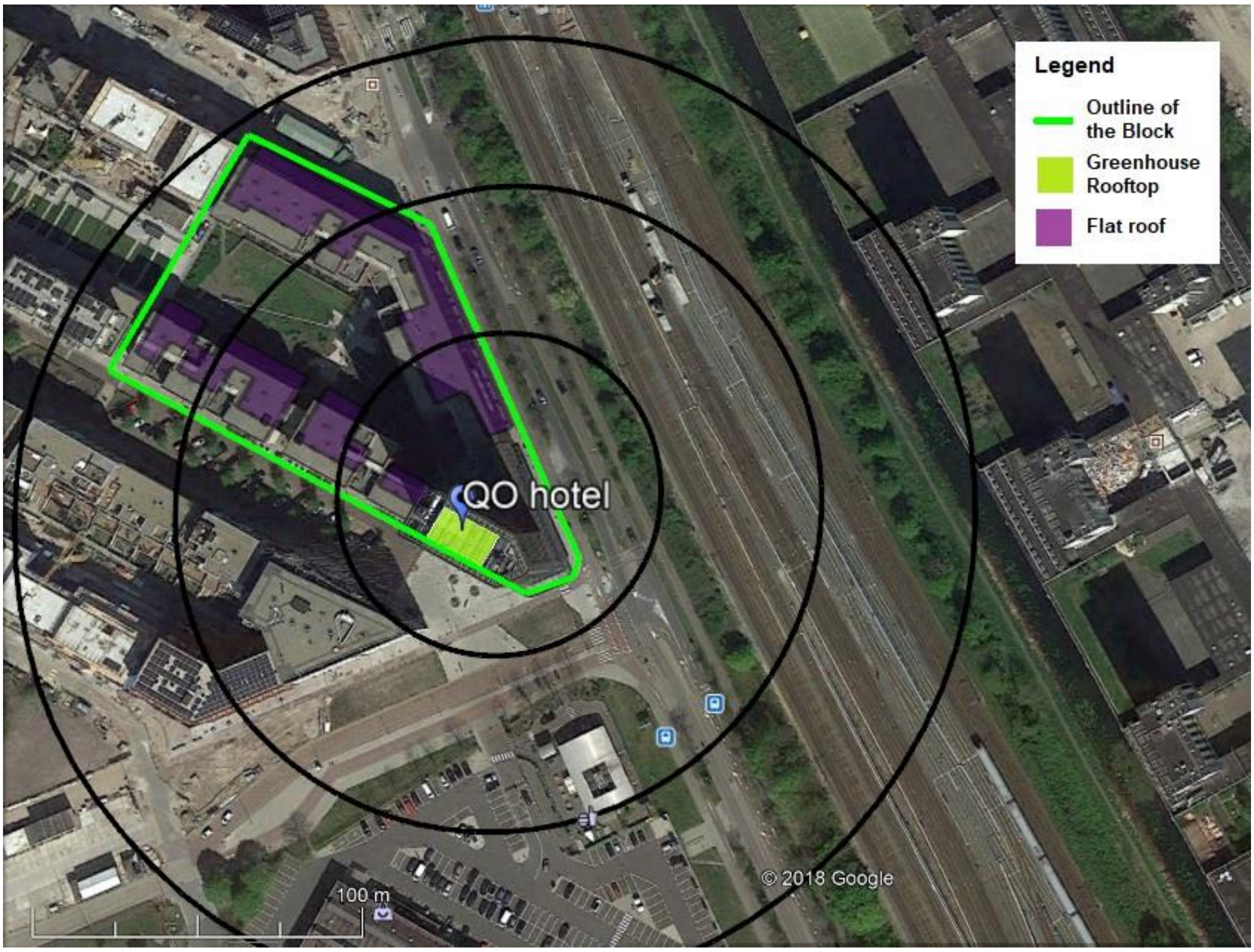


Figure 49 *Roof surfaces within a 50 m radius (inner circle), a 100-meter radius (middle circle) and 150-meter radius (outer circle) within the housing block that the QO greenhouse belongs to.*

10.3.2.2 Sewage

The sewer layout was used to determine the sewage quantity present for resource harvesting. The map that Waternet, the local drinking water and wastewater operator, provided shows that a separate sewer network is present in the Amstelkwartier neighbourhood. The flow direction of the sanitary sewer was determined by looking at a combination of the depth and design flow in order to identify the source area of the sewage and the wastewater quantity flowing past the hotel (fig. 50).

The sewer map seems to show pipelines suddenly ending, without them being connected to a bigger pipeline or treatment station. This is probably due to the fact that a large part of the neighbourhood is still under construction and not yet processed in the water company's models. Raw sewage is certainly not being discharged.

According to a Waternet employee, before the construction of residential dwellings in the Amstelkwartier, a large wastewater treatment plant for the city of Amsterdam was located in the area and as a result (remnants of) large collection pipelines run under the neighbourhood. However, again the data this study had at hand did not show that.

10.3.2.2.1 Wastewater quantity

Since no information was provided on the sewer layout outside the Amstelkwartier area, the source area could have been much bigger than indicated in fig. 50. However, it was decided to base the sewage availability analysis on the available information only.

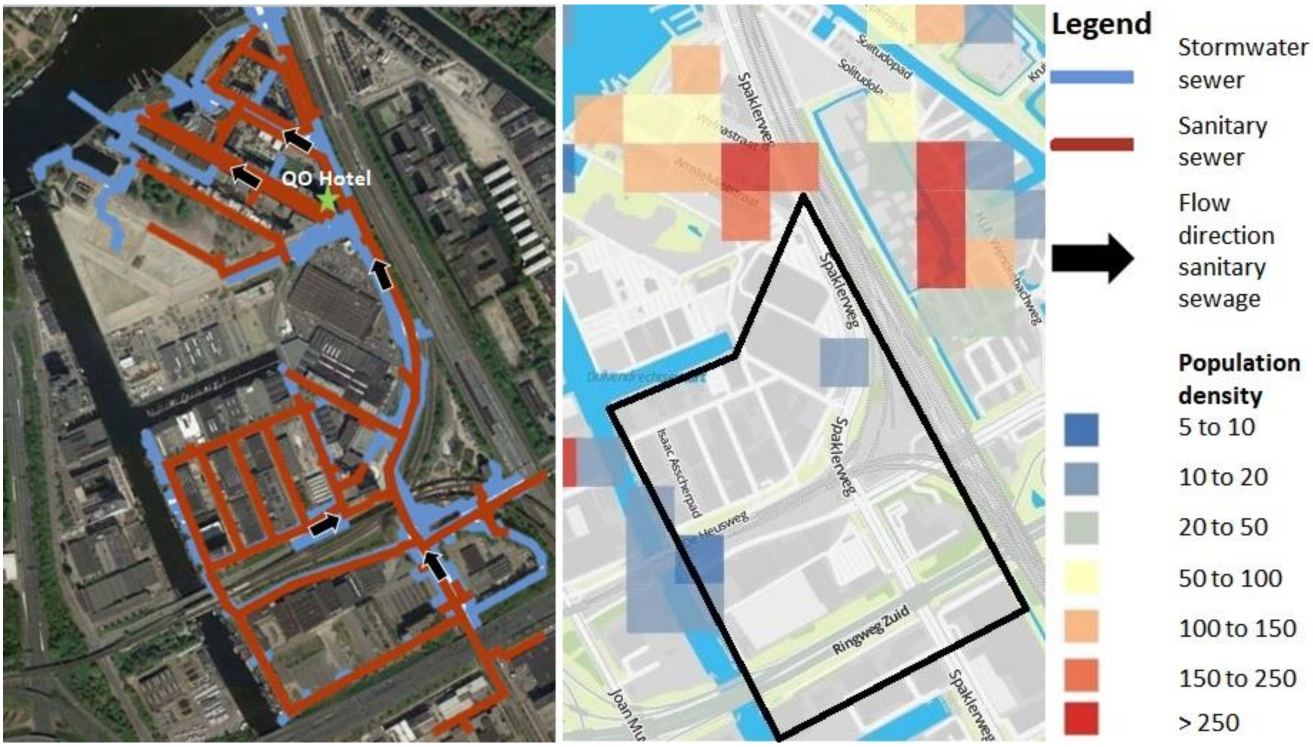


Figure 50 Sewage network and flow direction in the Amstelkwartier neighbourhood (left) Population density in the source area of sanitary sewage (indicated by the black delineation) flowing past the QO hotel (right)

On the west side of the hotel, a sanitary sewer originates. Unfortunately, it hardly contains any wastewater, as no upstream residences are connected. The number of dwellings connected to the sanitary sewer that runs past the QO hotel in the east is limited, since the hotel is located on the edge of a business park. This is also reflected in the low population density in the area. According to the population density data of the Central Bureau for Statistics (CBS, 2017-2) only 15 to 30 inhabitants are living in the source area (fig. 50), generating 1,600 to 3,200 litres of wastewater per day, based on an average daily drinking water use of 107 litres per capita (watering gardens not included) (Waternet, 2019). Of course, businesses, employees and visitors of the business park produce wastewater too. Their numbers are however unknown and therefore this potential source is left out of the equation.

Moreover, the hotel itself, which counts 288 rooms, could serve as a source of wastewater. When is assumed that half of the rooms are permanently filled with a least one guest, sanitary waste from at least 144 people could be captured and serve as a supply for nutrient and energy recovery. At 15,400 litres, this seems to be the most voluminous wastewater source of all in the area.

Wastewater quality

Wastewater from the Amstelkwartier is treated in Treatment plant West (Mol, 2018). A table containing data on the sewage quality is shown in appendix 3a. The wastewater influent contains on average 62 mg/L of nitrogen and 8 mg/L of dissolvable phosphorus. The average chemical oxygen demand (COD) amounts 613 mg/L. Striking is the fact that all these concentrations are significantly higher than those measured at the inlet of the treatment plant in Boston. Unfortunately, no data were provided on potassium presence in the sewage, nor on the concentrations of different molecules containing phosphorus and nitrogen. It was assumed that all forms of nitrogen and phosphorus in the sewage could be recovered.

10.3.2.2.2 Energy availability in sewage

On average, 2.0 kilograms of COD can be harvested from the public sewer running pas the hotel and 94 kilograms of COD flow daily through the hotel's pipelines (table 27). As described in the framework (section 8.3.3), for every gram of COD that is digested anaerobically 0.35 litres of biogas (CH_4) can be produced. All things considered, the potential daily biogas yield of wastewater generated in the hotel amounts 32.9 m^3 of methane, which equals an energy content of 1175 MJ/day, whereas the public sewer has the ability to provide 0.7 m^3 of methane (25 MJ/day) on average.

Pollutant	**Daily Load from hotel (15.4 m^3)**		**Daily Load from sanitary sewer (3.2 m^3)**	
COD	94,402	g/day	1,962	g/day
Nitrogen- total	955	g/day	198	g/day
Phosphorus - total	123	g/day	26	g/day

Table 27 Average daily load of pollutants originating from the local sanitary sewer and the wastewater stream of the hotel

10.3.2.2.3 Nutrient availability in sewage

Table 27 also shows the total load of several 'pollutants' in a wastewater flow of 3 m^3 and 15 m^3 per day, coming from the sewer nearby and the hotel itself respectively.

The average daily nitrogen load amounts 198 grams in the public sewer and 955 grams in the semi-booked hotel. Phosphorus loads are 26 grams and 123 grams in the central sewer and the hotel respectively.

Because of the discrepancy between the average daily concentrations of the constituents at the central treatment plant and the concentrations of a constituents in a purely sanitary sewer or collection pipeline inside the hotel, the computed nutrient load near the hotel is likely underestimated in this analysis.

10.3.3 Match resource requirements and resource availability

In this section the resource demand and availability in the area will be compared in order to find out if sufficient water, energy and nutrients are present in the urban waters surrounding the QO hotel greenhouse.

10.3.3.1 Water

Owing to the absence of knowledge on when exactly the greenhouse is in operation, two water assessments were made: the first one regarding a growing season between April 1 and October 31 and the second one between March 1 and October 31.

10.3.3.1.1 Water storage requirement

When a growing season between April and October is analysed, the 230 m^2 greenhouse roof had to be connected to a storage volume of at least 41,234 litres, to never have encountered water shortages, given the past 20 years of rainfall data (fig. 51). When once in those 20 years a water shortage would have been allowed, a storage volume of only 35,053 litres would have been required, which would have resulted in a 6,181-litre deficiency in 2018. Allowing for a water shortage every 20 years would save over 6 m^3 of storage space and 6000 kg of design weight on the hotel’s roof, making it an appealing option.

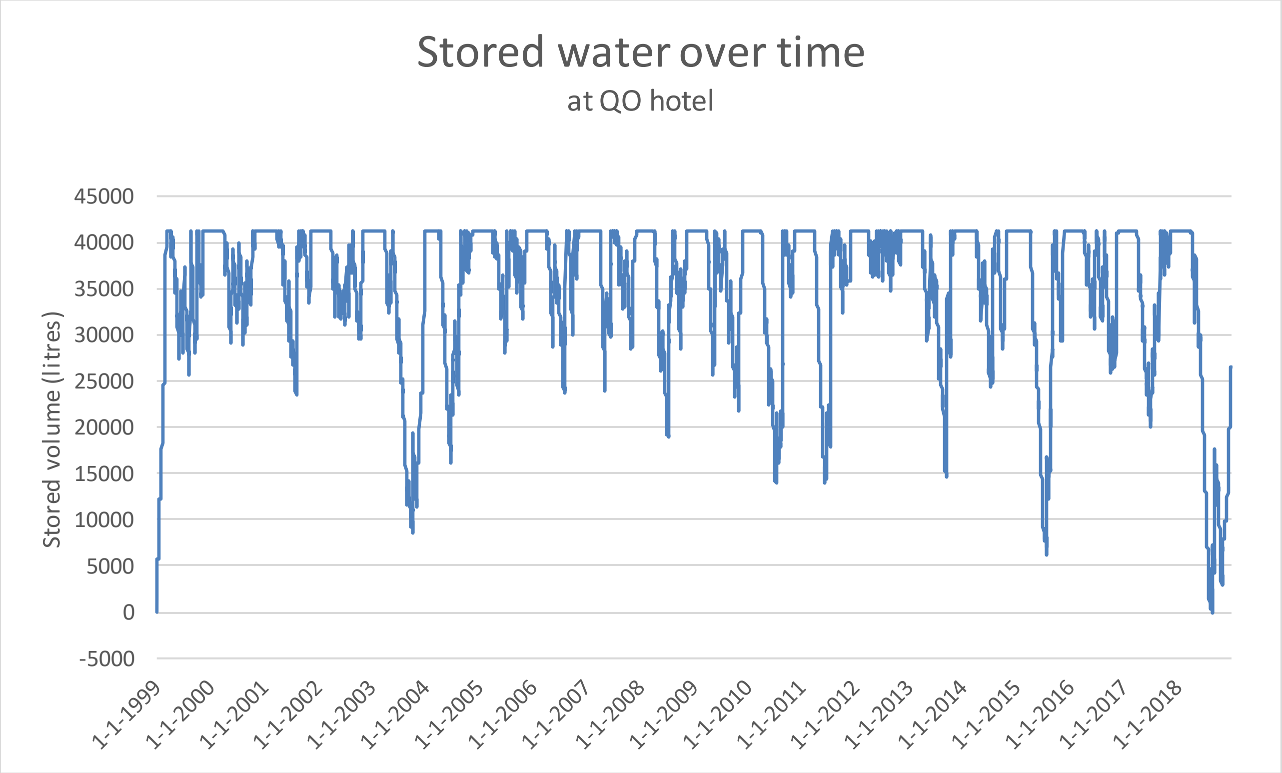


Figure 51 Stored water over time, based on a growing season from April 1 till October 31, a catchment surface of 230 m^2 and a maximum storage volume of 41,234.5 litres

When the analysis is made for a slightly longer growing season, starting in March, installing a 45,404-litre storage would have avoided a water shortage in the 20 years prior to this study (fig. 52). Allowing a water shortage during one of those 20 years, would reduce the storage requirements to 40,614 litres.

The differences in required storage volume between the longer and the shorter growing season are not caused by the fact that water tanks get less time to refill before the water demand takes off in spring. The maximum storage capacity, namely, is still filled completely every winter, even when the greenhouse is operated from March till October. During the extended growing season, however, water is abstracted from the storage for a longer period of time, consequently risking emptying the tanks at the end of the season when a smaller volume than suggested would be used.

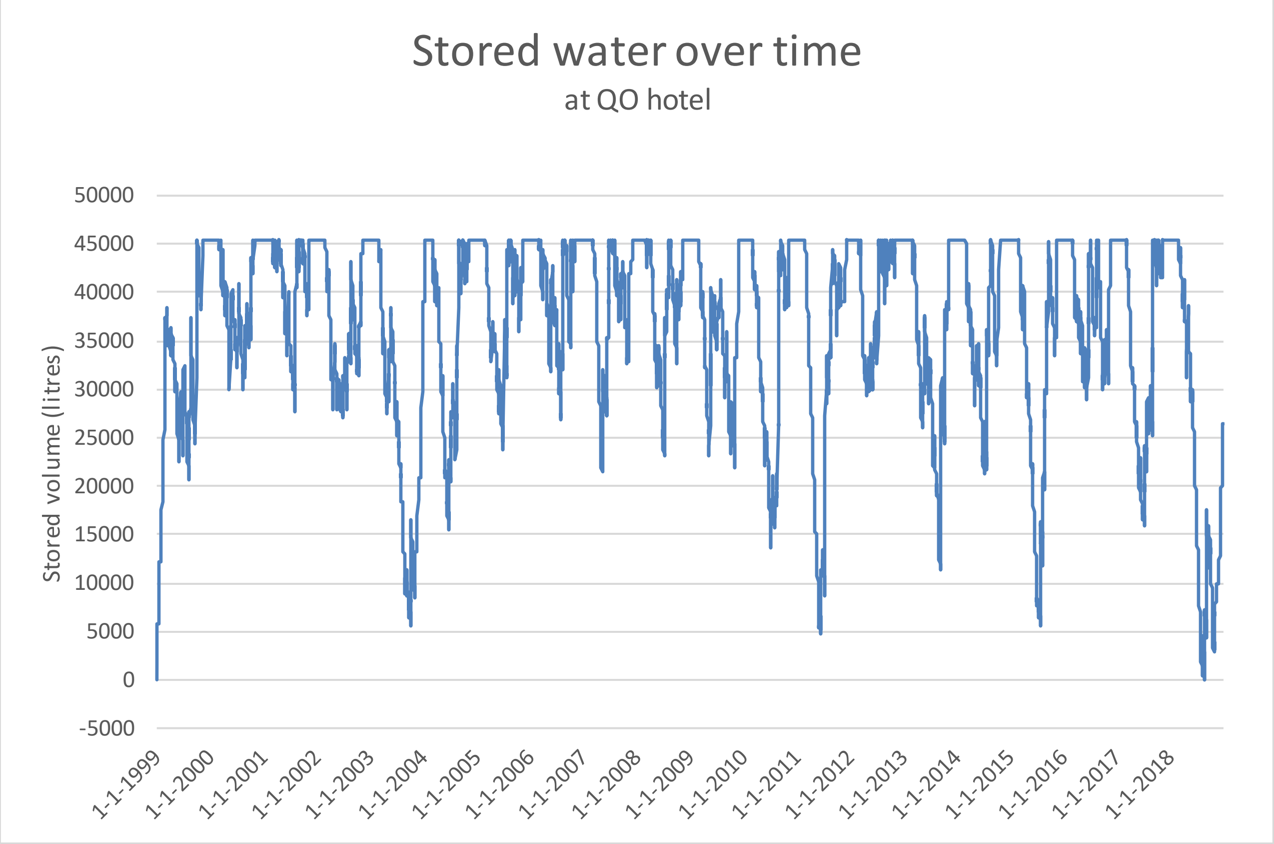


Figure 52 Stored water over time, based on a growing season from March 1 till October 31, a catchment surface of 230 m^2 and a maximum storage volume of 45,404 litres

10.3.3.1.2 *Water storage solutions*

Although blue-green infrastructure could be installed in the form of a basin or pond in parks, greenways or private roofs to store captured rainwater nearby the hotel, water harvesting and storage at the greenhouse's staggering altitude is preferred, to reduce energy required to pump the water up to the rooftop on the 22nd floor.

At first inspection, room for a large storage facility running alongside the greenhouse over a length of about 20 m and a width of approximately 1.8 meters (totalling ± 36 m^2) is available. At this target location the flooring is absent, and a connection is made with the restaurant one storey below. A white, enclosed and insulated storage tank could be installed here. The specific characteristics of the tank help to store water while limiting evaporating and keeping the temperature under control, which is crucial as plants perish when their irrigation water is too warm. An overflow spill at the required maximum water height can be installed to get rid of excess water. It is, however, up for debate which storage volume discussed in the previous section has to be realized. Sure is though, that the consideration should also take into account the structural integrity of the entire building and its capacity to carry such a heavy load of dead weight and water on its roof. By creating a storage box near the rim of the roof, the pressure of the water load will be best conveyed to the steel construction of the hotel, where the capacity to carry such a heavy load is highest. Nonetheless, a structural engineer should verify the structural feasibility of this idea.

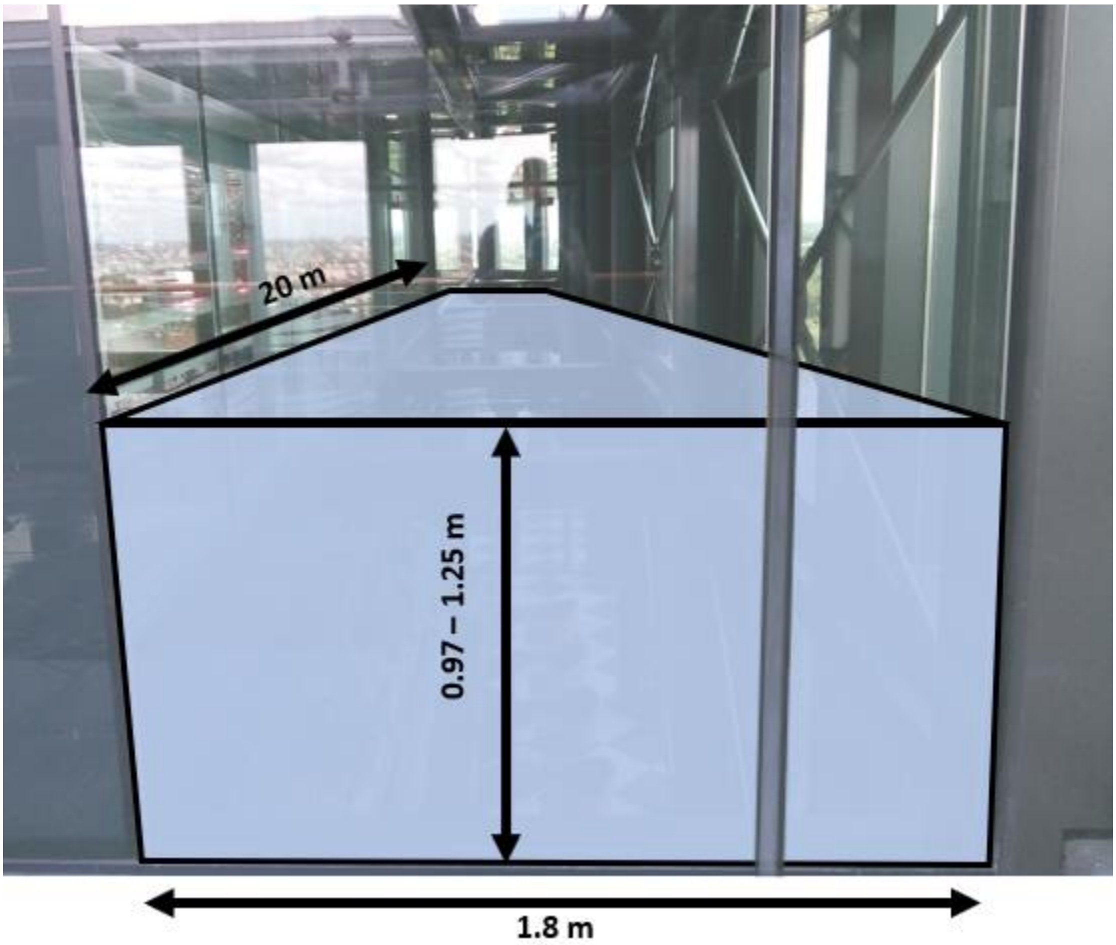


Figure 53 Suggested water storage solution, on top of building, right next to the greenhouse (on the left)

10.3.3.2 Energy

As mentioned before, this study simply misses data on the electricity use of the pumps inside the greenhouse as well as the air conditioning and the computer operated system. Those parameters would be required calculate the total energy use of the greenhouse. The energy supply to operate lighting and deliver heat was however recorded. The greenhouse received on average 31 kWh of heat per day (112 MJ/d), with a peak demand of 170 kWh/d (612 MJ/d). The electrical power for lighting consumed 105 kWh (378 MJ) per day on average, with a peak demand of 135 kWh (486 MJ) per day.

The chemical energy captured in biogas is directly released with a 100% efficiency in the form of heat during combustion, whereas for the production of electricity a biogas generator efficiency of

35% to transform the gas into electric power needs to be taken into account. This means that the greenhouse requires 112 MJ for heat supply and 1080 MJ for electricity production on an average day in summer. If peak light and heat demand coincide (which did not happen during this study, but is more likely to occur and be even more extreme in winters due to the relation between seasonal outside temperature and natural light hours), at least 612 MJ per day is needed for heating and 1389 MJ per day is required to generate sufficient electricity for lighting.

The energy content from biogas harvested from wastewater of a semi-full QO hotel amounts 1175 MJ/day, whereas the public sewer only can provide 25 MJ/day on average. All in all, it can be concluded that the public sewer cannot provide sufficient energy to run the greenhouse. The sanitary wastewater stream of a semi-full hotel, however, contains enough energy to accommodate 99% of the energy consumption of the rooftop greenhouse in summer.

10.3.3.3 Nutrients

The public sewer can deliver a nitrogen load of 198 g/d and the hotel's wastewater stream 955 g/d. Phosphorus loads are 26 and 123 grams per day for the central sewer and the hotel respectively. This means that not only average daily nutrient needs, but also the highest fertilizer addition registered (70 grams of nitrogen and 13 grams of phosphorus) can be met by the average daily nutrient load in wastewater flows either in or nearby the hotel.

10.3.4 Harvest

The QO greenhouse grows a wide selection of crops for the hotel's kitchen, ranging from cherry tomatoes, eggplants and cucumbers to rare and exotic crops like nasturtium flowers, oyster leaves and liquorice basil. All fruits, vegetables, leaves and flowers that were harvested were recorded by the cooks of the hotel in a logbook to hold track of the yield. This logbook is displayed in appendix 4a.

Plant mortality in the extremely warm summer months was rather high, as the water temperature in the greenhouse system exceeded the acceptable range and lots of plant roots died. Perished plants did not result in any harvest, although they were fed resources earlier in the season, skewing the resource need per yield unit throughout the season. One of the explanations for the reduced resource input during the last weeks of the data collection period is simply that not all dead plants had been replaced yet.

Theoretical resource requirements for most of the crops grown in the greenhouse are hard to come by as the greenhouse does cultivate many uncommon crops on which those data lack in academic literature. As the resource requirements for all crops in the greenhouse need to be known in order to make a reliable efficiency analysis, in this case no resource efficiency was calculated.

11 Results & Discussion: Governance

As Chang et al. (2016) already stated: "Nexus implementation goes beyond the technosphere and is anthropogenically imprinted". Therefore, the societal and economic context of WEF systems needs to be taken into account during decision making. In this chapter the institutional environment and governance regarding urban farming initiatives and (waste)water reuse will be outlined for both case study cities, based on several interviews with local policy makers and water management experts. Moreover, experiences and recommendations from projects on resource recovery from urban waters by local partners will be shared.

11.1 Amsterdam

The city of Amsterdam created a 'Green Agenda' in their food vision back in 2014. This plan exposes the city's ambitions on stimulating sustainable forms of urban farming. According to Frank Bakkum, a geographer of the department of spatial planning and sustainability of the municipality of Amsterdam, this vision predominantly concerns open field agriculture, as high-tech vertical farming with a commercial character is not yet ubiquitous in the city. Since food security is generally not a problem in Amsterdam, the social aspect of urban farming and the environmental awareness and educational benefits it brings along, are the principal motives to support agriculture within the city boundaries.

Our source within the municipality, however, reported that WEF nexus thinking does not play a central role in local governmental decision making yet. Hence, circularity aspects did not weigh in on the decision to support urban farming. Sustainability ambitions in Amsterdam are primarily related to the energy transition. Therefore, presently no binding policy has been formulated on urban farming and farms can appear in the townscape by making exceptions on zoning regulations. Moreover, our source explained that urban farming is simply a phenomenon that is too new to provide this study with recommendations founded on spatial plans, laws or experiences, as regulation always runs behind recent developments. Similarly, the city did not express any preferences on rainwater storage methods, although it is a partner in Rainproof, a network that aims to create a water resilient city and stimulates local rainwater catchment and storage.

Another partner of Rainproof is Waternet, which fulfils both water board and municipal tasks. Unlike in other Dutch regions, in Amsterdam the responsibility for both drinking water supply and wastewater collection and treatment lies with this organisation.

Stefan Mol, an energy, resources and water consultant at Waternet, explained that wastewater reuse in agriculture is prohibited by law in the Netherlands, as it is registered as a waste-material. Due to faecal contamination from a human origin, wastewater reuse in (urban) farming is deemed a microbiological hazard for food safety. The Netherlands is no exception with this policy. Smit & Nasr (1992) already stated that in many countries the fear of contamination by unclean water has become institutionalized in law by many governments. Mr. Mol himself found it odd that wastewater irrigation was considered a taboo, as animal manure is regularly applied to arable land. Struvite, harvested from wastewater, is however permitted as a fertilizer during the food production process.

Despite of the taboo on wastewater reuse in agriculture, Waternet already runs pilots on resource harvesting from sewage in Amsterdam, from which a few things can be learned. Struvite harvesting from combined wastewater registers an efficiency of about 5%, whereas nutrient recovery from black wastewater, could increase this efficiency to 25%. Moreover, separation at the source is beneficial for the production of biogas from sanitary waste.

Our source within Waternet doubted whether rainwater harvesting purely for agricultural input would be financially rewarding. The same holds for small-scale treatment, which is not yet profitable. Water, energy and fertilizer are cheap compared to decentralized treatment installations. Up-scaled or centralized resource recovery was considered to be a more lucrative alternative.

11.2 Boston

The responsibility for the urban water system in Boston is shared between multiple parties. First of all, the Massachusetts Water Resources Authority (MWRA) owns and manages the reservoirs and treats the source water to comply with drinking water quality standards. Consequently, drinking water is distributed to the cities in its service area. The Boston Water and Sewer Commission (BWSC) then takes the drinking water via special connections from the supply mains owned by the MWRA and sells it to costumers. In this context, BWSC basically functions as a water retailer. After water use by the consumer, the BWSC collects the wastewater again and discharges it to the MWRA trunk line, from where it is transported to the centralized wastewater treatment plant on Deer Island, where the MWRA executes the treatment process.

In the case of combined sewage the MWRA handles both sanitary waste and whatever else. Stormwater, captured in stormwater sewers of separate systems, however, are not the MWRA's responsibility. Besides operating and maintaining the local water distribution system and the sewer collection system in the city of Boston, local stormwater drains are the BWSC's responsibility.

According to one of our sources within the BWSC, it is a common problem not knowing who is responsible for what when dealing with water problems in Boston. Water management is segmented in various departments and organizations. Now that climate change challenges have to be tackled, this situation is getting increasingly challenging as even more jurisdictional boundaries have to be crossed.

11.2.1 Rainwater

In combined sewer areas, the MWRA is always on the lookout to decrease extreme flows as a result of rain events in their system and encourages local catchment and infiltration of stormwater. Although assuring adequate water quality and treatment is the MWRA's principal responsibility, the MWRA works with combined sewer communities to resolve combined sewer overflow problems, by funding separation of sewers.

Our source within the MWRA figured that the BWSC would probably prefer local extraction of sewage from their pipes for (private) decentralized treatment, as the BWSC needs to pay over the amount of water discharged into the MWRA trunk lines, but this driver was not mentioned by the other party. Although the BWSC does recognize the issue with local floods, they are principally putting green infrastructure in place for water quality issues (phosphorus), not for stormwater retention purposes.

The city of Boston, however, has been trying to manage the stormwater that falls on each development parcel, formerly encouraging and now requiring new development and substantial rehabilitation to be able to handle the first inch of rain (2.5 cm) on site. Anything beyond that can be transported to the storm water system and transported to the nearest water body. Urban agriculture could help getting rid of the stored water, while putting it to good use.

11.2.2 Wastewater reuse

Neither the BWSC nor the MWRA have infrastructure in place that facilitates decentralized sewage treatment by third parties. Besides, both our sources at the MWRA and the BWSC figured that rainfall patterns in Massachusetts would obviate the need for wastewater reuse for irrigation. Although climate change is expected to result in higher peaks in rainfall the BWSC does not consider water shortages in the agricultural sector to be an issue in Boston. The abundance of rain allows to be choosy on what water to use, permitting to disregard wastewater as irrigation water source.

Both parties, however, realize that wastewater contains other crucial resources for agriculture besides water. At the same time, they both warn about the microbiological quality of the sewage and for potential contamination by pharmaceuticals and heavy metals. Domestic sewage probably poses a very low risk for metal contamination. However, the presence of hardware stores or dentist practices could result in elevated metal concentrations in sewage. Especially mercury and sulphur contaminants from dental offices worries our sources.

It would be best to choose closed domestic systems or a predominantly residential area to drain sewage from for reuse, and to avoid business districts and industry. This would however not rule out any contamination with harmful substances. At the MWRA they found truth in the following statement of their director of planning and sustainability Stephen Estes-Smargiassi: 'If you can buy it, you can flush it'.

Charlie Jewell, director of planning at BWSC, figured that in an existing environment, where a sewer system needs to be retrofitted to withdraw sewage for local treatment, it might not be economically viable to create local connections for wastewater extractions. In a brand-new environment, where the system is set up to facilitate waste to resource conversion it was thought be more feasible.

Oddly, right after the data analysis for this study was completed, in the fall of 2019 a sewer and drain separation was executed right in front of container farm Corner Stalk Farm (BWSC, 2019). During this retrofit, no connection was created for local sewage withdrawal and decentralized treatment. Even though the author of this thesis also doubts the necessity and feasibility of local treatment for each urban farm, due to inconvenience for maintenance workers and the relatively high financial investment that is required, this move confirms that facilitating local resource reuse are not among the BWSC's priorities.

Another way to work around the water quality issue for local wastewater reuse, suggested by our MWRA source, would be to think about the most optimal place to put urban farms. In the situation where a centralized treatment plant is nearby its effluent and harvested resources could be used rather than taking raw sewage from the sewer and treating it at decentralized locations. This way only a small amount of additional treatment is required before the former sewage is applied to the crops. This kind of model is already applied in California and Arizona, where advanced secondary treatment is applied for (golf course) irrigation. In Boston they do not do that because the wastewater ends up pretty far away from the users, and therefore, it would be expensive.

The Charles River Watershed Association (CRWA), an organization which promotes sustainable water management in Massachusetts, made it its mission to come up with long-term, cutting-edge solutions to watershed problems. According to Julie Wood, director of projects at CRWA, rainwater nuisance is already considered a huge issue by the association and as a result they try to push for more infiltration infrastructure. Moreover, they have had some positive experiences with decentralized local wastewater treatment and resource harvesting from sewage.

For example, in the town of Littleton (MA), an on-site wastewater treatment system for an anaerobic digester scheme was created providing about 110 m^3 (30.000 gallon) per day of wastewater treatment. The construction of infrastructure required for this project costed $4.2 million, which is significantly less than the conventional centralized approach. Besides, according to the CWRA report on smart sewering in this village (2012), the anaerobic digestion process has the potential to produce biogas, residual stabilized solids and recycled water with higher nutrient levels than drinking water, which could be beneficially reused for agricultural purposes. Two other real-world examples of local resource extraction from food and from existing sewer pipes (in the Seaport & Stony Brook), treating 1 to 5 million gallon per day, also proved to be financially feasible, while meeting EPA effluent standards, according to Julie Woods.

All these cases are treating sewage in way larger quantities than required for urban farms like the ones under investigation in this thesis. Further financial research will have to prove whether such small-scale facilities are still financially viable.

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12 Discussion

In this section, limitations of the framework created in this study and the research in the WEF nexus in general will be discussed together, as they exhibit large similarities. Afterwards, recommendations on improved data collection on resource use in urban farms and resource availability in urban waters will be provided.

12.1 Discussion framework & WEF nexus research

It is safe to say that acquisition of quality data poses the biggest challenge in WEF nexus research. The mere absence of data collected at the urban level or the fact that it is scattered under the jurisdiction of various departments of local, provincial and even national institutions, result in information dissemination and eventually in a lack of coherency. This challenge has been mentioned too by other authors (Sahely et al., 2003; Chang et al., 2016).

In this study an attempt was made to compile and synthesize data gathered from a wide range of scientific articles, websites and renowned institutes into an integrated database. It makes use of research done in comprehensive (case) studies at different geographic scales, locations, in different ages and on various technological-specificities, resulting in inconsistent system boundaries. As Chang et al. (2016) legitimately stated, due to geographical variations in resource availability, climate conditions, environment, technological advancement, population, and market structures, one-size-fits-all analytic solutions to a sustainable WEF nexus are lacking in the real world. However, whenever possible, this study chose to utilize data recorded in western countries, in an attempt to match the conditions at the case study sites executed in this research best. The author realizes that this framework too is in no way complete as the field is constantly moving as a result of the energy transition and other technological and societal developments. Therefore, it cannot be ruled out that more connections are created in the future, whereas others might disappear.

Moreover, most work which has been published on the WEF nexus is very hypothetical and makes many assumptions. WEF studies very often lack hard quantifications. Much more research must be done to monitor local links in general, as this is where the nexus factually takes place. In particular, quantitative data on nexus flows must be gathered in the field to be able to make informed decisions on nexus sector integration and feasibility of sustainable solutions.

12.2 Issues with data collection during this study

Even though this study aimed to close a tiny gap in the WEF nexus quantification, a critical reflection teaches that not all data collected in this study have a sufficient reliability to contribute to solid quantitative recommendations on the feasibility and implementation of the integration of urban waters and urban farms (see table 28).

	Water demand	**Energy demand**	**Fertilizer demand**	**Sewage quantity**	**Sewage quality**	**Rainwater quantity**
Boston						
Corner Stalk Farm	Unfit	Adequate	Unknown	Mediocre	Unfit	Adequate
Eastie Farm	Unknown	N/A	Unknown	Mediocre	Mediocre	Adequate
Amsterdam						
QO hotel	Mediocre	Mediocre	Adequate	Mediocre	Unfit	Adequate

Table 28 Quality and adequacy of resource demand and availability data for the three different case study sites

12.2.1 Resource demand data

The issues encountered during the data collection varied from site to site. Different modes of operation, technological advancement and farming staff resulted in diverse challenges during the measurement period.

12.2.1.1 Water

The accuracy of water demand data varied per case. At Eastie Farm, the water data collected by a designated volunteer who watered plants and very regularly passed forward information on water consumption, were assumed to be accurate and complete (adequate). However, water abstractions by other volunteers, who despite notification signs were not informed about the ongoing data collection, might not have been counted in (which would make the collected data moderately reliable at most).

At Corner Stalk Farm, however, an impossibly high efficiency was recorded, as the water content in the harvested crops seems to have exceeded the total water input at the farm. Therefore, it is concluded that at least some water consumption data must be missing from the collection series, and consequently, that the water data measured at this site are unfit to carry out a reasonable analysis.

At the QO hotel, a computer operated system controls and monitors the water circulation through the greenhouse. However, because a water circulation system is installed, and part of the water fed to the crops passes through the water meter time and time again, this automatically monitored data do not concern the water consumption. To compensate for this fact, a rough assumption had to be made on the water circulation efficiency, which could have skewed the results significantly.

Another uncertainty factor that must be kept in mind, is the fact that because of the time limitations that initially stood for this project, it was decided to confine the measurement period for all three case study sites to only a few months. Using the average water demand measured during the measurement period for dates outside this measurement period, was considered the only way to generate an approximation of some sort on the yearly demand. This method is however tricky, as water demand can significantly vary throughout the year. Distorted views on water use have on their turn an adverse effect on the accuracy of the year-round continuous storage models that were created for every site, potentially leading to either an underestimation or overestimation of the required storage volume.

It is recommended for future research that water demand series are recorded during at least an entire growing period, whether that period lasts a year (like at container farm Corner Stalk), or from spring till fall (like at open field community farm Eastie Farm), to see the impact of seasons on resource use and to compute adequate storage requirements.

12.2.1.2 Energy

The average daily energy use calculated for Corner Stalk Farm is thought to be highly accurate and complete, as a cumulative energy consumption meter was installed and read that measured the energy demand for the entire container unit. Although the irregularity of the readings levelled out extremes, it allowed for accurate averaging. In winter the energy consumption is predicted to be significantly lower though, as then less/no air conditioning, generally the biggest energy consumer, is required indoors.

The energy consumption data that were measured at the QO greenhouse were very precise, and were automatically collected at a very high temporal resolution. However, those data only tell a part of the story, as data on energy consumption of the computer control system, the reverse osmosis water treatment and the pumps lack.

12.2.1.3 Nutrients

As no information is known on theoretical nutrient requirements of crops, and since nutrient additions do not seem to follow a regular pattern, it is quite impossible to determine the reliability and completeness of the nutrient input dataset on sites where manual addition took place. This reliability would have depended on the consistency of the administration regarding manual addition of fertilizer as well as on the accuracy of the weighting. None of this was however verified by the researchers. At the QO hotel, however, where a computer program recorded fertilizer addition data, the artificial nutrient supply data were considered very accurate. Also, data on organic fertilizer additions regarded as reliable, as the farmer kept the empty containers for this research to verify.

12.2.1.4 General observations and recommendations for data collection on resource use

Several challenges are faced during the data collection process of this thesis. In this section some recommendations will be given on how to work around them, based on empirical observations and advice from experts.

First of all, although it is tempting to jump right into data collection at the kick-off of a new farm, it is recommended not to measure resource needs at farms which have just started operating. It is better to wait with data collection when the farm has started sailing into calmer, more steady waters. Start-up problems, unrelated to normal production, are bound to create outliers and skew results. Moreover, during this period, farmers are even more occupied than else. Completely understandable, however, the busy schedule of commercial farmers seemed to impede them in general from consistently participating in data collection. This resulted in gaps in data series when manual data collection was required.

At community farms, where a large number of volunteers shares duties, it is easy to lose overview on whom is adding water, at which moment and in what quantity. In absence of the researcher, it is recommended to appoint one person or a very small group of committed volunteers to carry the responsibility for data collection at each farm. Although remaining volunteers are often highly motivated and willing to cooperate, it cannot be guaranteed that some resource additions are not registered due to ignorance, idleness, supposed lack of importance and/or occupation by other responsibilities. Therefore, especially when manual measurements need to be taken, it is important to visit the case study site regularly. In this way one gets a feel for the place and its operation, including potential data errors and assumptions in data collection. Moreover, it has proven to motivate farmers and encourage volunteers to continue the good work. Actively participating in community gardening sessions, while explaining the goal and importance of the study, and creating information signs for the farm, help to get all those involved on board.

A technical solution to be less dependent on farmers and/or volunteers for data collection, would be to merely investigate sites where data are automatically collected by monitoring systems. In those cases, it must be checked if all electricity consuming appliances are connected to the system in place and measured by the meter. Moreover, it is recommended to check exactly which flow is measured by the water meter, in order to avoid confusion when water circulation instead of net water use is registered. Having to install additional meters can pose a challenge, especially in high-tech farms where the water system is closed and electrical wiring is tucked away, because that makes it hard to reach target water pipelines and electricity cables. Anyway, only studying resource use at high-tech farms would provide a very limited view on the wide spectrum of existing farming forms.

A better option would be to install or make use of water and electricity meters equipped with pulse counting data loggers with a connection to the internet at all sorts of farms.
Not only will this set up simplify the entire collection procedure, it will also make the collected data series more reliable and consistent. Moreover, when such a system is in place, the farmer can give his attention to the farm's priority, which is producing crops, not collecting research data. The acquisition of pulse counting data loggers in particular is, however, costly and therefore, this set-up might not always financially feasible within the research budget.

12.2.2 Resource availability in urban waters

Both in Boston and in Amsterdam, rainfall data have been monitored by renowned institutes for a long time, supplying an extensive and reliable dataset to this study to execute rainwater availability computations. In both cities, however, sewage availability is determined using a wide range of generalized data and assumptions, making for a feeble assessment.

The wastewater quantity at a potential treatment facility's disposal is estimated based on neighbourhood sewer lay-out maps - which often fail to show the entire upstream sewer area - in combination with data on the average local water consumption and household composition. In further research, it is recommended to use city-wide sewer maps and more accurate population density data, in order not to underestimate the number of people discharging sewage into the pipe segment under investigation. Placing equipment at the target area in the sewer to carry out flow measurements, however, would be the most ideal solution to determine the available sewage quantity locally.

Assumptions made on wastewater quality are also way rougher than desired. Since no water quality data on sewage streams were available at a local scale, in both cities the availability of energy and nutrient in sewage stocks was estimated using information on concentrations in wastewater influent at the local centralized treatment station. However, during and after a rain event, the dry weather flow in a combined sewer system is highly diluted, and a much larger volume of water is needed to recover the required amount of nutrient and energy than during dry periods. Only making use of dry weather flows to calculate design requirements of treatment stations would therefore result in the design of undersized treatment facilities that turn out not to produce sufficient resources during rain events.

On the other hand, using water quality data of a sewer end station where flows from combined and separate sewers have been combined, underestimates the concentrations of compounds in sanitary waste pipelines of a separate sewer system. Therefore, when use is made of the sanitary waste flow only, this underestimation would still ensure resource supply, but would come at the cost of a waste of financial and building resources for the construction of oversize facilities.

Taking wastewater quality samples from the sewer segment under investigation, and analysing its COD, ammonium, nitrate and (ortho-)phosphate content, would solve this problem.

12.2.3 Further recommendations on future research on resource demand and availability

Although this study tried to explore visions of spatial planners on anticipated changes in infrastructure and future arrangements of the area, the expected local population growth and local manifestations of climate change, much of the information on local future scenarios was not readily available. Certain is, however, that the future is bound to look differently. Therefore, for prospective studies it is recommended to incorporate a scenario analysis. Especially when future-proof recommendations are requested it would be valuable to design for future needs instead of solely providing recommendations for current circumstances at the risk of under designing infrastructure or other measures.

Both scenarios on the future availability of and demand for resources need to be studied. Changes in spatial planning, urban development, demographics and trends in (water, energy, food and fertilizer) consumption and climate, can all influence the allocation of stocks and the dimension of flows, like wastewater production and rainwater availability in the local WEF nexus. Expansion of urban farming activities, however, could increase the demand for these resources. Also, further research should establish the effect of higher temperatures due to global warming and higher CO_2-concentrations in the atmosphere on agricultural production rates and resource consumption. Moreover, it would be valuable to get a grasp of a change in local rain patterns, to see if extremes of water availability and occurrence of dry spells would shift, resulting in higher storage and/or pumping requirements for farms that aim to be self-sufficient, affecting spatial arrangements.

13 Discussion on the Future of Urban Farming

Urban farming comes in many shapes and forms, what makes generalizations in general extremely blunt. There are however certain conclusions that can be drawn after having had a look behind the scenes at a wide variety of farms at different locations worldwide during this research process.

13.1 Financial struggles

The first thing that comes to mind is that commercial urban farms are having a hard time to make their operation financially feasible. Urban farms produce high quality crops and their yield per unit area outshine the yield density in conventional agriculture. However, high land prices, small-scale production and advanced indoor growing techniques make the produced crops significantly more expensive than similar products bought at the supermarket. On the globalized market, urban growers therefore have to fight an uphill battle against large scale open field farmers. It's for good reason that commercial farms switch to more high value crops, like marihuana (Corner Stalk) or grow niche products like liquorice basil and edible Nasturtium flowers (QO) to manage financially or add sufficient value to their existence.

The financial struggle, however, does not invalidate the existence of urban farms. Both commercial and other types of urban crop cultivation create added value to the local community, whether it is in the form of an improved food security, a green refuge in the city, a strengthened sense of community or as an educational experience.

13.2 Social recommendations for urban farming systems in a WEF nexus context

During this study some wonderful examples have been encountered on the positive impact of urban agriculture on local communities and sustainability. Especially community farms seem to have a large societal impact as they mobilize people to work together in a pleasant environment, creating social cohesion while improving food security. Exchange on knowledge about crop production, resource use, ecology and much more make that farms also serve as educational experience. Moreover, involvement of people in the farming process can create awareness on the value of resources. Letting people actively participate in compost production and rainwater harvesting on behalf of the farm, could support them to apply similar recycling/reuse practices at home, resulting in more resource savings.

Commercial farms run their operation to make money. Making a societal impact is not their greatest priority. Nonetheless, they too are advised to combine their farming affairs with educational activities. Providing information and guided tours could even generate some additional income for their business and the vast amount of knowledge farmers possess, combined with impressive high-tech installations, could have an inspirational effect on visitors, resulting in wider application of efficient techniques in society.

13.3 Technical recommendations on resource use and supply

Many (commercial) indoor farms seem to employ highly efficient techniques to arrange water, nutrient and energy supply to their crops. Red and blue LED lights (state-of-the-art photochemical energy suppliers), fertilizer dispenser systems (releasing nutrients depending on EC concentrations in the irrigation water) and water hydroponic circulation systems (catching water that dripped out of the growing medium before reapplying it again) all ensure a high efficiency of resource addition. Many of those techniques, however, supply artificial sources of input to the crop cultivation process.

Although artificialization also occurs in modern day conventional agriculture, where irrigation water is transported from afar and synthetic fertilizers are the norm, high-tech urban farming seems to have further stretched this trend. A common feature in (commercial) high-tech farms seems to be that natural sunlight is replaced or at least supplemented by artificial sources of light. Moreover, indoor farms tend to resist seasonal fluctuation in temperature by employing air conditioning and/or heaters.

Understandably, it is financially rewarding to allow crop cultivation year-round and even 24/7 by supplying extra light and heat in winter and/or at night. From a WEF-nexus perspective, however, it would be recommendable to make use of as many natural sources of light and heat as possible. Although LED lights are highly efficient when compared to other artificial light sources, they consume electricity nonetheless. Making use of the abundance of natural sunlight, could reduce the need for electricity to power LED lights during the day.

When closed shipping containers are used, where sunlight normally doesn’t reach the crops, a roof window placement could offer a more sustainable solution. Ideally, this window should be covered with reflecting curtains at times that electricity savings on light are outnumbered by the need for extra air conditioning on days that radiation is high.

If is decided that additional light has to be used to boost production anyhow, application of red and blue LED lights is recommended.

The installation of a thermal storage facility where cold water is stored during winter and released during summer, and warm water is stored during summer and released during winter could reduce the need for both heating and air conditioning in the indoor farms too.

Alternatively, solar panels could be installed on the roof in order to reduce the energy required from the net. All these solutions however, require large investments, which might be hard to earn back with the current energy prices.

Not only natural supply of energy should be encouraged, also natural local water sources should be optimally made use of. Unlike in rural areas with lots of farming, rain falling on urban surfaces usually doesn’t translate in added value but can result in nuisance instead. Therefore, harvesting rainwater could kill two birds with one stone. Moreover, local rainwater harvesting could reduce energy requirements for both wastewater transport, treatment and drinking water supply. As a first step, it is recommended to collect rain falling on the farm’s surfaces. If this doesn’t result in sufficient water to sustain the crops, it is advocated to try and convince owners of neighbouring dwellings to drain their rooftop runoff into the farm’s storage facility.

13.4 Spatial recommendations

Although urban farming will typically always be more small-scale than conventional open field culture, commercial urban farms of the larger sort are generally more viable as they benefit from economies of scale. Stacking container farms on top of each other, for example would increase the space efficiency even more, reducing the land price per unit production.

Whether stacked or not, urban farms, and container farms in particular, can put fallow land to good use, as they can be installed on places that are temporarily idle. This temporary placement would however make it financially unattractive to install an extensive water harvesting infrastructure and/or a local decentralized treatment facility for a connection with the sewer, which brings us to another reflection.

The arrangement of multiple small decentral treatment stations would reduce the volume to be treated at the centralized treatment station, potentially allowing for a piping system with reduced diameters downstream, which would save equipment costs for new networks. Furthermore, a smaller pollutant load will need to be treated centrally, reducing centralized treatment costs. Moreover, when smaller sewage quantities are transported over long distances, pumping costs could be reduced. Future studies should point out the breakeven point, indicating at which locally treated sewage volume resource savings surpass capital expenditures.

Although significant amounts of resources could be harvested from local sewers, it is questionable whether it is financially feasible to install small local treatment facilities to harvest small quantities of energy and nutrients from sewage. It was suggested by the owner of Corner Stalk container farm in Boston that the installation of a drinking water connection to the farm would cost over $10,000. It can only be imagined that a connection to the sewer system combined with the assembly of a decentralized treatment facility would cost even more. Although costs could be reduced by installing the linking infrastructure when refurbishing the sewer system, it remains certain that a relatively large investment needs to be made to excavate existent pipes and create a connection with the farms, including adequate treatment steps. As discussed before, many farms are struggling to keep their heads above the water financially, and such an investment in local treatment could be too much to ask.

The infliction of the required infrastructure to establish an afore mentioned link between urban farms and the sewer system, might not even be a sustainable one either, as production, transport and assembly of infrastructural parts cost energy, water and materials too.

A more fitting alternative for local resource harvesting from sewage, would be to apply resource harvesting techniques in the centralized treatment plant of an urban region. This would reduce the total amount of building materials required, simplify maintenance and waive costs for refurbishing the sewer to create connections with urban agriculture. The centralized treatment plant can then supply the harvested nutrients to local farms and supply energy to the net for everyone to benefit.

14 Conclusion

Acquisition of quality data poses the biggest challenge in WEF nexus research. This was not only experienced during the creation of the holistic nexus framework, but also the method for on-site data collection and local case study analysis that this study applied brought to the surface a wide range of data gaps.

The mere absence of data collected at the urban level or the fact that it is scattered under the jurisdiction of various departments result in information dissemination and eventually in a lack of coherency. Moreover, most work which has been published on the WEF nexus is very hypothetical and lacks hard quantifications. Much more research must be done to monitor local links in general, as this is where the nexus factually takes place. In particular, quantitative data on nexus flows must be gathered in the field to be able to make informed decisions on nexus sector integration and feasibility of sustainable solutions. Even though this study aimed to close a tiny gap in the WEF nexus quantification, a critical reflexion teaches that not all data collected in this study have a sufficient reliability to contribute to solid quantitative recommendations on the feasibility and implementation of the integration of urban waters and urban farms.

Nonetheless, a few conclusions will be drawn. First of all, it can be concluded that demands for water and nutrients (nitrogen & phosphorus) for a greenhouse in Amsterdam, a community farm and a container farm in East-Boston can be met by resources present in urban waters (rainwater and wastewater) in the direct vicinity. Whether enough energy is available to run each of these farms, seems to depend on the type of agriculture which is applied.

As long as enough rainwater collection surfaces are exploited by a farm, every farm can be supplied with sufficient water. The container farm and the greenhouse could even provide sufficient water for their operation by solely capturing water falling on their own roof. Although, not all water that could be captured on those rooftops has to be kept in stock, in all three case study farms a storage facility is needed to ensure enough water availability during dry periods.

A substantial storage of 5.7 to 6.8 m^3 needs to be realised at Eastie Farm to overcome the second largest and the largest drought in the last 20 years respectively. At the container farm a storage volume of 1.2 m^3 seemed to be sufficient to overcome the greatest drought in our records, but this is likely a large underestimation, due to missing water demand data. Storage requirements at the rooftop greenhouse varied between 35 m^3 and 45 m^3, depending on the length of the growing season and permitted occurrence of a water shortage.

Indoor culture at Corner Stalk container farm, applying artificial cooling, lighting and water distribution, while not making use of natural sunlight and ventilation, results in a substantial energy consumption. As a result of the extent of this energy use in combination with the limited energy load in the local sewage, the wastewater stream analysed in this study cannot provide sufficient energy to operate one – let alone four – container farm unit.

The QO greenhouse consumes a lot less energy, presumably because no air conditioning is used and the potential for catching natural sunlight is utilized optimally. The energy content from biogas harvested from the sanitary wastewater stream of a semi-full QO hotel can accommodate the vast majority of the average energy consumption of the rooftop greenhouse in summer. Extremes in energy use, however, cannot be met.

On average, sewage carried enough nutrients to provide the average daily nitrogen and phosphorus demand at all three case study sites. At the container farm and the hotel greenhouse, where fertilizer was added consistently, even extremes in daily demand could be met by the average daily nutrient load in wastewater. Only at the community farm in East-Boston, where nutrients were added occasionally in bulk in the form of compost, the nearby sewer could provide enough nitrogen to meet the largest outlier, but did not carry sufficient phosphorus to meet the peak demand. Striking is that the wastewater volume that needs to be treated to harvest sufficient nitrogen, is consistently and significantly smaller than the volume needed for phosphorus recovery. If a 100% recovery can be assured, less than half a cubic meter of Bostonian sewage contains enough nutrients for a farm residing in a single container, whereas almost 3 m^3 is required to accommodate fertilizer needs at Eastie Farm community garden. Treatment requirements for the greenhouse in Amsterdam are of a similar order of magnitude.

Spatial measures that have to be taken in order to facilitate urban agricultural initiatives to grow crops without requiring water, energy and nutrients inputs from outside the city, consist of installing rainwater harvesting infrastructure, creating storage capacity and realizing affordable treatment.

Rainwater harvesting constitutes a huge potential for reducing water scarcity. Roofs were considered the best catchment area, due to their omnipresence and their relatively clean runoff. Although not all roofs can support farming activities, most existing roofs can be used to harvest water. Only those structurally strong enough can also store (large) volumes of water on top.

Water storage can be realised in a variety of ways. Gathered data – although questionable - show that the container farm does not even have to create additional storage space when making use of rainwater as its sole water supply, since the barrels inside the farm should hold sufficient water to overcome drought. At the community farm, however, a large additional water storage needs to be accommodated. Here, water tanks underneath raised beds could space-efficiently store precipitation caught on neighbouring roofs. Realising required storage for the rooftop greenhouse in a large (35-45 m^3) tank on the 22nd floor of a hotel might however pose a problem. This water volume might be too heavy for the roof to hold, though that has to be checked by a structural engineer. From a nexus perspective of resource reuse and saving, this option is however much preferred, as it reduces pumping requirements to a minimum, saving energy.

In order to ensure a sustainable daily nutrient and energy supply to urban farms, a local connection to the nearby sewer can be created, which would honour wastewater as the valuable resource it is. Although most of the times nutrient demands can be met effortlessly, the local sewer cannot always provide sufficient energy to farms, especially when indoor farms are concerned which display a relatively high energy consumption.

This consideration, combined with the fact that extensive treatment facilities would have to be implemented to treat only a small amount of sewage, raises doubts on the financial stimulus that is created by such a sewer connection. A micro-economical study must point out for which decentrally treated volume exactly it becomes profitable for farmers to invest in a wastewater reuse installation.

All things considered, current large-scale resource recovery operations at centralized treatment facilities are preferred. Struvite harvested at these facilities can be distributed to local farms, and close the waste-to-resource loop in that way. Biogas produced during anaerobic digestion of sewage could serve as energy supply to the net for everyone to benefit.

15 Bibliography

- Adam, K.L. (2006) *Community Supported Agriculture*, National Sustainable Agriculture Information Service, National Center for Appropriate Technology. Retrieved on January 4, 2018, from: https://attra.ncat.org/attra-pub/summaries/summary.php?pub=262
- Adams, E.J., Grummer-Strawn, L. & Chavez, G. (2003) Food Insecurity Is Associated with Increased Risk of Obesity in California Women. *Journal of Nutrition*, *133* (4) 1070-1074.
- Adnan, A., Mavinic, D. S. & Koch, F. A. (2003) Pilot-scale study of phosphorus recovery through struvite crystallization -examining the process feasibility. *Environmental. Engineering & Sciences*, *2*, 315–324.
- Agriculture & Energy Efficiency (AGREE) (2015) Economic and Environmental Analysis of Energy Efficiency Measures in Agriculture: Case Studies and Trade Offs. Retrieved from: http ://www.agree.aua.gr/Files/Publications/D3.1_Econ+enviro_analysis_of_EE_measures_in_Agr.pdf [Secondary citation]
- Ahsan, S., Knaeco, S., Rahman, M.A., Katsumata, H. (2005) Effect of temperature on wastewater treatment with natural and waste materials. *Clean Technologies and Environmental Policy* 7, 198–202.
- Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D. & Rounsevell, M.D.A. (2017) Losses, inefficiencies and waste in the global food system. *Agricultural Systems*, 153, 190-200.
- Allan, T., Keulertz, M. & Woertz, E. (2015) The water–food–energy nexus: an introduction to nexus concepts and some conceptual and operational problems. *International Journal of Water Resources Development*, 31 (3), 301–311.
- American Hydroponics (AmHydro) (2019) AmHydro Lettuce Nutrient Formulation. Retrieved on June 15, 2019, from: https://shop.amhydro.com/collections/leafy-greens-herbs-etc/products/88112r
- Ammerlaan, L. (2018) Samenstelling voeding [Excel Data Set]
- Arienzo, M., Christen, E.W., Quayle, W. & Kumar, A. (2009) A review of the fate of potassium in the soil–plant system after land application of wastewaters. *Journal of Hazardous Materials*, 164, 415–422.
- Asano, T. (1998) *Wastewater Reclamation and Reuse* (Boca Raton, FL: CRC Press)
- Atkinson, D.E. (1977) *Cellular Energy Metabolism and its Regulation*. New York: Academic Press Inc.
- Babayan, M., Javaheri, M., Tavassoli, A., & Esmaeilian, Y. (2012) Effects of using wastewater in agricultural production. *African Journal Pharmacy Pharmacology*, 6(1), 1–6.
- Baras, T. (2018) *The Quality Standards for Hydroponic Lettuce.* Retrieved on October 21, 2019, from: https://urbanagnews.com/blog/exclusives/the-quality-standards-for-hydroponic-lettuce/
- Barles, S. (2007-1) Urban metabolism and river systems: an historical perspective – Paris and the Seine, 1790-1970. Hydrology and Earth System Sciences 11 (6), 1757–1769.
- Barles, S. (2007-2) Feeding the city: food consumption and flow of nitrogen, Paris 1801-1914. *Science of the Total Environment*, 375 (1-3), 48-58.
- Barthel, S. & Isendahl, C. (2013) Urban gardens, agriculture, and water management: Sources of resilience for long-term food security in cities. *Ecological Economics*, 86, 224–234.
- Baptista, P. (2014) *Water Use Efficiency in Hydroponics and Aquaponics*. Retrieved on September 26, 2019, from: http://blog.zipgrow.com/water-use-efficiency-hydroponics-aquaponics/
- Bartone, C.R. et al. (1985) Monitoring and Maintenance of Treated Water Quality in the San Juan Lagoons, PAHO/WHO/CEPIS, Lima. [Secondary citation]

- Bazilian, M., Rogner, H., Hoells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. S. J. & Yumkella, K. K. (2011) Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy,* 39, 7896–7906.
- Belfer Center (2010) Water Consumption of Energy Resource Extraction, Processing, and Conversion, Retrieved from: http://belfercenter.ksg.harvard.edu/files/ETIP-DP-2010-15-final-4.pdf [Secondary citation]
- Betz, A., Buchli, J., Gobel, C. and Muller, C. (2018) Food waste in swiss food industry magnitude and potential for reduction. *Journal of Waste Management,* 35:218-26.
- Beuken, R.H.S., Lavooij, C.S.W., Bosch, A. & Schaap, P.G. (2008) Low leakage in the Netherlands confirmed. [Conference Paper]. doi:10.1061/40941(247)174
- Bloomberg (Year unknown) *Ethanol Demand in U.S. Adds to Food Fertilizer Costs (Update3),* http://www.bloomberg.com/apps/news?pid=newsarchive&sid=aUIPybKj4IGs [Secondary citation]
- Born, B. & Purcell, M. (2006) Avoiding the Local Trap. *Journal of Planning Education and Research, 26*, 195-207.
- Boston Landmarks Commission (BLC) (1994) *East Boston: Exploring Boston's Neighborhoods*. Retrieved on September 6, 2019, from: https://www.cityofboston.gov/images_documents/East_Boston_brochure_tcm3-19117.pdf
- Boston Planning & Development Agency (BPDA) (2017) *Neighborhood profile East Boston*. Retrieved on September 10, 2019, from: http://www.bostonplans.org/getattachment/28c2e99c-af11-47e0-b65e-b609fbdc44bd
- Boston Water and Sewer Commission (BWSC) (2019) *Project Lookup: East Boston -Brooks St–12389*. Retrieved on September 29, 2019, from: https://www.bwsc.org/projects/east-boston/12389
- Boxman, A.W., Cobben, P.L.W. & Roelofs, J.G.M. (1994) Does (K+Mg+Ca+P) fertilization lead to recovery of tree health in a nitrogen stressed Quercus rubra L. stand? *Environmental Pollution*, 85, 297–303.
- Brown, C. (2003) Consumers' preferences for locally produced food: A study in southeast Missouri. *American Journal of Alternative Agriculture, 18* (4), pp. 213-224
- Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) (German Ministry for the Environment, Nature Conservation, Building and Nuclear Safety) (2015) *Grün in der Stadt – Für eine lebenswerte Zukunft: Grünbuch Stadtgrün.* Berlin, Germany: BMUB, p. 100 (in German). [Secondary citation]
- Butler, D. & Davies, J. (2010) *Urban Drainage.* 3rd edition, CRC Press, 656p.
- Buzby J.C., Wells H.F. and Hyman J. (2014) The estimated amount, value and calories of postharvest food losses at the retail and consumer level in the United States. *Economic Research Service, 121*, United States Department of Agriculture [Secondary citation]
- Campbell, J.E., Lobell, D.B., Genova, R.C. & Field, C.B. (2008) The global potential of bioenergy on abandoned agriculture lands. *Environmental Science & Technology*, 42, 5791–5794. [Secondary citation]
- Campos, J.L., Crutchik, D., Franchi, Ó., Pavissich, J.P., Belmonte, M., Pedrouso, A., Mosquera-Corral, A. & Val del Río, Á. (2019) Nitrogen and Phosphorus Recovery from Anaerobically Pretreated Agro-Food Wastes: A Review. *Frontiers in Sustainable Food Systems*. doi: 10.3389/fsufs.2018.00091
- Canet, W. (1988) Determination of the Moisture Content of Some Fruits and Vegetables by Microwave Heating. *The Journal of microwave power and electromagnetic energy*. doi: 10.1080/08327823.1988.11688062
- Carey, W.K., Ashlynn, S.S., Kelly, M.T. & Michael, E.W. (2013) Coherence between water and energy policies. *Natural Resources Journal*, 53, 117–215.

- Carpio, C.E. & Isengildina-Massa, O. (2009) Consumer Willingness to Pay for Locally Grown Products: The Case of South Carolina. *Agribusiness, 25* (3) 412–426.
- Center for Sustainable Systems, University of Michigan (CSS) (2010) U.S. Water Supply and Distribution Fact Sheet. Pub No. CSS05-17, Retrieved from: http://css.snre.umich.edu/css_doc/CSS05-17.pdf [Secondary citation]
- Centraal Bureau voor de Statistiek (CBS) (2014) *Milieurekeningen; watergebruik 2003 – 2011.* Retrieved on January 14, 2018, from: http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=81398NED&D1=0-1,4&D2=2-25,39-40,43-44,48-51,54,58&D3=0,l&HDR=T,G2&STB=G1&VW=T
- Centraal Bureau voor de Statistiek (2017-1) *Watergebruik bedrijven en particuliere huishoudens; nationale rekeningen.* Retrieved on March 11, 2019, from: https://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82883NED&D1=0-1,4&D2=0-1,3,5-7,15,39-41,43,45-48&D3=8,l&HDR=T&STB=G1,G2&VW=T
- Centraal Bureau voor de Statistiek (2017-2) *Aantal inwoners – 100 meter vierkant.* Retrieved on October 31, 2019, from: https://cbsinuwbuurt.nl/#sub-vierkant100m_aantal_inwoners_2017
- Centraal Bureau voor de Statistiek (CBS) (2019) *Watergebruik bedrijven en particuliere huishoudens; nationale rekeningen.* Retrieved on September 4, 2019, from: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82883NED/table?fromstatweb
- Chang, Y., Li, G., Yao, Y., Zhang, L. & Yu, C. (2016) Quantifying the Water-Energy-Food Nexus: Current Status and Trends, *Energies* 9 (65). doi:10.3390/en9020065
- Charles River Watershed Association (CWRA) (2012) *Littleton, Massachusetts Smart Sewering Strategy*. Retrieved on May 15, 2018, from: https://www.crwa.org/hs-fs/hub/311892/file-663447085-pdf/
- City of Boston (2019) *East Boston*. Retrieved on September 10, 2019, from: https://www.boston.gov/neighborhood/east-boston
- Colby, S.L. & Ortman, J.M. (2015) *Projections of the Size and Composition of the U.S. Population: 2014 to 2060*, Current Population Reports, P25-1143, Washington, DC: U.S. Census Bureau.
- Coleman-Jensen, A., Gregory, C., Singh, A. (2014) *Household Food Security in the United States in 2013*, ERR-173, U.S. Department of Agriculture, Economic Research Service
- Coley, D., Howard, M., Winter, M. (2009) Local food, food miles and carbon emissions: A comparison of farm shop and mass distribution approaches. *Food Policy, 34*, 150–155.
- Cordell, D., Drangert, J.-O., White, S. (2009) The story of phosphorus: Global food security and food for thought. *Global Environmental Change 19 (2)*, 292–305.
- Corominas, L.L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S. & Shaw, A. (2013) Life cycle assessment applied to wastewater treatment: state of the art. *Water Research*, 47(15), 5480-92.
- Cook, J.T., Frank, D.A., Berkowitz, C., Black, M.M., Casey, P.H., Cutts, D.B., Meyers, A.F. Zaldivar, N., Skalicky, A., Levenson, S., Heeren, T., & Nord, M. (2004) Food Insecurity Is Associated with Adverse Health Outcomes among Human Infants and Toddlers. *Journal of Nutrition, 134* (6) 1432-1438.
- Curtis, F. (2003) Eco-localism and sustainability. Ecological Economics, 46, 83−102.
- Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., Song, X., Jia, B., Xue, W., Yang, Q. (2018) Water-energy nexus: A review of methods and tools for macro-assessment. *Applied Energy*, 210, 393-408.
- Daigger, G.T. (2009) Evolving Urban Water and Residuals Management Paradigms: Water Reclamation and Reuse, Decentralization, and Resource Recovery. *Water Environment Research, 81* (8), August, pp. 809-823

- Decker, E.H., Elliot, S., Smith, F.A., Blake, D.R., & Rowland, F.S. (2000) Energy and material flow through the urban ecosystem. *Annual Review of Energy and Environment*, 25, 685–740.
- Dewey, C. (2017) The surprising number of American adults who think chocolate milk comes from brown cows. *Washington Post*. Retrieved on March 15, 2018, from: https://www.washingtonpost.com/news/wonk/wp/2017/06/15/seven-percent-of-americans-think-chocolate-milk-comes-from-brown-cows-and-thats-not-even-the-scary-part/?noredirect=on&utm_term=.156135b8cf72
- Dieter, C.A., Linsey, K.S., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Maupin, M.A., & Barber, N.L. (2017) *Estimated use of water in the United States county-level data for 2015: U.S. Geological Survey data release*. Retrieved on October 3, 2017, from https://doi.Org/10.5066/F7TB15V5 [Secondary citation]
- Dieter, C.A., Maupin, M.A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Barber, N.L., & Linsey, K.S. (2018) Estimated use of water in the United States in 2015: U.S. Geological Survey, 65 p., https://doi.org/10.3133/cir1441
- Douglas, I. (1983) *The urban environment*. London, U.K.: Edward Arnold.
- Elger, D.F., Williams, B.C., Crowe, C.T. & Roberson, J.A. (2014) Engineering Fluid Mechanics: SI version. New York: John Wiley & Sons Inc. 10th ed. ISBN: ES8-1-118-31875-1
- Elliot, S., Decker, E.H., Smith, F.A., Blake, D.R., Simpson, I.J., & Rowland, F.S. (2000) Cities in the earth system. *Environmental Science & Policy*, 3, 157–160.
- Endo, A., Tsurita, I., Burnett, K., Orencio, P.M. (2017) A review of the current state of research on the water, energy, and food nexus, *Journal of Hydrology: Regional Studies*, 11, 20–30.
- Energieonderzoek Centrum Nederland (ECN) (2017) Nationale Energieverkenning 2017. Amsterdam/Petten
- Energy Information Administration of the U.S. (EIA) (2017-1) U.S. Energy Facts Explained: Consumption & production. Retrieved on January 15, 2018, from: https://www.eia.gov/energyexplained/index.cfm?page=us_energy_home
- Energy Information Administration of the U.S. (EIA) (2017-2) U.S. Energy Facts Explained: Basics. Retrieved on January 15, 2018, from: https://www.eia.gov/energyexplained/index.cfm?page=us_energy_industry
- Energy Information Administration of the U.S. (EIA) (2019) *Use of energy explained.* Retrieved on September 18, 2019, from: https://www.eia.gov/energyexplained/use-of-energy/
- Ensink, J.H.J., Blumenthal, U.J. & Brooker, S. (2008) Wastewater quality and the risk of intestinal nematode infection in sewage farming families in Hyderabad, India. *The American Journal of Tropical Medicine and Hygiene*, 79, 561–567
- Environmental Research and Education Foundation (EREF) (2015) Anaerobic digestion of municipal solid waste. [Secondary citation]
- Ernstson, H., Van der Leeuw, S.E., Redman, C.L., Meffert, D.J., Davis, G., Alfsen, C. & Elmqvist, T. (2010) Urban transitions: on urban resilience and human-dominated ecosystems. *Ambio*, 39 (8), 531–545.
- European Environment Agency (EEA) (2012) Climate Change, Impacts and Vulnerability in Europe. EEA: Copenhagen, Denmark, p. 304.
- Fabiola, R. & De Rosa, D. (2016) How the nexus of water/food/energy can be seen with the perspective of people well-being and the Italian BES framework. *Agriculture and Agricultural Science Procedia*, 8, 732–740.
- Farreny, R., Morales-Pinzón, T., Guisasola, A., Tayà, C., Rieradevall, J. & Gabarrell, X. (2011) Roof selection for rainwater harvesting: Quantity and quality assessments in Spain. *Water research*, 45, 3245-3254.

- Faure, G. (1998) *Principles and Applications of Geochemistry: a comprehensive textbook for geology students*. 2nd ed., 600 p. ISBN: 0-02-336450-5.
- Feng, K., Chapagain, A., Suh, S., Pfister, S. & Hubacek, K. (2011) Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. *Economic Systems Research*, 23, 371–385. [Secondary citation]
- Fischer, G., Shah, M., Tubiello, F.N., & Van Velhuizen, H. (2005) Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Philosophical Transactions of the Royal Society B 360 (1463),* 2067–2083
- Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M.A., Munch, J.C. & Beese, F. (2002) Integrated evaluation of greenhouse gas emissions (CO2, CH4, N2O) from two farming systems in southern Germany. *Agriculture, Ecosystems & Environment*, 91, 175–189. [Secondary citation]
- Food and Agriculture Organization of the United Nations (FAO) (1996). *Rome declaration on world food security and world food summit plan of action*. World Food Summit. FAO, Rome, pp. 13–17.
- Food and Agriculture Organization of The United Nations (FAO) (1997) *Quality control of wastewater for irrigated crop production*. Chapter 2. FAO: Rome. ISSN 1020-1203
- Food and Agriculture Organization of the United Nations (FAO) (2011) *Energy Smart Food for People and Climate*, Rome. [Secondary citation]
- Food and Agriculture Organization of the United Nations (FAO) (2012) *Energy-Smart Food at FAO: An Overview*. Rome, Italy: FAO. [Secondary citation]
- Food and Agriculture Organization of The United Nations (FAO) (2014*) The Water-Energy-food Nexus A new approach in support of food security and sustainable agriculture*, Rome FAO Publishing [Secondary citation]
- Food and Agriculture Organization of the United Nations (FAO) (2015-1) *World fertilizer trends and outlook to 2018*. FAO: Rome. ISBN 978-92-5-108692-6.
- Food and Agriculture Organization of the United Nations (FAO) (2015-2) *Water Uses Database*. [Secondary citation] Retrieved from: http://www.fao.org/nr/water/aquastat/water_use/index.stm
- Food and Agriculture Organization of the united Nations (FAOSTAT) (2017) *FAOSTAT: Crops*. Retrieved on November 2, 2019, from: http://www.fao.org/faostat/en/#data/QC
- Food and Agriculture Organization of the United Nations (FAO) (2019-1) *Chapter 3: Crop Water Needs*. Retrieved on October 21, 2019, from: http://www.fao.org/3/S2022E/s2022e07.htm#3.2%20influence%20of%20crop%20type%20on%20crop%20water%20needs%20(kc)
- Food and Agriculture Organization of the United Nations (FAO) (2019-2) *Food Balance Sheets – Download Data*. Retrieved on July 26, 2019, from: http://www.fao.org/faostat/en/#data/FBS
- Food and Agriculture Organization of the United Nations (FAO) (2019-3) *Chapter 2: Crop Water Needs*. Retrieved on October 21, 2019, from: http://www.fao.org/3/s2022e/s2022e02.htm
- Freeze, R.A. & Cherry, J.A. (1979) *Groundwater*. Prentice Hall, 604 pp.
- Future Cities (2013) The Future Cities Guide: Creating Liveable and Climate-Proof Cities. Munich, Germany: Lippeverband Publishers. p. 80. [Secondary citation]
- Garnett, T., Bakker, et al. (2000) Urban agriculture in London: rethinking our food economy. Growing Cities, Growing Food: Urban Agriculture on the Policy Agenda. A Reader on Urban Agriculture, p. 540. [Secondary citation]
- Gellings, C.W. & Parmenter, K.E. (2004) *Energy Efficiency in Fertilizer Production and Use*. Oxford, UK: Eolss Publishers. [Secondary citation]
- Gemeente Amsterdam Dienst Ruimtelijke Ordening (2011) *Bestemmingsplan Amstelkwartier Binnendijks*. Retrieved on September 6, 2018, from:

http://www.ruimtelijkeplannen.nl/documents/NL.IMRO.03630000U002BPGST-/p_NL.IMRO.03630000U002BPGST-.pdf

- Gemeente Amsterdam (2018) *Amstelkwartier: van industrie naar stadswijk en park aan het water.* Retrieved on September 11, 2018, from: https://www.amsterdam.nl/projecten/amstelkwartier/
- Gerbens-Leenes, P.W., Hoekstra, A.Y., Van Der Meer, T. (2009) The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecological Economics*, 68, 1052–1060. [Secondary citation]
- Gerbens-Leenes, P.W., Van Lienden, A. R., Hoekstra, A. Y. & Van der Meer, T. H. (2012) Biofuel scenarios in a water perspective: the global blue and green water footprint of road transport in 2030. *Global Environmental Change*, 22 (3), 764–775.
- Giancoli, D.C. (2005) *Physics: Principles with Applications*. 6th ed., 945 p.
  Pearson Eduction Inc. ISBN: 0-13-191183-X.
- Gikas, G.D. & Tsihrintzis, V.A. (2012) Assessment of water quality of first-flush roof runoff and harvested rainwater. *Journal of Hydrology*, (466–467), 115–126.
- Gondhalekar, D. & Ramsauer, T. (2017) Nexus City: Operationalizing the urban Water-Energy-Food Nexus for climate change adaptation in Munich, Germany. *Urban Climate* 19, 28–40.
- Graamans, L J.A. (2015) Vertical – The re-development of vacant urban structures into viable food production centres utilising agricultural production techniques. [Master Thesis] Delft University of Technology.
- Grace, J. (2001) Carbon Cycle. *Encyclopedia of Biodiversity* (pp. 609-629). Academic Press.
- Hall, J.W., Henriques, J.J., Hickford, A.J. & Nicholls, R.J. (2012) *A Fast Track Analysis of Strategies for Infrastructure Provision in Great Britain: Technical Report.* Environmental Change Institute, University of Oxford.
- Hanjra, M.A., Blackwell, J., Carr, G., Zhang, F., & Jackson, T.M. (2012) Wastewater irrigation and environmental health: Implications for water governance and public policy. *International Journal of Hygiene Environment Health*, 215 (3), 255–269.
- Hedin, L.O., Vitousek, P.M. & Matson, P.A. (2003) Nutrient losses over four million years of tropical forest development. *Ecology*, 84, 2231–2255.
- Heidrich, E.S., Curtis, T.P., Dolfing, J. (2011) Determination of the Internal chemical Energy of wastewater. *Environmental Sciences & Technology*, 2, 827-832.
- Henze, M. & Comeau, Y. (2008) Wastewater characterization. *Biological Wastewater Treatment: Principles, Modelling and Design*. pp. 33-52. London: IWA Publishing.
- High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security (HLPE) (2013) *Biofuels and food security*, Rome [Secondary citation]
- Hightower, M. (2011) Energy meets water. *Mechanical Engineering*, 133(7), 34–39.
- Hill, H. (2008) *Food Miles: Background and Marketing*. National Sustainable Agriculture Information Service (ATTRA). 12 pp.
- Hochman, G., Wang, S., Li, Q., Gottlieb, P.D., Xu, F. & Li, Y. (2015) Cost of organic waste technologies: A case study for New Jersey. *AIMS Energy*, 3 (3), 450–462.
  doi: 10.3934/energy.2015.3.450
- Hoff, H. (2011). Understanding the nexus. In Background paper for the Bonn conference on the water-food-energy nexus. Stockholm: SEI [Secondary citation]
- Holt-Giménez, E., Shattuck, A., Altieri, M., Herren, H. & Gliessman, S. (2012): We Already Grow Enough Food for 10 Billion People … and Still Can't End Hunger, *Journal of Sustainable Agriculture, 36* (6), 595-598
- Houlton, B.Z., Wang, Y.P., Vitousek, P.M., Christopher, B. & Field, C.B. (2008) A unifying framework for dinitrogen fixation in the terrestrial biosphere. *Nature*, 454, 327–330.

- Howell, T.A. (2001) Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, 93, 281–9.
- Hussey, K. & Pittock, J. (2012) The energy–water nexus: managing the links between energy and water for a sustainable future. *Ecology and Society* 17 (1).
- International Energy Agency (IEA) (2008) World energy outlook 2008. Paris: IEA/OECD
- Intergovernmental Panel on Climate Change (IPCC) (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 996 pp.
- Intergovernmental Panel on Climate Change (IPCC) (2012) *Special Report on Renewable Energy Sources and Climate Change Mitigation.* Cambridge University Press: Cambridge, UK; New York, NY, USA [Secondary citation]
- Intergovernmental Panel on Climate Change (IPCC) (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Summaries, Frequently Asked Questions, and Cross-Chapter Boxes. A Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken,P.R. Mastrandrea, and L.L. White (eds.)]. Geneva, Switzerland: World Meteorological Organization, 190 pp.
- International Energy Agency (IEA) (2012) *World Energy Outlook*. Paris, France, 2012. [Secondary citation]
- International Renewable Energy Agency (IRENA) (2015) *Renewable Energy in the Water, Energy & Food Nexus*. Abu Dhabi, UAE. [Secondary citation]
- Jaffer, Y., Clark, T.A., Pearce, P. & Parsons, S.A. (2002) Potential phosphorus recovery by struvite formation. *Water Research, 36,* 1834–1842.
- Jensen, H.M. (1981) *Hydroponics worldwide – A technical overview*. Retrieved from https://pdfs.semanticscholar.org/d4a7/1ef04b4d174d00d65fc4238629db99f9bd1a.pdf [Secondary citation]
- Johansson, A.; Kisch, P.; Mirata, M. (2005) Distributed economies – A new engine innovation. J. Cleaner Prod. 13 (10−11), 971−979.
- Kessier, R. (2013) Urban Gardening: Managing the Risks of Contaminated Soil. *Environmental Health Perspectives*, 121 (11-12). https://doi.org/10.1289/ehp.121-A326
- Koninklijk Nederlands Meteorologisch Instituut (KNMI) (2018) *Late start natuur*. Retrieved on May 12, 2019, from: https://www.knmi.nl/over-het-knmi/nieuws/late-start-natuur
- Koninklijk Nederlands Meteorologisch Instituut (KNMI) (2019) *Klimatologie-Daggegevens van het weer in Nederland – Download.* Retrieved on August 29, 2018 & May 15, 2019, from: http://projects.knmi.nl/klimatologie/daggegevens/selectie.cgi
- Kooij, K. (2015) *Booster pumping stations for wastewater transport work well in practice*. Retrieved on July 11, 2019, from: https://www.deltares.nl/en/news/booster-pumping-stations-for-wastewater-transport-work-well-in-practice/
- Kurian, M. & Ardakanian, R. (Eds.) (2014) *Governing the Nexus: Water, Soil and Waste Resources Considering Global Change.* Cham: Springer International Publishing, ISBN: 978-3-319-05746-0. doi:10.1007/978-3-319-05747-7.
- Kurian, M. (2017) The water-energy-food nexus: Trade-offs, thresholds and transdisciplinary approaches to sustainable development. Environmental Science & Policy vol. 68, p. 97-106
- Kuttler, W. (2010) Urbanes Klima (Urban climate). *Umweltmeteorologie*, 70 (9), 378–382 (in German). [Secondary citation]

- Kwietniewska, E. & Tys, J. (2014) Process characteristics, inhibition factors and methane yields of anaerobic digestion process, with particular focus on microalgal biomass fermentation. *Renewable and Sustainable Energy Reviews,* 34, 491–500.
- Lancaster, B. (2006) *Guiding principles to welcome rain into your life and landscape. Rainwater Harvesting for Drylands and Beyond*. Tucson, Arizona: Rainsource Press [Secondary citation]
- Leck, H., Conway, D., Bradshaw, M. & Rees, J. (2015) Tracing the Water–Energy–Food Nexus: Description, Theory and Practice. Geography Compass 9/8: 445–460, 10.1111/gec3.12222
- Leung Pah Hang, M.Y., Martinez-Hernandez, E., Leach, M. & Yang, A. (2017) Insight-Based Approach for the Design of Integrated Local Food-Energy-Water Systems. *Environmental Science & Technology,* 51, 8643−8653. doi: 10.1021/acs.est.7b00867
- Lide, D.R. (2003) CRC Handbook of Chemistry and Physics. 84th Ed. Edited (National Institute of Standards and Technology). CRC Press LLC: Boca Raton. 2616 pp.
- Lin, C. (2008) A negative-pressure aeration system for composting food wastes. *Bioresource Technology,* 99, 7651–7656.
- Lunven, P. (1992) [Presentation at Urban Nutrition Conference, Mexico City, February]. [Secondary citation]
- Mara, D. D., & Cairncross, S. (1989) *Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture: Measures for public health protection*. Geneva, Switzerland: WHO.
- Margat, J. & Van der Gun, J. (2013) *Groundwater around the World: A Geographic Synopsis.* Boca Raton (FL, USA): CRC Press, ISBN: 978-0-203-77214-0.
- Markovič, G., Zeleňáková, M., Káposztásová, D. & Hudáková, G. (2014) Rainwater Infiltration in the Urban Areas. *WIT Transactions on Ecology and the Environment,* 181, 313-320. doi: 10.2495/EID140271.
- Martinez, S., Hand, M.S., Da Pra, M., Pollack, S., Ralston, K., Smith, T., Vogel, S., Clark, S., Lohr, L., Low, S.A., & Newman, C. (2010) *Local Food Systems: Concepts, Impacts, and Issues*, Economic Research Report No 97, U.S. Department of Agriculture, Economic Research Service. 87 pp
- Massachusetts Water Resources Authority (MWRA) (2016) *Annual Water and Sewer Retail Rate Survey*. Retrieved on September 26, 2019, from: http://mwraadvisoryboard.com/wp-content/uploads/2017/01/0-Combined.pdf
- Massachusetts Water Resources Authority (MWRA) (2017) *NPDES compliance summary report, fiscal year 2015.* Boston: Massachusetts Water Resources Authority. Report 2015-12. 152 pp
- Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., & Linsey, K.S. (2014) *Estimated use of water in the United States in 2010*: U.S. Geological Survey Circular 1405, 56 p.
- McLauchlan, K. (2006) The Nature and Longevity of Agricultural Impacts on Soil Carbon and Nutrients: A Review. *Ecosystems,* 9: 1364–1382, doi: 10.1007/s10021-005-0135-1.
- McKendry, P. (2002) Energy production from biomass: Overview of biomass. *Bioresource Technology,* 83, 37–46. [Secondary citation]
- McMahon, J.E. & Price, S.K. (2011) Water and energy interactions. *Annual Review of Environment and Resources,* 36, 163–191. [Secondary citation]
- Mekonnen, M.M. & Hoekstra, A.Y. (2011) The green, blue and grey water footprint of crops. *Hydrology and Earth System Sciences,* 15, 1577–1600.
- Mendez, C.B., Klenzendrof, J.B., Afshar, B.R., Simmons, M.T., Barrett, M.E., Kinney, K.A. & Kirisits, M.J. (2011) The effect of roofing material on the quality of harvested rainwater. *Water research,* 45, 2049-2059.
- Metabolic (2017) Hotel QO: Greenhouse Operations [Memo]
- Metcalf & Eddy, Inc. (2003) Wastewater Engineering: Treatment and Reuse, 4th ed., Revised by Tchobanoglous, G., Burton, F.L., Stensel, H.D.. McGraw-Hill Education – Europe

- Miles, A. & Ellis, T.G. (2001) Struvite precipitation potential for nutrient recovery from anaerobically treated wastes. *Water Science and Technology, 43* (11), 259-66.
- Miller-Robbie, L., Ramaswami, A. & Amerasinghe, P. (2017) Wastewater treatment and reuse in urban agriculture: exploring the food, energy, water, and health nexus in Hyderabad, India. *Environmental Research Letters*, 12 https://doi.org/10.1088/1748-9326/aa6bfe
- Mladenov, M. (2018) Chemical Composition of Different Types of Compost. *Journal of Chemical Technology and Metallurgy*, 53 (4), 712-716.
- Mo, W., Zhang, Q., Mihelcic, J.R. & Hokanson, D.R. (2016) Embodied energy comparison of surface water and groundwater supply options. *Water Research*, 45, 5577–5586.
- Mohtar, R.H. & Daher, B. (2012) Water, energy, and food: The Ultimate Nexus. doi: 10.1081/E-EAFE2-120048376.
- Mougeot, L.J.A. (2000) Urban Agriculture: Definition, Presence, Potentials and Risks and Policy Challenges. In Bakker, N., Dubelling, M., Gründel, S., Sabel-Koschella, U. and de Zeeuw, H. (Eds.) Growing cities, Growing food: Urban Agriculture on the Policy Agenda (42 pp). Feldafing, Germany: Deutsche Stiftung für internationale Entwicklung (DSE).
- Moustier, P., Mbaye, A. (1999) Introduction générale. In: Moustier, P., Mbaye, A., de Bon, H., Guérin, H. & Pagès, J. (Eds.), *Agriculture périurbaine en Afrique subsaharienne.* Actes de l'atelier international du 20 au 24 avril 1998, Montpellier, France: CIRAD, pp. 7–16.
- Murty, B.S., Venkobachar, C. & Ligy, P. (2011) Water and waste water engineering, Retrieved from: http://nptel.iitm.ac.in/video.php?subjectId=105106119S [Secondary citation]
- Nackers, L.M. & Appelhans, B.M. (2013) Food Insecurity Is Linked to a Food Environment Promoting Obesity in Households with Children. *Journal of Nutrition Education and Behavior. 45* (6), 780–784.
- National Gardening Association (NGA) (2019) *When to Plant Vegetables in Boston, MA*. Retrieved on May 12, 2019, from: https://garden.org/apps/calendar/?q=Boston%2C+MA
- National Weather Service Forecast Office (NWS) *NOWData – NOAA Online Weather Data*. Retrieved on May 23, 2019, from: https://w2.weather.gov/climate/xmacis.php?wfo=box
- Neirynck, J., Maddelein, D., de Keersmaeker, L., Lust, N. & Muys, B. (1998) Biomass and nutrient cycling of a highly productive Corsican pine stand on former heathland in northern Belgium. *Annales des Sciences Forestieres*, 55, 389– 405.
- Olesen, J.E. & Bindi, M. (2002) Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy*, *16* (4), 239–262.
- Oluchukwu, A.C., Nebechukwu, A.G. & Egbuna, S.O. (2018) Enrichment of nutritional content of sawdust by composting with other nitrogen rich agro wastes for biofertilizer synthesis. *Journal of Chemical Technology and Metallurgy*, 53(3), 430-436.
- Opitz, I., Berges, R., Piorr, A., Krikser, T. (2015) Contributing to food security in urban areas: differences between urban agriculture and peri-urban agriculture in the Global North. *Agriculture and Human Values*, *33* (2), 341–358
- Organisation for Economic Co-operation and Development & Food and Agriculture Organization of the United Nations (OECD-FAO) (2007) *Agricultural Outlook 2007–2016*. FAO: Rome, Italy. [Secondary citation]
- Oxford Dictionaries (2010) *Oxford Dictionary of English* (3rd ed.) Oxford: Oxford University Press
- Ouyang, W., Guo, B., Cai, G., Li, Q., Han, S., Liu, B. & Liu, X. (2015) The washing effect of precipitation on particulate matter and the pollution dynamics of rainwater in downtown Beijing. *Science of the Total Environment*, 505, 306–314.
- Palhares, J.C.P., Guidoni, A.L., Steinmetz, R.L.R., Mulinari, M.R., & Sigua, G.G. (2012) Impacts of mixed farms on water quality of Pinhal river sub-basin, Santa Catarina Brazil. *Archivos de Zootecnia*, 61, 493–504.

- Peronne, D. & Hornberger, G.M. (2014) Water, food, and energy security: scrambling for resources or solutions? *WIREs Water*, 1 (1), pp. 49–68. doi:10.1002/wat2.1004.
- Pescod, M.B. (1992) Wastewater quality guidelines for agricultural use. *FAO irrigation and drainage, 47*.
- Pimentel, D., Berardi, G. & Fast, S. (1983) Energy efficiency of farming systems: Organic and conventional agriculture. *Agriculture, Ecosystems & Environment*, 9, 359–372. [Secondary citation]
- Pimentel, D. & Patzek, T.W. (2005) Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Natural Resources Research*, 14, 65–76. [Secondary citation]
- Pirog, R.S., Van Pelt, T., Enshayan, K. & Cook, E. (2001) *Food Fuel, and Freeways: An Iowa Perspective on How Far Food Travels, Fuel Usage, and Greenhouse Gas Emissions.* Leopold Center for Sustainable Agriculture. www.leopold.iastate.edu/pubs/staff/ppp/food_mil.pdf [Secondary citation]
- Plappally, A.K. & Lienhard V.J.H. (2012) Energy requirements for water production, treatment, end use, reclamation,and disposal. R*enewable and Sustainable Energy Reviews*, 16, 4818–4848.
- Qadir, M., Sharma, B.R., Bruggeman, A., Choukr-Allah, R. & Karajeh, F. (2007) Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries. *Agricultural Water Management*, 87 (1), 2–22.
- Qadir, M., Wichelns, D., Raschid-Sally, L., McCornick, P., Drechsel, P., Bahri, A. & Minhas, P.S. (2008) The challenges of wastewater irrigation in developing countries. *Agricultural Water Management*, 97, 561–8.
- Qin, Y., Curmi, E., Kopec, G.M., Allwood, J.M. & Richards, K.S. (2015) China's energy-water nexus—Assessment of the energy sector's compliance with the "3 red lines" industrial water policy. *Energy Policy*, 82, 131–143. [Secondary citation]
- Qiu, G., Li, H., Zhang, Q., Chen, W., Liang, X. & Li, X. (2013) Effects of Evapotranspiration on Mitigation of Urban Temperature by Vegetation and Urban Agriculture. *Journal of Integrative Agriculture*, 12 (8), 1307-1315.
- Rahaman, M.S., Ellis, N. & Mavinic, D.S. (2008) Effects of various process parameters on struvite precipitation kinetics and subsequent determination of rate constants. Water *Science & Technology, 57* (5), 647-654.
- Ramaswami, A., Boyer, D., Singh Nagpure, A., Fang, A., Bogra, S., Bakshi, B., Cohen, E. & Rao-Ghorpade, A. (2017) An urban systems framework to assess the trans-boundary food-energy-water nexus: implementation in Delhi, India. *Environmental Research Letters*, 12. https ://doi.org/10.1088/1748-9326/aa5556
- Raschid-Sally, L. & Jayakody, P. (2008) *Drivers and characteristics of wastewater agriculture in developing countries—results from a global assessment*. Colombo, Sri Lanka: International Water Management Institute. 35p.
- Renski, H, Koshgarian, L., Strate, S. (2015) *Long-term Population Projections for Massachusetts Regions and Municipalities.* Boston: UMass Donahue Institute
- Ringler, C., Bhaduri, A. & Lawford, R. (2013) The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? *Environmental Sustainability*, 5, 617–624. http://dx.doi.org/10.1016/j.cosust.2013.11.002
- Ronteltap, M., Maurer, M. & Gujer, W. (2007) Struvite Precipitation Thermodynamics in Source-separated Urine. *Water Research,* 41 (5), 977-984.
- Roy, R.N., Finck, A., Blair, G.J. & Tandon, H.L.S. (2006) *Plant nutrient for food security: A guide for integrated nutrient management.* Rome: FAO Fertilizer and Plant Nutrition Bulletin. 366 p.
- Sahely, H.R., Dudding, S. & Kennedy, C.A. (2003) Estimating the urban metabolism of Canadian cities: Greater Toronto Area case study. Canadian Journal of Civil Engineering, 30, 468–483. doi: 10.1139/L02-105.

- Sanusi, A., Wortham, H., Millet, M. & Mirabel, P. (1996) Chemical Composition of Rainwater In Eastern France. *Atmospheric Environment*, 30 (1), 59-71.
- Sardans, J. & Peñuelas, J. (2015) Potassium: a neglected nutrient in global change. *Global Ecology and Biogeography*, 24, 261–275.
- Sarker. T., Kibler, K. & Reinhart, D. (2016) Concept Mapping of Food Waste Management Alternatives within the Food-Energy-Water Nexus. World Environmental and Water Resources Congress 2016. [Secondary citation]
- Scarlat, N., Dallemand, J.-F.O. & Banja, M. (2013) Possible impact of 2020 bioenergy targets on European Union land use. A scenario-based assessment from national renewable energy action plans proposals. *Renewable & Sustainable Energy Reviews*, 18, 595–606. [Secondary citation]
- Schönfelder, W., Giese, T., Augustin, K., Bertram, N.P., Kuck, W., Li, Z., Meinzinger, F., Reuschel, A., (2013) Energetische Optimierung de HAMBURG WATER Cycle® im Stadtquartier Jenfelder Au. Final Report. EnEff:Stadt Programme, Bundesministerium für Wirtschaft und Technologie (German Ministry for Economy and Technology), Berlin, Germany. P. 293 (in German) [Secondary citation].
- Schröder, J.J., Cordell, D., Smit, A.L. & Rosemarin, A. (2009) *Sustainable Use of Phosphorus*. Wageningen: Plant Research International (357), 122 pp.
- Schwalb, M., Rosevear, C., Chin, R., & Barrington, S. (2011). Food waste treatment in a community center. *Waste Management*, 31(7), 1570–1575.
- Seitzinger, S, Emilio Mayorga, E., Bouwman, A.F., Kroeze, C., Beusen, A.H.W., Billen, G., Van Drecht, G., Dumont, E., Fekete, B.M., Garnier, J. et al. (2010) Global river nutrient export: a scenario analysis of past and future trends. Global Biogeochemical Cycles. 10.1029/2009GB003587.
- Semiat, R. (2008) Energy issues in desalination processes. *Environmental Science & Technology*, 42 (22) 8193-8201.
- Sengupta, S. & Nawaz, T. & Jeffrey Beaudry, J. (2015) Nitrogen and Phosphorus Recovery from Wastewater. *Current Pollution Reports, 1* (3), 155–166
- Shaffer, J., & Cox, B. (2006) *USDA Releases New Farmers' Market Statistics*. Washington, DC. U.S. United States Department of Agriculture, Agricultural Marketing Service. [Secondary citation]
- Sherwood, J., Clabeaux, R. & Carbajales-Dale, M. (2017) An extended environmental input-output lifecycle assessment model to study the urban food-energy-water nexus. *Environmental Research Letters*, 12. https://doi.org/10.1088/1748-9326/aa83f0
- Shuval, H.I. et al. (1986) *Wastewater Irrigation in Developing Countries*, World Bank Technical Paper No. 51, Washington DC [Secondary citation]
- Siebert, S., Burke, J., Faures, J.M., Frenken, K., Hoogeveen, J., Doll, P., Portmann, F.T. (2010) Groundwater use for irrigation — a global inventory. *Hydrology and Earth System Sciences*, 14, 1863-1880.
- Silvennoinen, K., Heikkila, L., Katajajuuri, J.M. & Reinkainen, A. (2015) Food Waste volume and origin: Case studies in the Finnish food service sector. *Waste Management*, 46, 140-145. doi: 10.1016/j.wasman.2015.09.010
- Smajgl, A., Ward, J. & Pluschke, L. (2016) The water–food–energy Nexus – Realising a new paradigm, *Journal of Hydrology*, 533, 533–540.
- Smit, J. & Nasr, J. (1992) Urban agriculture for sustainable cities: using wastes and idle land and water bodies as resources. *Environment and Urbanization*, 4 (2), 141-152.
- Smith, A. (1776) *An Inquiry into the Nature and Causes of the Wealth of Nations*. London: Methuen & Co., Ltd.
- Sparks, D.L. (2003) *Environmental Soil Chemistry*. Chapter 6: Ion Exchange Processes. 2nd ed. Academic Press. 352p. ISBN: 978-0-12-656446-4

- Steinberg, S. (2008) *Financial speculators reap profits from global hunger*. Retrieved from: http://www.globalresearch.ca/index.php?context=va&aid=8794 [Secondary citation]
- STOWA (2012) Struviet productie door middel van het airprex proces. Amersfoort: Kruyt grafisch adviesbureau. 37p
- Talboys, P.J., Heppell, J., Roose, T., Healey, J.R., Jones, D.L. & Withers, P.J.A. (2016) Struvite: a slow-release fertiliser for sustainable phosphorus management? *Plant and Soil*, 401 (1-2), 109–123. doi: 10.1007/s11104-015-2747-
- Ten Caat, P.N. (2017) Towards energetic circularity: Greenhouse-supermarket-dwelling energy exchange. [Master thesis] Delft University of Technology.
- Trenberth, K.E., Dai, K., Van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J. (2013) Global warming and changes in drought. *Nature Climate Change, 4*. 17-22.
- Tukker, A. (2006), Identifying Priorities for Environmental Product Policy. *Journal of Industrial ecology 10* (3) 1-4.
- United Nations Department of Economic and Social Affairs (UN) (2015) *World Urbanization Prospects: The 2014 Revision*. Retrievable from https://esa.un.org/unpd/wup/ [Secondary citation].
- United Nations, Department of Economic and Social Affairs, Population Division (UN DESA) (2017). *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables*. Working Paper No. ESA/P/WP/248.
- United States Census Bureau (Census) (2016) QuickFacts Boston city, Massachusetts Retrieved on January 4, 2018, from: https://www.census.gov/quickfacts/fact/table/bostoncitymassachusetts/IPE120216
- United States Census Bureau (Census) (2018) *QuickFacts Boston city, Massachusetts*. Retrieved on September 26, 2019, from: https://www.census.gov/quickfacts/bostoncitymassachusetts
- United States Department of Agriculture, Agricultural Marketing Service (USDA AMS) (2009) *Farmers' Market Growth: 1994-2009*. [Secondary citation]. Retrieved from: http://www.ams.usda.gov/AMSv1.0/ams.fetchTemplateData.do?template=TemplateS&navID=WholesaleandFarmersMarkets&leftNav=WholesaleandFarmersMarkets&page=WFMFarmersMarketGrowth&description=Farmers%20Market%20Growth&acct=frmrdirmkt
- United States Department of Agriculture, Agricultural Marketing Service (USDA AMS) (2018) Local Food Directories: National Farmers Market Directory. Retrieved on January 7, 2018, from: https://www.ams.usda.gov/local-food-directories/farmersmarkets
- United States Department of Energy (USDOE) (2006) Energy Demands on Water Resources: Washington, DC, USA.
- United States Department of Energy (USDOE) (2014) *The Water-Energy Nexus: Challenges and Opportunities*. Retrieved on February 16, 2018, from: https://www.energy.gov/sites/prod/files/2014/07/f17/Water%20Energy%20Nexus%20Full%20Report%20July%202014.pdf
- United States Environmental Protection Agency (USEPA) (2009) Clean Water Act. Washington, DC, USA. [Secondary citation]
- United States Environmental Protection Agency (USEPA) (2014) Municipal Solid Waste Generation, Recycling and Disposal in the United States: Facts and Figures for 2012., *Solid Waste and Emergency Response* (5306P) EPA-530-F-14-001 [Secondary citation]
- United States National Intelligence Council (US NIC) (2012) *Global Trends 2030: Alternative Worlds*. US NIC: Washington DC, USA, pp. 137.
- Van der Hoek, W., Hassan, M.U., Ensink, J.H.J., Feenstra, S., Raschid-Sally, L., Munir, S., Aslam, R., Ali, N., Hussain, R. and Matsuno, Y. (2002) *Urban wastewater: a valuable resource for agriculture: A Case Study from Haroonabad, Pakistan*. Colombo: International Water Management Institute.

- Van de Ven, F.H.M. (2011) Water Management in Urban Areas [Class Reader] Delft University of Technology.
- Van de Ven, F.H.M. & Voortman, B.R. (1985) De waterbalans van een stedelijk gebied; ervaringen in twee meetgebieden in Lelystad. H_2O, 18 (8), 170-176.
- Vanham, D. (2015) Does the water footprint concept provide relevant information to address the water-food-energy-ecosystem nexus? Ecosystem Services, 17, 298-307. [Secondary citation]
- Van Lier, J. (Lecturer). (2016) Anaerobic Treatment: Introduction calculating CH_4: COD balance [Lecture December 13, 2016] Delft University of Technology.
- Van Linden, V. & Herman, L. A (2014) Fuel consumption model for off-road use of mobile machinery in agriculture. *Energy*, 77, 880–889. [Secondary citation]
- Verkerk, G., Broens, J.B., Bouwens, R.E.A., De Groot, P.A.M., Kranendonk, W., Vogelezang, M.J., Westra, J.J. & Wevers-Prijs, I.M. (2008) *Binas* (table 11). Noordhoff Uitgevers: Groningen. 5th ed.
- Villarroel Walker, R., Beck, M.B., Hall, J.W., Dawson, R.J. & Heidrich, O. (2014) The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. *Journal of Environmental Management*, 141, 104-115.
- Vitousek, P.M. & Howarth, R.W. (1991) Nitrogen limitation on land and in the sea: how can it occur? *Biogeochemistry*, 13, 87–115.
- Walker, M.E., Theregowda, R.B., Safari, I., Abbasian, J., Arastoopour, H., Dzombak, D.A., Hsieh, M.-K. & Miller, D.C. (2013) Utilization of municipal wastewater for cooling in thermoelectric power plants: Evaluation of the combined cost of makeup water treatment and increased condenser fouling. *Energy*, 60, 139–147. [Secondary citation]
- Walker, T.W. & Syers, J.K. (1976) The fate of phosphorus during pedogenesis. *Geoderma*, 15, 1–19.
- Walsh, C.M. & Van Rooyen, F.C. (2014) Household Food Security and Hunger in Rural and Urban Communities in the Free State Province, South Africa. *Ecology of Food and Nutrition, 54* (2) 118-137.
- Wang, S., Cao, T. & Chen, B. (2017) Urban energy–water nexus based on modified input–output analysis, *Applied Energy*, 196, 208–217.
- Waterloo, M.J, Post, V.E.A. & Horner, K. (2014) Introduction to Hydrology and Climate [Syllabus] Vrije Universiteit Amsterdam
- Waternet (2018) Vijfjarenoverzicht Amsterdam West [Excel Data Set]
- Waternet (2019) *Gemiddeld waterverbruik*. Retrieved on October 31, 2019, from: https://www.waternet.nl/ons-water/drinkwater/gemiddeld-waterverbruik/
- Water Environment Federation (WEF) (2010) Energy conservation in water and waste water facilities. 1st ed. New York: McGraw-Hill Education
- Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., Van der Mensbrugghe, D., Biewald, A., Bodirsky, B., Islam, S., Kavallari, A., Mason-D'Croz, D. (2015) Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters, 10* (8)
- Whitaker, R.C., Phillips, S.M., Orzol, S.M. (2006) Food Insecurity and the Risks of Depression and Anxiety in Mothers and Behavior Problems in their Preschool-Aged Children. *Pediatrics, 118* (3), 859-868.
- Whitlegg, J. (1993) *Transport for a Sustainable Future: The Case for Europe*. London: Bellhaven Press
- Whittemore, D.O. (1995) Geochemical differentiation of oil and gas brine from other saltwater sources contaminating water resources: Case studies from Kansas and Oklahoma. *Environmental Geosciences*, 2, 15–31.
- Worldbank (2016-1) Population, total. Retrieved on January 4, 2018, from: https://data.worldbank.org/indicator/SP.POP.TOTL?locations=US

- Worldbank (2016-2) Urban Population (% of total). Retrieved on January 10, 2018, from: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS
- World Bank (2017) Urban population growth (annual %). Retrieved on January 7, 2018, from: https://data.worldbank.org/indicator/SP.URB.GROW
- World Bank (2019) *Renewable energy consumption (% of total final energy consumption).* Retrieved on November 8, 2019, from: https://data.worldbank.org/indicator/eg.fec.rnew.zs
- World Resources Institute (WRI) (2013) Creating a sustainable food future: Reducing food loss and waste. United Nations Environment Program, Working Paper, pp 1-39 [Secondary citation].
- Wouters, H., De Ridder, K., Poelmans, L., Willems, P., Brouwers, J., Hosseinzadehtalaei, P., Tabari, H., Van den Broucke, S., Van Lipzig, N.P.M. & Demuzere, M. (2017) Heat stress increase under climate change twice as large in cities as in rural areas: A study for a densely populated midlatitude maritime region. *Geophysical Research Letters*, 44 (17). https://doi.org/10.1002/2017GL074889
- Wu, M., Mintz, M., Wang, M. & Arora, S. (2008) *Consumptive Water Use in the Production of Bioethanol and Petroleum Gasoline*. Argonne National Laboratory: Lemont, IL, USA. [Secondary citation]
- Xureb, M. (2005) *Food Miles: Environmental Implication of Food Imports to Waterloo Region.* www.leopold.iastate.edu/research/marketing__les/foodmiles_Canada_1105.pdf [Secondary citation]
- Zezza, A. & Tasciotti, L. (2010) Urban agriculture, poverty, and food security: Empirical evidence from a sample of developing countries. *Food Policy 35* (4), 265–273.
- Zhang, X. & Vesselinov, V.V. (2017) Integrated modelling approach for optimal management of water, energy and food security nexus. *Advances in Water Resources*, 101, 1–10.
- Zhuang, D., Jiang, D., Liu, L. & Huang, Y. (2011) Assessment of bioenergy potential on marginal land in China. *Renewable & Sustainable Energy Reviews*, 15, 1050–1056. [Secondary citation]
- Zou, X., Li, Y.E., Cremades, R., Gao, Q., Wan, Y. & Qin, X. (2013) Cost-effectiveness analysis of water-saving irrigation technologies based on climate change response: A case study of China. *Agricultural Water Management*, 129, 9–20. [Secondary citation]

15.1 References to Interviews

- Frank Bakkum
  Geographer of the Department of Spatial Planning and Sustainability
  Municipality of Amsterdam
  (Personal communication, March 2, 2018)
- Stefan Mol
  Energy, Resources and Water Consultant
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  (Personal communication, February 28, 2018)
- Charlie Jewell
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  (Personal communication, May 9, 2018)
- Stephen Estes-Smargiassi
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  (Personal communication, July 20, 2018)
- Julie Wood
  Director of Projects
  Charles River Watershed Association (CRWA)
  (Personal communication, May 14, 2018)

16 Appendices

Appendix 1.1a:	Raw Resource Demand Data QO hotel: Water
Appendix 1.1b:	Raw Resource Demand Data QO hotel: Energy
Appendix 1.1c:	Raw Resource Demand Data QO hotel: Nutrients
Appendix 1.2:	Resource Demand Data Eastie Farm: Water & Nutrients
Appendix 1.3:	Resource Demand Data Corner Stalk Farm: Water, Energy & Nutrients
Appendix 2a:	Sewer Lay-out Boston: Eastie Farm
Appendix 2b:	Sewer Lay-out Boston: Corner Stalk
Appendix 3a:	Wastewater quality Amsterdam
Appendix 3b:	Wastewater quality Boston
Appendix 4a:	Yield Data QO Hotel
Appendix 4b:	Yield Data Eastie Farm
Appendix 4c:	Yield Data Corner Stalk Farm
Appendix 5:	Theoretical Water Demand Corner Stalk Farm & Eastie Farm

Appendix 1.1a: Raw Resource Demand Data

QO hotel: Water

Date	Subsystems			
	1	2	3	4
	m^3	m^3	m^3	m^3
27-6-2018	28.53	22.57	9.88	0.00
28-6-2018	18.80	14.86	14.30	0.00
29-6-2018	27.06	22.14	16.59	0.00
30-6-2018	22.80	20.72	6.77	0.00
1-7-2018				
2-7-2018	11.25	11.95	12.88	0.00
3-7-2018	16.65	21.83	21.47	0.00
4-7-2018	18.10	21.02	14.69	0.00
5-7-2018	11.05	10.83	7.23	0.00
6-7-2018	1.72	2.06	4.84	0.00
7-7-2018	0.25	2.03	4.98	0.00
8-7-2018	0.56	2.03	4.29	0.00
9-7-2018	0.99	2.01	1.54	0.00
10-7-2018	0.67	2.07	2.76	0.00
11-7-2018	1.42	2.11	5.26	0.00
12-7-2018	1.65	3.31	5.99	0.00
13-7-2018	1.63	3.39	5.80	0.00
14-7-2018	1.02	3.44	5.95	0.00
15-7-2018	1.61	3.49	5.64	0.00
16-7-2018	1.61	3.48	3.06	0.00
17-7-2018	1.61	2.85	5.06	0.00
18-7-2018	1.71	3.39	5.87	0.00
19-7-2018	1.69	3.36	5.89	0.00
20-7-2018	1.64	3.37	5.84	0.00
21-7-2018	1.62	3.37	5.87	0.00
22-7-2018	1.63	3.37	2.20	0.00
23-7-2018	1.65	3.48	3.61	0.00
24-7-2018	1.66	3.49	5.87	0.00
25-7-2018	1.33	2.96	2.74	0.00
26-7-2018	1.53	3.56	3.53	0.32
27-7-2018	1.30	3.60	5.81	0.31
28-7-2018	0.68	3.62	5.78	0.30
29-7-2018	0.31	3.62	5.75	0.33
30-7-2018	0.15	2.41	1.38	0.22
31-7-2018	0.61	3.66	5.66	0.34

Date	Subsystems			
	1	2	3	4
	m^3	m^3	m^3	m^3
1-8-2018	0.56	3.42	5.49	0.35
2-8-2018	0.33	3.56	5.96	0.38
3-8-2018	0.59	3.63	5.66	0.38
4-8-2018	0.95	3.66	5.92	0.07
5-8-2018	0.93	3.64	1.88	0.16
6-8-2018	0.77	3.57	4.36	0.43
7-8-2018	0.94	3.64	7.87	0.47
8-8-2018	0.78	3.64	4.46	0.52
9-8-2018	0.61	3.48	5.78	0.46
10-8-2018	0.74	3.45	3.86	0.36
11-8-2018	0.67	3.57	4.61	0.38
12-8-2018	0.66	3.56	2.86	0.14
13-8-2018	0.75	3.62	6.41	0.03
14-8-2018	0.36	1.70	2.58	0.10
15-8-2018	0.87	3.66	5.59	0.29
16-8-2018	0.63	2.46	2.33	0.25
17-8-2018				
18-8-2018	0.91	3.57	1.72	0.26
19-8-2018	0.92	3.59	1.05	0.28
20-8-2018	0.90	3.01	3.32	0.19
21-8-2018	0.74	1.63	8.24	0.24
22-8-2018	0.70	3.41	8.68	0.29
23-8-2018	0.60	3.30	12.13	0.24
24-8-2018	0.21	1.44	5.60	0.04

Table 29 Water consumption at the QO hotel greenhouse. A red colour indicates incomplete daily datasets. A dark red colour indicates data absence

Appendix 1.1b: Raw Resource Demand Data
QO hotel: Energy

Date	Electric Power for Lighting	Net Heat Supply	Net Solar Radiation
	kWh	*kWh*	*kWh*
24-4-2018	162.3	44.8	610.1
25-4-2018	153.0	58.2	959.4
26-4-2018	146.2	58.7	1089.7
27-4-2018	158.1	46.3	746.7
28-4-2018	163.3	41.8	436.6
29-4-2018	163.8	129.8	266.5
30-4-2018	163.8	144.0	214.9
1-5-2018	140.0	133.0	1111.1
2-5-2018	123.5	50.2	1332.0
3-5-2018	120.4	39.1	1565.7
4-5-2018	120.4	33.2	1544.2
5-5-2018	120.6	30.4	1543.2
6-5-2018	121.7	19.5	1550.8
7-5-2018	122.2	0.0	1529.9
8-5-2018	123.2	0.0	1505.2
9-5-2018	122.2	0.0	1422.8
10-5-2018	146.5	33.4	983.7
11-5-2018	133.6	90.2	1447.0
12-5-2018	142.6	55.7	1222.3
13-5-2018	163.8	11.8	477.4
14-5-2018	121.4	116.9	1435.7
15-5-2018	121.4	8.4	1547.7
16-5-2018	127.6	16.8	1361.4
17-5-2018	123.0	101.1	1591.0
18-5-2018	161.2	108.8	872.2
19-5-2018	163.8	107.9	378.3
20-5-2018	121.4	75.0	1579.8
21-5-2018	126.1	32.4	1465.6
22-5-2018	163.8	0.0	275.8
30-5-2018	134.1	0.0	1171.2
31-5-2018	145.4	0.0	976.7
1-6-2018	145.2	35.1	878.0
2-6-2018	163.8	88.0	418.7
3-6-2018	129.2	11.5	1404.5
4-6-2018	147.8	22.4	1010.2
5-6-2018	137.5	50.7	1230.5
6-6-2018	117.8	55.3	1658.0
7-6-2018	127.6	0.0	1515.6
8-6-2018	163.8	0.0	306.4
9-6-2018	141.6	6.3	1243.5
10-6-2018	139.0	26.2	1303.0
11-6-2018	124.5	50.4	1586.7
12-6-2018	163.8	19.6	507.0
13-6-2018	137.5	82.4	1180.7
14-6-2018	162.3	93.7	671.4
15-6-2018	138.0	44.6	1226.2
16-6-2018	154.0	6.8	1069.3
17-6-2018	157.8	48.1	1003.9
18-6-2018	164.6	79.8	623.6
19-6-2018	159.4	39.4	756.2
20-6-2018	139.2	39.4	1145.5
21-6-2018	144.2	103.5	1171.5
22-6-2018	154.7	171.8	899.1
23-6-2018	142.1	115.5	1092.4
24-6-2018	157.6	80.3	971.5
25-6-2018	134.9	84.1	1296.7
26-6-2018	112.1	84.4	1809.3
27-6-2018	124.0	75.3	1456.7

Date	Electric Power for Lighting	Net Heat Supply	Net Solar Radiation
	kWh	*kWh*	*kWh*
23-5-2018	149.3	15.9	1023.3
24-5-2018	162.3	4.7	830.9
25-5-2018	137.7	5.9	1256.2
26-5-2018	123.7	0.0	1483.8
27-5-2018	150.1	0.0	1020.1
28-5-2018	125.8	0.0	1493.1
29-5-2018	129.4	0.0	1185.8
5-7-2018	116.3	4.5	1667.5
6-7-2018	128.2	11.3	1404.8
7-7-2018	122.0	15.3	1469.2
8-7-2018	114.4	19.0	1757.1
9-7-2018	163.0	14.0	700.6
10-7-2018	156.8	93.1	582.4
11-7-2018	152.4	59.2	1101.6
12-7-2018	116.3	54.0	1608.5
13-7-2018	122.0	50.6	1608.5
14-7-2018	115.8	37.3	1676.6
15-7-2018	114.7	20.3	1695.8
16-7-2018	125.1	0.0	1540.3
17-7-2018	116.7	0.0	1631.3
18-7-2018	135.4	5.3	1227.6
19-7-2018	128.4	0.0	1372.7
20-7-2018	127.4	0.0	1438.3
21-7-2018	122.2	0.0	1458.0
22-7-2018	128.9	5.3	1406.9
23-7-2018	120.6	0.0	1467.2
24-7-2018	122.2	0.0	1412.0
25-7-2018	148.3	0.0	932.6
26-7-2018	119.4	0.0	1368.0
27-7-2018	108.5	0.0	1353.8
28-7-2018	119.4	0.0	1127.1
29-7-2018	133.3	0.0	901.4

Date	Electric Power for Lighting	Net Heat Supply	Net Solar Radiation
	kWh	*kWh*	*kWh*
28-6-2018	113.2	11.5	1763.1
29-6-2018	112.7	14.5	1771.3
30-6-2018	111.1	18.8	1854.9
1-7-2018	110.1	3.0	1883.8
2-7-2018	111.1	8.1	1852.5
3-7-2018	111.6	0.0	1824.6
4-7-2018	120.4	33.0	1660.1
30-7-2018	128.2	0.0	982.5
31-7-2018	112.1	0.0	1315.7
1-8-2018	108.5	0.0	1435.4
2-8-2018	106.5	0.0	1421.5
3-8-2018	106.5	0.0	1433.8
4-8-2018	116.8	0.0	1051.1
5-8-2018	104.9	0.0	1474.8
6-8-2018	107.0	0.0	1398.6
7-8-2018	114.2	0.0	1223.1
8-8-2018	152.7	0.0	651.7
9-8-2018	155.3	6.8	464.1
10-8-2018	126.3	57.2	1085.4
11-8-2018	110.8	60.7	1373.7
12-8-2018	132.0	12.9	921.6
13-8-2018	156.8	0.0	555.5
14-8-2018	126.6	30.3	1051.9
15-8-2018	151.4	0.0	612.0
16-8-2018	158.6	6.8	505.5
17-8-2018	116.3	7.8	1258.7
18-8-2018	158.1	28.0	521.0
19-8-2018	160.2	0.0	399.4
20-8-2018	134.4	0.0	808.5
21-8-2018	134.9	0.0	874.1
22-8-2018	119.4	0.0	1049.2
23-8-2018	162.3	0.0	351.5

Appendix 1.1c: Raw Resource Demand Data

QO hotel: Nutrients

Date	Subsystems			
	1	2	3	4
	ml	ml	ml	ml
27-6-2018	73	56	105	0
28-6-2018	87	0	0	0
29-6-2018	67	1	19	0
30-6-2018	125	0	1	0
1-7-2018				
2-7-2018	66	31	34	0
3-7-2018	0	0	0	0
4-7-2018	26	0	125	0
5-7-2018	1	65	14	0
6-7-2018	19	0	0	0
7-7-2018	370	0	0	0
8-7-2018	0	0	0	0
9-7-2018	1	0	0	0
10-7-2018	2	0	22	0
11-7-2018	0	0	13	0
12-7-2018	0	0	0	0
13-7-2018	497	0	5	0
14-7-2018	0	18	0	0
15-7-2018	0	43	0	0
16-7-2018	0	19	15	0
17-7-2018	167	1	62	0
18-7-2018	0	0	2	0
19-7-2018	0	0	1	0
20-7-2018	0	0	2	0
21-7-2018	0	0	1	0
22-7-2018	0	0	0	0
23-7-2018	0	0	20	0
24-7-2018	0	29	1	0
25-7-2018	0	30	2	0

Table 30 Nutrient additions in the form of artificial fertilizer at the QO hotel greenhouse. A red colour indicates incomplete datasets. A dark red colour indicates absence of data.

Appendix 1.2: Raw Resource Demand Data Eastie Farm: Water & Nutrients

	Manual Water supply					**Rainfall**	**Fertilizer use**
Meter	**1**	**2**	**3**	**4**	**5**		**Compost**
Date	*(gallon)*					*(mm)*	*(buckets)*
April 28, 2018	0	0	0	0	0	0.0	
April 29, 2018						1.3	
April 30, 2018						5.1	
May 1, 2018						0.0	
May 2, 2018						0.0	
May 3, 2018						2.3	
May 4, 2018						0.0	
May 5, 2018						0.0	1
May 6, 2018						4.8	
May 7, 2018						0.0	
May 8, 2018						0.0	
May 9, 2018						0.0	
May 10, 2018	59.3	41.1	98.1	0	0	0.0	
May 11, 2018						0.0	
May 12, 2018	0	0	0	0	0	5.3	
May 13, 2018	-	-	-	-	-	0.0	
May 14, 2018	7.2	11.6	28.4			0.0	
May 15, 2018	-					25.4	
May 16, 2018	9.1	12.5	26.2			0.0	
May 17, 2018	9.2	12.7	26.2			0.0	
May 18, 2018	14	11	12.1			0.0	
May 19, 2018						5.1	
May 20, 2018						2.0	
May 21, 2018	13.6	12.5	28.9			0.0	
May 22, 2018						0.8	
May 23, 2018	10.6	10.6	25.6			0.5	
May 24, 2018	17.8	12.9	15.5			0.0	
May 25, 2018						0.0	
May 26, 2018						0.0	
May 27, 2018						0.5	
May 28, 2018						1.5	
May 29, 2018	-	17.1	25			0.0	

	Manual Water supply					**Rainfall**	**Fertilizer**
May 30, 2018		3.9	12.6	22.4		0.0	
May 31, 2018		3.9	12.6	22.4		0.0	
June 1, 2018		6		10.2		0.3	
June 2, 2018						0.3	
June 3, 2018						0.0	
June 4, 2018					4	15.7	
June 5, 2018					41	8.6	
June 6, 2018						0.0	
June 7, 2018			26.8		21	0.0	
June 8, 2018					51	0.0	
June 9, 2018						0.0	
June 10, 2018						0.0	
June 11, 2018	1.2	4	20.6		18	0.0	
June 12, 2018			3			0.0	
June 13, 2018			1			0.0	
June 14, 2018						0.0	
June 15, 2018						0.0	
June 16, 2018						0.0	
June 17, 2018						0.0	
June 18, 2018					3	3.3	
June 19, 2018					43	0.3	
June 20, 2018					39	0.0	3
June 21, 2018					35	0.0	
June 22, 2018					47	0.0	1
June 23, 2018						0.0	
June 24, 2018						6.6	
June 25, 2018				58		8.4	
June 26, 2018				46		0.0	
June 27, 2018				39		2.3	
June 28, 2018				43		29.5	
June 29, 2018		12	23.6	13		0.0	
June 30, 2018						0.0	
July 1, 2018						0.0	
July 2, 2018						0.0	
July 3, 2018		13	24.8	11		0.3	
July 4, 2018						0.0	
July 5, 2018		10.5	26.7	14.1		0.0	
July 6, 2018		9.9	29.5	7		8.9	
July 7, 2018						0.0	

	Manual Water supply					Rainfall	Fertilizer
July 8, 2018						0.0	
July 9, 2018						0.0	
July 10, 2018		7.9	28	6		0.0	
July 11, 2018		3.7	26	9		4.8	
July 12, 2018					35	0.0	
July 13, 2018						0.0	
July 14, 2018						7.9	
July 15, 2018						0.3	
July 16, 2018					34	0.0	
July 17, 2018						68.1	
July 18, 2018			9	7.8	21	1.5	
July 19, 2018			6	8	41	0.0	
July 20, 2018						0.0	
July 21, 2018						0.0	
July 22, 2018						4.3	
July 23, 2018						0.8	
July 24, 2018			7	11	22	0.0	
July 25, 2018			5	9	25	3.6	
July 26, 2018			8	5	28	15.2	
July 27, 2018						0.0	
July 28, 2018						0.0	
July 29, 2018						0.0	
July 30, 2018						0.0	
July 31, 2018			9	12	24	0.0	
August 1, 2018					48	0.0	
August 2, 2018					39	0.0	
August 3, 2018						1.5	
August 4, 2018						16.3	
August 5, 2018						0.0	
August 6, 2018						0.0	
August 7, 2018					36	0.0	
August 8, 2018	0	0	0	0	0	24.9	
August 9, 2018					32	1.5	
August 10, 2018						0.0	
August 11, 2018						9.9	
August 12, 2018						35.1	
August 13, 2018	0	0	0	0	0	7.4	
August 14, 2018					27	0.3	
August 15, 2018					29	0.0	
August 16, 2018						0.0	
August 17, 2018	0	0	0	0	0	5.1	

Appendix 1.3: Raw Resource Demand Data

Corner Stalk Farm: Water, Energy & Nutrients

Date	Water use	Electricity use	Fertilizer use
	(gallon)	*(kWh)*	*(oz)*
April 16, 2018			
April 17, 2018			
April 18, 2018			
April 19, 2018			
April 20, 2018	98		11
April 21, 2018			
April 22, 2018			
April 23, 2018			
April 24, 2018		0.4	
April 25, 2018			
April 26, 2018			
April 27, 2018			
April 28, 2018			
April 29, 2018			
April 30, 2018			
May 1, 2018	85	763	16
May 2, 2018			
May 3, 2018		1040	
May 4, 2018	98	1145	8
May 5, 2018			
May 6, 2018			
May 7, 2018			
May 8, 2018		1591.2	
May 9, 2018			
May 10, 2018			
May 11, 2018			
May 12, 2018			
May 13, 2018			
May 14, 2018		2280	
May 15, 2018			
May 16, 2018			

Date	Water use	Electricity use	Fertilizer use
	(gallon)	*(kWh)*	*(oz)*
May 17, 2018			
May 18, 2018	84	2738	
May 19, 2018			
May 20, 2018			
May 21, 2018			
May 22, 2018			
May 23, 2018			
May 24, 2018			
May 25, 2018			
May 26, 2018			
May 27, 2018			
May 28, 2018			
May 29, 2018			
May 30, 2018			
May 31, 2018	166	4192	8
June 1, 2018			
June 2, 2018			
June 3, 2018			
June 4, 2018			
June 5, 2018			
June 6, 2018			
June 7, 2018			
June 8, 2018	55		4
June 9, 2018			
June 10, 2018			
June 11, 2018			
June 12, 2018			
June 13, 2018			
June 14, 2018			
June 15, 2018			
June 16, 2018			

Date	Water use (gallon)	Electricity use (kWh)	Fertilizer use (oz)
June 17, 2018			
June 18, 2018	55		8
June 19, 2018			
June 20, 2018			
June 21, 2018			
June 22, 2018			
June 23, 2018			
June 24, 2018			
June 25, 2018			
June 26, 2018			
June 27, 2018			
June 28, 2018			
June 29, 2018			
June 30, 2018			
July 1, 2018			
July 2, 2018			
July 3, 2018			
July 4, 2018			
July 5, 2018			
July 6, 2018			
July 7, 2018			
July 8, 2018			
July 9, 2018	47		8
July 10, 2018			
July 11, 2018			
July 12, 2018			
July 13, 2018			
July 14, 2018			
July 15, 2018			
July 16, 2018			

Date	Water use (gallon)	Electricity use (kWh)	Fertilizer use (oz)
July 17, 2018			
July 18, 2018			
July 19, 2018	49		4
July 20, 2018			
July 21, 2018			
July 22, 2018			
July 23, 2018			
July 24, 2018			
July 25, 2018			
July 26, 2018			
July 27, 2018			
July 28, 2018			
July 29, 2018			
July 30, 2018			
July 31, 2018			
August 1, 2018			
August 2, 2018	84		8
August 3, 2018			
August 4, 2018			
August 5, 2018			
August 6, 2018			
August 7, 2018			
August 8, 2018			
August 9, 2018			
August 10, 2018			
August 11, 2018			
August 12, 2018			
August 13, 2018			
August 14, 2018			
August 15, 2018	75	14958	8

Appendix 2a: Sewer Lay-out Boston: Eastie Farm

Figure 54 Sewer lay-out East-Boston near Eastie Farm (Source: BWSC, 2018)

Appendix 2b: Sewer Lay-out
Boston: Corner Stalk

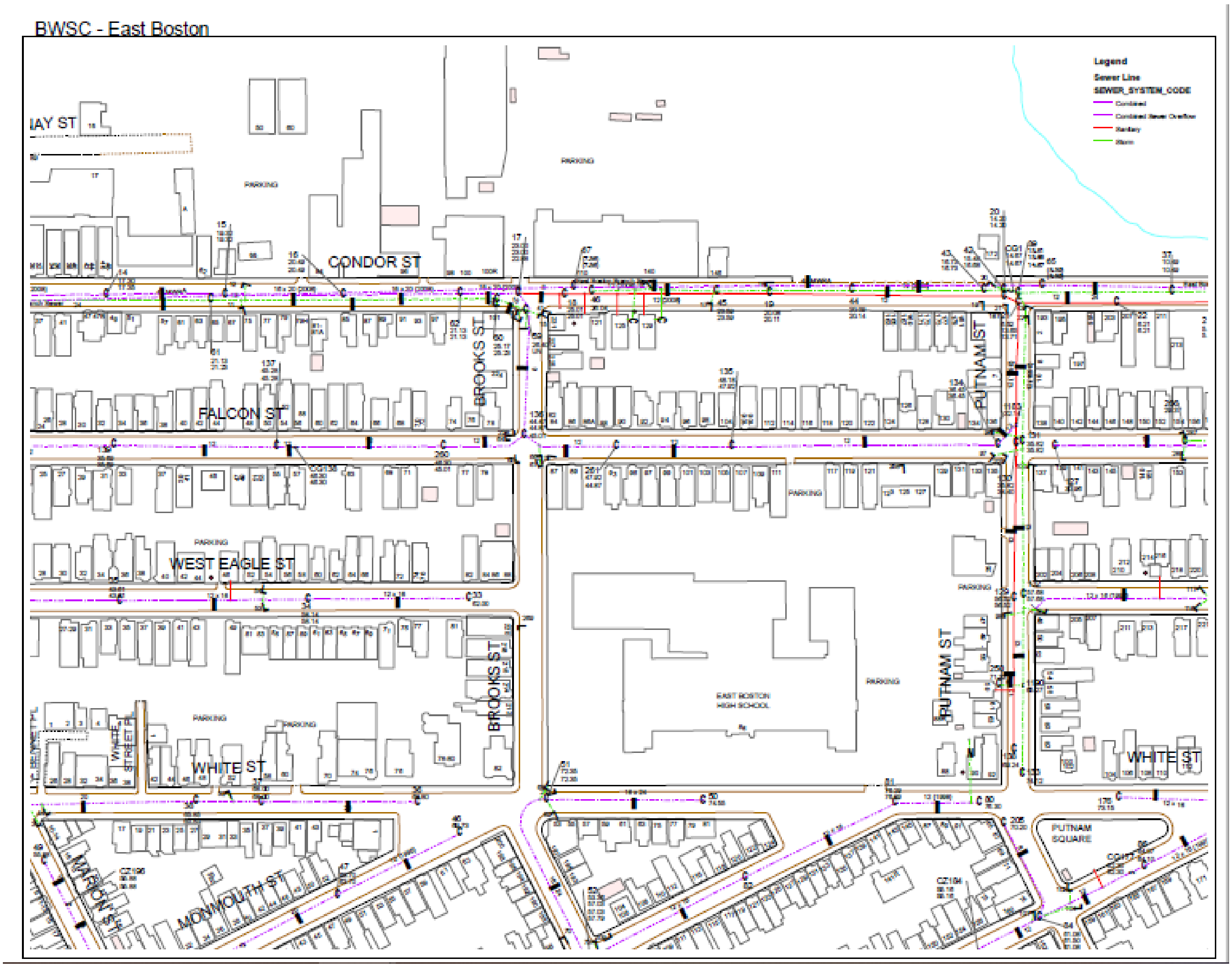

Figure 55 Sewer lay-out East-Boston near Corner Stalk Farm (Source: BWSC, 2018)

Appendix 3a: Wastewater quality Amsterdam

Pollutant	**Influent concentrations (weighted average) (mg/L)**
COD	613
BOD	281
Total Kjeldahl Nitrogen	62
Total Nitrogen	62
Total phosphorus	8
TSS	318

Table 31 Wastewater quality of the influent at the WWTP in Amsterdam West (Source: Waternet, 2018)

Appendix 3b: Wastewater quality Boston

Pollutant	Concentration (mg/L)
Total Suspended Solids (TSS)	
Minimum Concentration	50
Average Concentration	192
Maximum Concentration	746
Carbonaceous Biochemical Oxygen Demand	
Minimum Concentration	29
Average Concentration	115
Maximum Concentration	284
Settleable Solids	
Minimum Concentration	0.2
Average Concentration	6.6
Maximum Concentration	78
Total Kjeldahl Nitrogen	
Minimum Concentration	10
Average Concentration	32.5
Maximum Concentration	66
Ammonia - nitrogen	
Minimum Concentration	6.1
Average Concentration	21.6
Maximum Concentration	32.1
Nitrates	
Minimum Concentration	0.01
Average Concentration	0.25
Maximum Concentration	3.31

Pollutant	Concentration (mg/L)
Nitrites	
Minimum Concentration	0.01
Average Concentration	0.31
Maximum Concentration	1.41
Orthophosphates	
Minimum Concentration	0.5
Average Concentration	2
Maximum Concentration	3.2
Total Phosphorus	
Minimum Concentration	1.3
Average Concentration	4.6
Maximum Concentration	8.1
BOD	
Minimum Concentration	53
Average Concentration	190
Maximum Concentration	719
COD	
Minimum Concentration	126
Average Concentration	399
Maximum Concentration	1170
Temperature	
Mininum (deg F)	52.2
Average (deg F)	63.8
Maximum (deg F)	74.3

Table 32 Deer Island wastewater treatment plant influent characterization of the north system in 2015
(Source: Massachusetts Water Resources Authority (MWRA), 2017)

Appendix 4a: Yield Data
QO Hotel

Crop name	Crop part / species	Yield	
		Pieces	Gram
Agastache		104	23.5
Basil	*Cinnamon*	-	62
	Flower	394	225
	Genovese	-	6,502
	Lemon	-	1,714
	Licorice	45	5,582
	Purple	-	130
	Red	-	3,021
	Vanilla	-	321
Borage Flower		822	-
Calendula	*Flower*	16	-
Chives		-	8,427
Cucumber		-	9,650
Dock		37.5	150
Eggplant		4	1,500
French marigold	*Flower*	920	-
Lemon Balm		-	440
Mint		-	33
Monarda		19	-
Nasturtium	*Flower*	1875	773
Oyster Leaf		496	26
Parsley		-	985
Tomatoes	*Cherry tomatoes*	-	580
		-	8,343
Unknown	*Flowers*	247	800

Appendix 4b: Yield Data
Eastie Farm

Crop	Weight	Weight
	(pounds)	*(kg)*
Asian pear	10	4.5
Beets	20	9.1
Brussel Sprouts	20	9.1
Cabbage	20	9.1
Carrots	40	18.2
Cauliflower	20	9.1
Garlic	80	36.3
Greens (edible leafy)	120	54.5
Herbs	20	9.1
Husk cherries	30	13.6
Kale	60	27.2
Mulberries	40	18.2
Onions	20	9.1
Peas	10	4.5
Spinach	20	9.1
Squash (green & yellow)	120	54.5
Tomatillos	70	31.8
Tomatoes	50	22.7
	Total	**Total**
	770	350

Appendix 4c: Yield Data
Corner Stalk Farm

Crops grown at Corner Stalk Farm	
Lettuce varieties	**Additional crops**
Antonnet	Basil
Black Hawk	Arugula
Blade	Swiss chard
Cegolaine	Kale
Cherokee Crisp	Mint
Galactic Red	Mustard greens
Garrison Red Oakleaf	
Livigna Lollo	
Oscarde	
Panisse	
Rex Bibb	
Rhazes Bibb	
Rosaine	
Salanova Green Butter	
Salanova Green Oakleaf	
Salanova Red Butter	
Salanova Red Oakleaf	
Salanova Sweet	
Sulu Green Oakleaf	
Tropicana	

Yield

An equivalent of 600 to 1000 heads of lettuce per container per week is harvested depending on the size of the heads. More detailed information is not available.

Appendix 5: Theoretical Water Demand Corner Stalk Farm & Eastie Farm

Boston				**Corner Stalk**		**Eastie Farm**								
Date			**Mean Temp.**	**ET0**	**ET Lettuce**	**ET0**	**ET Carrots**	**ET Peas**	**ET Spinach**	**ET Onions**	**ET Greens**	**ET Cabbage**	**ET Squash**	**ET Tomatoe**
			Celcius	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day
2018	April	7	4.7	10.2	6.9	3.1	1.4	1.4	1.4	1.5	1.4	1.4	1.4	1.4
2018		8	2.4	9.1	6.2	2.7	1.2	1.2	1.2	1.4	1.2	1.2	1.2	1.2
2018		9	2.8	9.3	6.3	2.8	1.3	1.3	1.3	1.4	1.3	1.3	1.3	1.3
2018		10	3.3	9.5	6.5	2.9	1.3	1.3	1.3	1.4	1.3	1.3	1.3	1.3
2018		11	2.9	9.4	6.4	2.8	1.3	1.3	1.3	1.4	1.3	1.3	1.3	1.3
2018		12	7.1	11.2	7.6	3.4	1.5	1.5	1.5	1.7	1.5	1.5	1.5	1.5
2018		13	12.4	13.7	9.3	4.1	1.8	1.8	1.8	2.1	1.8	1.8	1.8	1.8
2018		14	7.5	11.5	7.8	3.4	1.5	1.5	1.5	1.7	1.5	1.5	1.5	1.5
2018		15	1.6	8.7	5.9	2.6	1.2	1.2	1.2	1.3	1.2	1.2	1.2	1.2
2018		16	6.2	10.9	7.4	3.3	1.5	1.5	1.5	1.6	1.5	1.5	1.5	1.5
2018		17	7.6	11.5	7.8	3.4	1.5	1.5	1.5	1.7	1.5	1.5	1.5	1.5
2018		18	6.8	11.1	7.6	3.3	1.5	1.5	1.5	1.7	1.5	1.5	1.5	1.5
2018		19	4.7	10.1	6.9	3.0	1.4	1.4	1.4	1.5	1.4	1.4	1.4	1.4
2018		20	6.6	11.0	7.5	3.3	1.5	1.5	1.5	1.7	1.5	1.5	1.5	1.5
2018		21	9.2	12.2	8.3	3.7	1.7	1.7	1.7	1.8	1.7	1.7	1.7	1.7
2018		22	10.2	12.7	8.6	3.8	1.7	1.7	1.7	2.9	1.7	1.7	1.7	1.7
2018		23	10.2	12.7	8.6	3.8	1.7	1.7	1.7	2.9	1.7	1.7	1.7	1.7
2018		24	12.5	13.8	9.4	4.1	1.9	1.9	1.9	3.1	1.9	1.9	1.9	1.9
2018		25	10.3	12.7	8.7	3.8	1.7	1.7	1.7	2.9	1.7	1.7	1.7	1.7
2018		26	13.9	14.4	9.8	4.3	1.9	1.9	1.9	3.2	1.9	1.9	1.9	1.9
2018		27	9.7	12.4	8.5	3.7	1.7	3.0	2.2	2.8	1.7	1.7	1.7	1.7
2018		28	12.6	13.8	9.4	4.1	1.9	3.3	2.5	3.1	1.9	1.9	1.9	1.9
2018		29	11.8	13.4	9.1	4.0	1.8	3.2	2.4	3.0	1.8	1.8	1.8	1.8
2018		30	7.2	11.3	7.7	3.4	1.5	2.7	2.0	2.5	1.5	1.5	1.5	1.5
2018	May	1	12.1	13.6	9.2	4.5	2.0	3.6	2.7	3.4	2.0	2.0	2.0	2.0
2018		2	24.1	19.1	13.0	6.3	4.7	5.0	3.8	4.7	2.8	4.7	4.4	2.8
2018		3	22.7	18.5	12.5	6.1	4.6	4.9	3.7	4.6	2.7	4.6	4.3	2.7
2018		4	21.1	17.7	12.0	5.8	4.4	4.7	3.5	4.4	2.6	4.4	4.1	2.6
2018		5	19.6	17.0	11.6	5.6	4.2	4.5	3.4	4.2	2.5	4.2	3.9	2.5
2018		6	15.1	15.0	10.2	4.9	3.7	3.9	3.0	3.7	2.2	3.7	3.5	2.2
2018		7	11.7	13.4	9.1	4.4	3.3	3.5	2.6	3.3	2.0	3.3	3.1	2.0
2018		8	10.4	12.8	8.7	4.2	3.2	3.4	2.5	3.2	1.9	3.2	3.0	1.9

Boston				Corner Stalk		Eastie Farm								
Date			Mean Temp.	ET0	ET Lettuce	ET0	ET Carrots	ET Peas	ET Spinach	ET Onions	ET Greens	ET Cabbage	ET Squash	ET Tomatoe
			Celcius	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day
2018		9	10.7	12.9	8.8	4.3	3.2	3.4	2.6	3.2	1.9	3.2	3.0	1.9
2018		10	12.8	13.9	9.4	4.6	3.4	3.7	2.7	3.4	2.1	3.4	3.2	2.1
2018		11	16.6	15.6	10.6	5.2	3.9	4.1	3.1	3.9	2.3	3.9	3.6	2.3
2018		12	10.0	12.6	8.6	4.2	3.1	3.3	2.5	3.1	2.5	3.1	2.9	3.1
2018		13	10.1	12.6	8.6	4.2	3.1	3.3	2.5	3.1	2.5	3.1	2.9	3.1
2018		14	13.7	14.3	9.7	4.7	3.5	3.8	2.8	3.5	2.8	3.5	3.3	3.5
2018		15	18.8	16.6	11.3	5.5	4.1	4.4	3.3	4.1	3.3	4.1	3.8	4.1
2018		16	12.4	13.7	9.3	4.5	3.4	3.6	2.7	3.4	2.7	3.4	3.2	3.4
2018		17	15.9	15.3	10.4	5.1	3.8	4.0	3.0	5.3	3.0	3.8	3.5	3.8
2018		18	12.5	13.8	9.4	4.5	3.4	3.6	2.7	4.8	2.7	3.4	3.2	3.4
2018		19	10.6	12.9	8.8	4.3	3.2	3.4	2.6	4.5	2.6	3.2	3.0	3.2
2018		20	19.1	16.8	11.4	5.5	4.2	4.4	3.3	5.8	3.3	4.2	3.9	4.2
2018		21	19.0	16.7	11.4	5.5	4.1	4.4	3.3	5.8	3.3	4.1	3.9	4.1
2018		22	15.4	15.1	10.3	5.0	3.7	4.0	3.0	5.2	3.0	3.7	3.5	3.7
2018		23	18.5	16.5	11.2	5.4	4.1	4.4	3.3	5.7	3.3	4.1	3.8	4.1
2018		24	14.7	14.7	10.0	4.9	3.6	3.9	2.9	5.1	2.9	3.6	3.4	3.6
2018		25	23.1	18.6	12.7	6.1	4.6	4.9	3.7	6.5	3.7	4.6	4.3	4.6
2018		26	23.6	18.9	12.8	6.2	4.7	5.0	3.7	6.5	3.7	4.7	4.4	4.7
2018		27	12.6	13.8	9.4	4.6	3.4	3.6	2.7	4.8	2.7	3.4	3.2	3.4
2018		28	11.8	13.4	9.1	4.4	3.3	3.5	2.7	4.7	2.7	3.3	3.1	3.3
2018		29	20.7	17.5	11.9	5.8	4.3	4.6	3.5	6.1	3.5	4.3	4.0	4.3
2018		30	17.1	15.9	10.8	5.2	3.9	4.2	3.1	5.5	3.1	3.9	3.7	3.9
2018		31	20.1	17.3	11.7	5.7	4.3	4.6	3.4	6.0	3.4	4.3	4.0	4.3
2018	June	1	22.1	18.2	12.4	6.2	4.6	7.1	6.2	6.5	3.7	6.5	4.3	4.6
2018		2	21.4	17.9	12.1	6.1	4.6	7.0	6.1	6.4	3.6	6.4	4.3	4.6
2018		3	13.3	14.1	9.6	4.8	3.6	5.5	4.8	5.0	2.9	5.0	3.4	3.6
2018		4	11.1	13.1	8.9	4.4	3.3	5.1	4.4	4.7	2.7	4.7	3.1	3.3
2018		5	12.4	13.7	9.3	4.7	3.5	5.4	4.7	4.9	2.8	4.9	3.3	3.5
2018		6	13.6	14.3	9.7	4.8	5.1	5.6	4.8	5.1	2.9	5.1	4.4	3.6
2018		7	16.3	15.5	10.5	5.3	5.5	6.1	5.3	5.5	3.2	5.5	4.7	3.9
2018		8	19.3	16.9	11.5	5.7	6.0	6.6	5.7	6.0	3.4	6.0	5.2	4.3
2018		9	22.6	18.4	12.5	6.2	6.6	7.2	6.2	6.6	3.7	6.6	5.6	4.7
2018		10	18.7	16.6	11.3	5.6	5.9	6.5	5.6	5.9	3.4	5.9	5.1	4.2
2018		11	15.8	15.3	10.4	5.2	5.5	6.0	5.2	5.5	3.1	5.5	4.7	3.9
2018		12	19.6	17.0	11.6	5.8	6.1	6.6	5.8	6.1	3.5	6.1	5.2	4.3
2018		13	20.7	17.5	11.9	6.0	6.3	6.9	6.0	6.3	3.6	6.3	5.4	4.5
2018		14	21.9	18.1	12.3	6.2	6.5	7.1	6.2	6.5	3.7	6.5	5.5	4.6

Boston				Corner Stalk		Eastie Farm								
Date			Mean Temp.	ET0	ET Lettuce	ET0	ET Carrots	ET Peas	ET Spinach	ET Onions	ET Greens	ET Cabbage	ET Squash	ET Tomatoe
			Celcius	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
2018		15	14.2	14.5	9.9	4.9	5.2	5.7	4.9	5.2	3.0	5.2	4.4	3.7
2018		16	21.8	18.0	12.3	6.1	6.4	7.0	6.1	6.4	3.7	6.4	5.5	4.6
2018		17	20.6	17.5	11.9	5.9	6.2	6.8	5.9	6.2	3.6	6.2	5.3	4.5
2018		18	24.9	19.4	13.2	6.6	6.9	7.6	6.6	6.9	4.0	6.9	6.0	5.0
2018		19	25.1	19.6	13.3	6.6	7.0	7.6	6.6	7.0	4.0	7.0	6.0	5.0
2018		20	23.1	18.6	12.7	6.3	6.6	7.3	6.3	6.6	3.8	6.6	5.7	4.7
2018		21	21.7	18.0	12.2	6.1	6.4	7.0	6.1	6.4	3.7	6.4	5.5	4.6
2018		22	18.8	16.7	11.3	5.7	5.9	6.5	5.7	5.9	3.4	5.9	5.1	4.2
2018		23	16.4	15.6	10.6	5.3	5.6	6.1	5.3	5.6	3.2	5.6	4.8	4.0
2018		24	19.3	16.9	11.5	5.7	6.0	6.6	5.7	6.0	3.4	6.0	5.2	4.3
2018		25	19.1	16.8	11.4	5.7	6.0	6.6	5.7	6.0	3.4	6.0	5.1	4.3
2018		26	20.3	17.4	11.8	5.9	6.2	6.8	5.9	6.2	3.5	6.2	5.3	6.8
2018		27	21.4	17.9	12.1	6.1	6.4	7.0	6.1	6.4	3.6	6.4	5.5	7.0
2018		28	21.8	18.0	12.3	6.1	6.4	7.0	6.1	6.4	3.7	6.4	5.5	7.0
2018		29	26.7	20.3	13.8	6.9	7.2	7.9	6.9	7.2	4.1	7.2	6.2	7.9
2018		30	27.3	20.5	14.0	7.0	7.3	8.0	7.0	7.3	4.2	7.3	6.3	8.0
2018	July	1	27.0	20.4	13.9	6.7	7.1	7.7	6.7	7.1	6.7	7.1	6.1	7.7
2018		2	23.5	18.8	12.8	6.2	6.5	7.1	6.2	6.5	6.2	6.5	5.6	7.1
2018		3	29.2	21.4	14.6	7.1	7.4	8.1	7.1	7.4	7.1	7.4	6.4	8.1
2018		4	28.3	21.0	14.3	6.9	7.3	8.0	6.9	7.3	6.9	7.3	6.2	8.0
2018		5	29.2	21.4	14.6	7.1	7.4	8.1	7.1	7.4	7.1	7.4	6.4	8.1
2018		6	26.3	20.1	13.7	6.6	7.0	7.0	6.6	7.0	6.6	7.0	6.0	7.6
2018		7	20.4	17.4	11.8	5.7	6.0	6.0	5.7	6.0	5.7	6.0	5.2	6.6
2018		8	21.9	18.1	12.3	6.0	6.3	6.3	6.0	6.3	6.0	6.3	5.4	6.9
2018		9	25.6	19.8	13.5	6.5	6.9	6.9	6.5	6.9	6.5	6.9	5.9	7.5
2018		10	28.2	21.0	14.3	6.9	7.3	7.3	6.9	7.3	6.9	7.3	6.2	8.0
2018		11	21.6	17.9	12.2	5.9	6.2	6.2	5.3	6.2	5.9	6.2	4.4	6.8
2018		12	21.0	17.7	12.0	5.8	6.1	6.1	5.2	6.1	5.8	6.1	4.4	6.7
2018		13	21.4	17.8	12.1	5.9	6.2	6.2	5.3	6.2	5.9	6.2	4.4	6.8
2018		14	20.8	17.6	12.0	5.8	6.1	6.1	5.2	6.1	5.8	6.1	4.4	6.7
2018		15	21.4	17.9	12.1	5.9	6.2	6.2	5.3	6.2	5.9	6.2	4.4	6.8
2018		16	21.3	17.8	12.1	5.9	6.2	6.2	5.3	6.2	5.9	6.2	4.4	6.8
2018		17	23.6	18.9	12.8	6.2	6.5	6.5	5.6	6.5	6.2	6.5	4.7	7.2
2018		18	24.5	19.3	13.1	6.4	6.7	6.7	5.7	6.7	6.4	6.7	4.8	7.3
2018		19	21.6	17.9	12.2	5.9	6.2	6.2	5.3	6.2	5.9	6.2	4.4	6.8
2018		20	22.4	18.3	12.5	6.0	6.3	6.3	5.4	6.3	6.0	6.3	4.5	7.0
2018		21	20.4	17.4	11.8	5.7	6.0			6.0	5.7	6.0	4.3	6.6

Boston				Corner Stalk		Eastie Farm								
Date			Mean Temp.	ET0	ET Lettuce	ET0	ET Carrots	ET Peas	ET Spinach	ET Onions	ET Greens	ET Cabbage	ET Squash	ET Tomatoe
			Celcius	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day
2018		22	21.8	18.0	12.3	6.0	6.3			6.3	6.0	6.3	4.5	6.8
2018		23	25.9	19.9	13.6	6.6	6.9			6.9	6.6	6.9	4.9	7.6
2018		24	26.4	20.1	13.7	6.6	7.0			7.0	6.6	7.0	5.0	7.6
2018		25	26.2	20.1	13.6	6.6	7.0			7.0	6.6	7.0	5.0	7.6
2018		26	25.1	19.5	13.3	6.4	6.8			5.5	6.4	6.8	4.8	7.4
2018		27	26.2	20.1	13.6	6.6	7.0			5.6	6.6	7.0	5.0	7.6
2018		28	25.7	19.8	13.5	6.5	6.9			5.6	6.5	6.9	4.9	7.5
2018		29	26.1	20.0	13.6	6.6	6.9			5.6	6.6	6.9	5.0	7.6
2018		30	24.1	19.1	13.0	6.3	6.6			5.3	6.3	6.6	4.7	7.2
2018		31	24.0	19.0	12.9	6.3	6.6			5.3	6.3	6.6	4.7	7.2
2018	August	1	24.2	19.1	13.0	5.9	6.2			5.0	5.9	6.2	4.4	6.8
2018		2	28.7	21.2	14.4	6.6	6.9			5.6	6.6	6.9	4.9	7.6
2018		3	27.7	20.7	14.1	6.4	6.7			5.5	6.4	6.7	4.8	7.4
2018		4	24.7	19.4	13.2	6.0	6.3			5.1	6.0	6.3	4.5	6.9
2018		5	25.3	19.7	13.4	6.1	6.4			5.2	6.1	5.5		7.0
2018		6	29.9	21.7	14.8	6.7	7.1			5.7	6.7	6.1		7.8
2018		7	29.6	21.6	14.7	6.7	7.0			5.7	6.7	6.0		7.7
2018		8	25.6	19.8	13.4	6.1	6.4			5.2	6.1	5.5		7.0
2018		9	27.1	20.4	13.9	6.3	6.7			5.4	6.3	5.7		7.3
2018		10	25.6	19.8	13.4	6.1	6.4			5.2	6.1	5.5		7.0
2018		11	20.7	17.5	11.9	5.4	5.7			4.6	5.4	4.9		6.2
2018		12	21.1	17.7	12.0	5.5	5.8			4.7	5.5	4.9		6.3
2018		13	21.1	17.7	12.0	5.5	5.8			4.7	5.5	4.9		6.3
2018		14	22.9	18.6	12.6	5.8	6.0			4.9	5.8	5.2		6.6
2018		15	25.3	19.7	13.4	6.1	5.5			5.2	5.5	5.5		7.0
2018		16	28.2	21.0	14.3	6.5	5.9			5.5	5.9	5.9		7.5
2018		17	23.9	19.0	12.9	5.9	5.3			5.0	5.3	5.3		6.8
2018		18	24.3	19.2	13.1	5.9	5.4			5.1	5.4	5.4		6.8
2018		19	20.7	17.5	11.9	5.4	4.9			4.6	4.9	4.9		6.3
2018		20	20.7	17.5	11.9	5.4	4.9			4.6	4.9	4.9		6.3
2018		21	20.1	17.2	11.7	5.3	4.8			4.5	4.8	4.8		6.1
2018		22	22.5	18.4	12.5	5.7	5.1			4.8	5.1	5.1		6.5
2018		23	22.2	18.2	12.4	5.6	5.1			4.8	5.1	5.1		6.5
2018		24	22.9	18.5	12.6	5.7	5.2			4.9	5.2	5.2		6.6
2018		25	23.8	18.9	12.9	5.9	5.3			5.0				6.8
2018		26	23.9	19.0	12.9	5.9	5.3			5.0				6.8
2018		27	27.6	20.7	14.1	6.4	5.8			5.5				7.4

Boston				Corner Stalk		Eastie Farm								
Date			Mean Temp.	ET0	ET Lettuce	ET0	ET Carrots	ET Peas	ET Spinach	ET Onions	ET Greens	ET Cabbage	ET Squash	ET Tomatoe
			Celcius	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day	mm/day
2018		28	30.4	22.0	15.0	6.8	6.1			5.8				7.8
2018		29	31.7	22.6	15.3	7.0	6.3			5.9				8.0
2018		30	26.4	20.2	13.7	6.3	5.6			5.3				7.2
2018		31	20.6	17.5	11.9	5.4	4.9			4.6				6.2
2018	September	1	20.3			4.9	4.4			4.1				5.6
2018		2	23.1			5.2	4.7			4.4				6.0
2018		3	27.8			5.8	5.2			4.9				6.7
2018		4	26.9			5.7								4.6
2018		5	26.0			5.6								4.5
2018		6	27.2			5.7								4.6
2018		7	20.9			4.9								3.9
2018		8	19.1			4.7								3.8
2018		9	16.1			4.3								3.5
2018		10	17.9			4.6								3.6
2018		11	19.9			4.8								3.8
2018		12	20.2			4.8								3.9
2018		13	20.5			4.9								3.9
2018		14	20.4			4.9								3.9
2018		15	19.2			4.7								3.8
2018		16	22.2			5.1								4.1
2018		17	22.9			5.2								4.2
2018		18	22.4			5.1								4.1
2018		19	18.1			4.6								3.7
2018		20	17.1			4.4								3.6
2018		21	18.9			4.7								3.7
2018		22	20.2			4.8								3.9
2018		23	15.0			4.2								3.3
2018		24	13.7			4.0								3.2
2018		25	17.4			4.5								3.6
2018		26	24.3			5.4								4.3
2018		27	18.9			4.7								3.7
2018		28	15.4			4.2								3.4
2018		29	17.5			4.5								3.6
2018		30	16.7			4.4								3.5
2018	Octobe	1	15.7			3.6								2.9
2018		2	14.9			3.6								2.9
2018		3	14.7			3.5								2.8

Boston	
Date	Mean Temp.
	Celcius

Corner Stalk	
ET0	ET Lettuce
mm/ day	mm/ day

Eastie Farm								
ET0	ET Carrots	ET Peas	ET Spinach	ET Onions	ET Greens	ET Cabbage	ET Squash	ET Tomatoe
mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day	mm/ day
Total ET during growing season (mm)								
	729.6	503.9	427.7	744.5	560.8	674.8	473.2	852.1
Total ET during measuring period (mm)								
	608.5	470.5	395.0	618.9	493.3	607.3	441.1	594.2

Table 33 Theoretical Water Demand at Corner Stalk Farm and Eastie Farm based on the Blaney-Criddle method