Scenario analysis of rainwater harvesting and use on a large scale – assessment of runoff, storage and economic performance for the case study Amsterdam Airport Schiphol

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Abstract

Research on rainwater harvesting mainly focuses on a building scale. Scant information is available about its performance on a large scale. This study aims to determine the potential for, and economic viability of meeting non-potable water demand by rainwater harvesting for a large scale case (21.5 km²): Amsterdam Airport Schiphol. A dynamic model was developed to analyse scenarios of varying rainfall, catchment surfaces and storage capacity. Four potential system configurations of catchments and non-potable uses were analysed for their economic performance with different water prices and storage options. This study found that, given sufficient storage and catchment size, all non-potable water demand of Schiphol can be supplied, reducing drinking water demand by up to 58%. Diminishing returns for adding storage and catchment to the system make full supply inefficient. Current water charges make most large scale system configurations not viable due to high investment costs for supply networks and storage infrastructure.

1. Introduction

Rainwater harvesting systems for replacing non-potable water demand are receiving increasing attention, due to their potential to enhance water security, reduce water costs and mitigate environmental impacts from water abstraction (Furumai, 2012; Ward et al., 2010). Implementation of rainwater harvesting and reuse infrastructure is challenging in urban areas, because achieving the benefits claimed above requires installation of dual piping networks to supply non-potable water. Airports are urban areas with high water demand, diverse urban functions and large catchments from which to harvest rainwater. They represent a mix of dense urban land-use functions such as hotels, catering and offices, but also green space and paved catchments. Furthermore, the water demand of international airports is comparable to that of small cities. In the case of Amsterdam Airport Schiphol (hereafter referred to as: Schiphol) the annual water demand is comparable to that of a Dutch town of 30,000 inhabitants. Increasingly, airports act as forerunners for implementation of innovative water supply systems including rainwater harvesting; examples are Frankfurt am Main, Brussels, São Paulo (Viracopos), Hong Kong, Singapore and Adelaide (Leung et al., 2012; Neto et al., 2012a; Trautner, 2001). Airports are suitable for rainwater harvesting on a large scale because they have institutional and infrastructural advantages compared with cities. In the latter, responsibilities and ownership of the various elements of water supply and rainwater harvesting are distributed across diverse agents. Water companies are responsible for water treatment and distribution, whereas private households or real estate owners are responsible for installation and management of rainwater harvesting systems. In many airports, including Schiphol investigated here, management of water and wastewater is centralized and all responsibilities rest with the authority of the airport. For instance, Schiphol purchases the water from the supplier and then uses its own distribution network to deliver the water to businesses and residents of the area. Customers are charged for this service directly by Schiphol, rather than by the water supplier. Schiphol is also responsible for drainage of public areas, airfields and roofs.

In this research the potential for implementation of rainwater harvesting and use on a large scale will be investigated. While most studies focus on buildings with rooftop catchments, or on roof catchments from a collection of buildings (Agudelo-Vera, 2012; Blokker et al., 2011; Rathnayaka et al., 2011; Ward et al., 2010), few studies consider larger scale applications. Kim and Furumai (2012) combined a GIS analysis with a rainwater harvesting model to assess rainwater supply for an area of about 1 km². Campisano and Modica (2012) - for the island of Sicily - and Liaw and Chiang (2014) for Taiwan, suggest a method to assess rainwater storage tank’s sizes. Their method is suitable when detailed spatial information, demand patterns and rainwater data are missing. However, the trade-off of this method is that
it is not spatially explicit and does not account for demand and supply patterns. Furthermore, studies at this scale do not assess the economic viability of implementation of rainwater harvesting systems. For Tancredo Neves International Airport, the economic viability of treatment and differing tank materials was studied (Neto et al., 2012a, 2012b), suggesting that non-potable water use is economically viable when costs for storage are kept low.

The aim of this research is to i) assess the potential for rainwater harvesting to supply the non-potable water demand at Schiphol, factoring spatial, functional and temporal variations; and ii) assess the economic performance of rainwater harvesting at different scales and storage options.

The paper is structured as follows. In Section 2 the case study is introduced and the methodology described. In Section 3 the results for the annual water balance and economic analysis are presented and discussed. Finally, conclusions are drawn in Section 4. Extra information about costing and design of rainwater harvesting systems is provided in the supplemental material.

2. Methodology

2.1. Study case: Amsterdam Airport Schiphol

Schiphol in the Netherlands is the fourth largest airport in Europe. It has an area of 21.5 km² and serves over 50 million passengers annually, who spend two hours at the airport on average (Schiphol group, 2015). Schiphol consists of four zones (Figure 1), with contrasting characteristics and functions:

1. North: long term parking spaces and business.
2. Centre: terminals, hotels, offices and car parking. Furthermore, hangars and flight buildings are located in this zone.
3. South: hangars, cargo terminal and parking. Abandoned aircraft fuel tanks with a total volume of 7300 m³ are located in this area.
4. East: hangars, business and parking places.

Total water consumption in 2011 equalled 1.12 million m³/year (Schiphol, 2012 "Water Totaal" – unpublished dataset) while average annual rainfall is 850 mm (KNMI, 2012). 58% of the total demand in Schiphol is non-potable water and can be replaced with rainwater, equalling 650,000 m³ in 2011 (Schiphol, 2012 “Water Totaal” – unpublished dataset). Three types of rainwater harvesting catchment surfaces (Figure 1) were identified: ‘roofs’, ‘paved landside’ and ‘paved airside’. Roofs take up 6% of total surface catchment. Paved airside surfaces include all the sealed surfaces used by airplanes such as runways and tarmac; they cover a total area of 25%. Paved landside surfaces are drained catchments with public roads and car parking; they cover 11% of the total area. Finally, land use types not included in the run-off estimation are ‘grassland’ located between runways (32%), and ‘other’ (26%), representing all remaining land.

Figure 1. Schiphol land use map, including zone boundaries.
Per zone, land use, and thus the catchments for harvesting of runoff differs. In the East, grassland dominates (47%), in the Centre paved airside is the most abundant catchment surface (45%), while in the North and the South un-drained catchments (‘other’) are abundant (42% and 50% respectively). The highest percentage of roof catchment can be found in South and Centre (8% and 7% respectively). These different types of land cover are reflected in water demand. The highest water demand occurs in the Centre, where terminal building functions abound (78% of total water demand). Water use in the East accounts for about 16% of total demand, mainly as a result of toilet flushing by business and in hangars. The smallest demand occurs in the South and in the North. Water demand comes from terminal buildings (38.9%) offices (14.3%), hotels (10.1%), catering (9.9%), firefighting (5.4%), cooling (5.1%), freight buildings (4.0%), hangars (3.8%) and other uses (8.6%).

2.2. Rainwater harvesting model

Modelling of rainwater harvesting and use systems has three dimensions: demand modelling, supply modelling and determination of storage to balance supply and demand (Agudelo-Vera, 2012; Blokker et al., 2011; Rathnayaka et al., 2011; Ward et al., 2010). Supply is driven by precipitation patterns in combination with the properties of the catchment. Human behaviour drives demand, expressed in weekly and daily rhythms and user types (office, terminal, hotel, etc.). The rainwater utilisation rate (RUR) indicator suggested by Kim and Furumai (2012) was adopted for this research to determine the fraction of the total non-potable water demand supplied by rainwater.

2.3. Non-potable water demand

A literature review of urban water uses and interviews with airport staff were conducted to determine replacement factors, which indicate the fraction of water suitable for substitution with water of non-potable quality (i.e. rainwater). The highest replacement factor of 0.7 was found for hotels, resulting from abundant usage of drinking water for food preparation and showering (Blokker et al., 2012). This high factor is a result of the high proportion of toilet flushing in water usage of these buildings. A replacement factor of 0.5 was defined for hangars and freight buildings. The lowest replacement factor of 0.1 was determined for hotels, resulting from abundant usage of drinking water for food preparation and showering (Blokker et al., 2011; Deng & Burnett, 2002).

Hourly demand patterns were estimated for each building from bi-monthly water meter data as follows. Firstly, hourly demand patterns for non-potable water uses were defined using information from literature (Blokker et al., 2011; House-Peters & Chang, 2011; Lazarova et al., 2003; Proença & Ghisi, 2010). These patterns were then enlisted to weight the bi-monthly demand patterns for each building, with seasonal variations reflected in the bi-monthly water meter data.

2.4. Supply – quantitative scenarios of rainwater harvesting

In total nine scenarios for rainwater harvesting were generated by applying three different rain years to three combinations of rainwater catchments (Figure 2). The combinations of catchment surfaces were arranged by increasing size, with roofs covering the smallest area followed by paved landside and paved airside. The three rain years, representing a dry, an average and a wet year, for which runoff is modelled are:

- Dry year: 628 mm (27% below average, year 1996);
- Average year: 854 mm (year 2005);
- Wet year: 1197 mm (40% above average, year 1998).

These years were selected from the period between 1991 and 2011 (KNMI, 2012), to estimate the impact of the variability in precipitation patterns and total rainfall.

For each of these rain years, individual rainfall events were identified from hourly rainfall data measured with an accuracy of 0.1 mm (KNMI, 2012). Rainfall events were distinguished by an antecedent dry weather period long enough to offset depression storage and surface wetting by evaporation. Empirical values for the Netherlands were used: 6 hours for summer (April–September) and 20 hours for winter (October–March) (van de Ven, 1989).

An extensive loss model was used to determined runoff (van de Ven, 1989):

\[ P_n = P - il \]  

Where \( P_n \) is the runoff, \( P \) is the total precipitation and \( il \) are the initial losses. Initial losses comprise interception, wetting of surfaces and surface depression storage (Butler & Davies, 2000). In catchments without tree canopies and shrubs like Schiphol, interception is not applicable (Loucks et al., 2005). Models that account only for initial losses – and not for continuous losses - have been applied in catchments that are effectively fully sealed and have a direct connection to gullies and drainage, as is the case in Schiphol (Arnberg-Nielsen & Harremoes, 1996; Chiew & McMahon, 1999; Van de Ven, 1989). Continuous losses are assumed to be negligible in the case of Schiphol, as the maximal daily evaporation is 3 mm and near zero during rain events (KNMI, 2015). Furthermore, all catchment surfaces considered in this study are sealed and no infiltration occurs.

The variables ‘surface wetting’ and ‘depression storage’ depend on the type of catchment surface and on intervals between rainfall events. Initial losses from surface wetting are 0.2 mm for roofs and paved catchments (Grotengast et al., 1988). Depression storage for flat roofs is 2.5 mm (Butler & Davies, 2000; Van de Ven, 1989). For paved landside this value is 0.5 mm. Finally, for paved airside this value is 0.6 mm, accounting for the fact that the airside is more level than the landside. The majority of roofs at Schiphol are flat roofs, with only a few roofs slightly pitched. In this research all were considered to be flat roofs, thereby avoiding overestimation of harvesting.

The model excludes runoff from paved airside surfaces on days when temperatures fall below 0 °C, when de-icing agents are used and runoff is unsuitable for reuse. Temperature data for the years 1991 to 2011 were used to determine such ‘frost days’ (KNMI, 2012).

2.5. Storage

To enable comparisons to other cases, storage depth was assessed in millimetres, specifying the amount of storage relative to catchment size. The initial value of the water level in
storage at commencement of the simulation was determined by running the model for one year, using an average rainfall year. This is necessary since the amount of water in storage at commencement of simulation affects the indicator RUR.

At Schiphol South, five empty and unused aircraft fuel silos with a total volume of 7300 m³ are available for storage (source: internal unpublished report Schiphol), corresponding to a storage depth of 0.34 mm when related to Schiphol’s total surface area (0.81 mm relative to all rainwater harvesting catchment surfaces). Fractions and multiples of this storage depth were used to examine the impact of storage on RUR: 0, 0.17, 0.34, 0.68, 1.36 and 5 mm.

The model produces hourly data series of water storage using the following iterative function:

\[ S_i = S_{i-1} + (Sup_i - Dem_i) \]  

Where \( S_i \) is storage volume at hour \( i \) (\( S_i \geq 0 \)), \( Sup_i \) is supply at hour \( i \) and \( Dem_i \) is demand at hour \( i \). Once the storage depth has been determined, the Rainwater Utilisation series are calculated as follows:

1. If \( S_{i-1} + Sup_i \geq Dem_i \) → \( RU_i = Dem_i \)  
2. If \( S_{i-1} + Sup_i < Dem_i \) → \( RU_i = S_{i-1} + Sup_i \)  
3. If \( S_{i-1} = 0 \) and \( Sup_i = 0 \) → \( RU_i = 0 \)

Where \( RU_i \) is Rainwater Utilisation at hour \( i \). Using these logic functions, the RUR is calculated:

\[ RUR = \frac{\sum_{i=1}^{n} RU_i}{\sum_{i=1}^{n} Dem_i} \]  

Where \( n \) equals the number of days in the year RUR is calculated for.

### 2.6. Sensitivity of the model

A sensitivity analysis was performed to evaluate the impact of over- or under estimation of initial losses. The parameter was increased and decreased by 10%, 50% and 100%. Impact on the RUR was then assessed by running the model with each of these new input values.

### 2.7. Cost evaluation

To explore the economic performance of rainwater harvesting and use, costs for construction and operation of rainwater harvesting and non-potable water supply systems were evaluated. Return on investment periods were determined using net present valuation with a discount rate of 5%. Return on investment periods were assessed for three different water prices: the current water charges Schiphol has to pay to the water service provider of €0.80/m³, double the current water price (i.e. €1.60/m³, which is roughly the price private customers in the Amsterdam area pay – Waternet, 2013) and by the highest national average domestic water price in Europe of €2.5/m³ (OECD, 2010).

Capital expenditure was estimated using commercial software for planning infrastructure projects (RHDHV, 2015). Operational costs for each option were determined for pumping electricity use rate of €0.20/kWh and by using the relative operational expenditure assessment of 7% of the capital expenditure for pumps and treatment (RIONED, 2015). Costs for cleaning the storage tanks were estimated to be €2500 per 1000 m³ with a the cleaning interval of five years (Neto et al, 2012). Details of the costs and the design underlying the cost assessment are provided in the supplemental material.

Four potential system configurations - or ‘options’ - were selected to explore the viability for rainwater harvesting, differing in their combinations of catchments and non-potable water demands. The currently present drainage infrastructure is used for all options, hence costs for utilised infrastructure that is already in place are not included in the costing:

- I. Schiphol-wide supply from roofs, paved landside and paved airside runoff (RUR = 0.9)
- II. Supply of Centre terminal by roof runoff (RUR = 0.27)
- III. Supply of Centre terminal by roof, paved landside and paved airside runoff (RUR = 0.7)

![Figure 2. Standard scenarios for supply, with varying rain years (dry, average, wet) and catchment surfaces. Dark red indicates the scenario with the smallest- and dark blue with the highest harvesting (colours are only indicative). Catchment surface included in system: R is Roofs, PL is Paved Landside and PA is Paved Airside.](image-url)
Option I represents an airport-wide implementation of the harvesting and supply system and thus provides the maximum amount of mains water replacement. Pumps are installed to pump the runoff into storage tanks. As half of the required storage capacity is already in place, an additional 7300 m³ of storage is built. Water is treated using rapid sand filtration. This method reduces suspended solids (98%) and turbidity (90%) sufficiently to avoid unwanted particular matter in the supply system (Göbel et al., 2007; May & Prado, 2006; Rajala et al., 2003). Pathogen removal efficiencies of this treatment are not sufficient to meet drinking water standards. However, as the water use purpose is non-potable and no contact with humans is made this parameter is neglected for the analysis.

Rainwater is supplied to 1080 public and non-public toilets in the terminal (unpublished report: Active Sanitair – AFS Service Unit), 2340 hotel toilets, 175 office toilets and 11 cooling installations. Information about these fixtures were obtained from internal reports, internet surveys of hotels and for offices derived from the water demand.

With option II, the supply system is restricted to meet non-potable water demand in the Centre terminal, while harvesting from roofs in the Centre. This option was chosen as the majority of demand comes from terminal buildings in the Centre, while they also have the largest rooftop catchments. The water treatment method is similar to that of option I. If existing storage is used, new piping infrastructure is built to and from the South zone and supplies 1080 public and non-public toilets in the terminal, 940 hotel toilets, 100 office toilets and eight cooling installations.

Option III only differs from option II in that it includes paved landside and paved airside as rainwater harvesting surfaces.

Finally, option IV is the cheapest and easiest to implement, as this is just a local application of rainwater harvesting for firefighting drills. It requires minor investments into network upgrading, and no treatment. No supply infrastructure is implemented, because existing firefighting equipment - including mobile pumps and hoses - are harnessed during the drills.
alone can cover non-potable water demand in the East and South zones, even in dry years. In the Centre, where demand is high, roof runoff alone does not cover demand. Runoff from paved landside and paved airside or water transfer from other zones is required.

The supply variable is the main factor determining system performance, due to its erratic pattern. Most hours of the year the weather is dry and rainwater harvesting is zero, with sharp increases in hours of rain. In contrast, demand patterns are balanced and repetitive. Weekly peaks in water use occur when fire drills are executed in the North zone. However, peaks in rainwater harvesting from roofs are between 6–27 times higher than peaks in demand. This difference between supply and demand patterns is exacerbated with the inclusion of additional catchment surfaces. In the next section, the supply and demand patterns are used as input for the dynamic model to determine the RUR.

### 3. Results and discussion

#### 3.1. Annual water demand and supply

Figure 3 shows that in all but one scenario (A1), rainwater harvesting at Schiphol is enough to cover non-potable demand. When considering the water supply and demand balance for different zones, it becomes apparent that runoff from roofs alone can cover non-potable water demand in the East and South zones, even in dry years. In the Centre, where demand is high, roof runoff alone does not cover demand. Runoff from paved landside and paved airside or water transfer from other zones is required.

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#### 3.2. Rainwater supply at varying storage depths

During all hours that the water level in storage is nonzero, rainwater supply covers the entire non-potable water demand. With a small storage capacity, full storage is reached even after minor rainfall events (Figure 4). Figure 5 presents the relationship between RUR and storage depth for all nine scenarios. A RUR of 1 is achieved for all scenarios except A1 (dry year, roofs only).
by adding paved airside catchments further increases RUR by just 0.04 to 0.72 (scenario B3).

Diminishing marginal returns for increasing storage depth and catchment size are a consequence of runoff and demand patterns. Due to the relatively frequent and distributed rainfall events in the Netherlands (Figure 2), a relatively small storage of 0.17 mm can supply almost 50% of demand in an average year with just harvesting from roofs (B1). More storage is effective only during long dry periods, as it increases the supply duration. These characteristics can be observed in Figure 4, where doubling, tripling or quadrupling the storage depth does not reduce the white spaces (no rainwater supply) proportionally. Similarly, increasing the catchment size increases overflow, as more water is available than can be stored. This explains the decreasing marginal returns as observed in Figure 5.

3.3. Sensitivity analysis

The sensitivity analysis shows that doubling initial losses (i.e. +100%) reduces RUR between 7% and 26% (scenarios A2 and A1). Setting initial loss values to zero (i.e. −100%) increases the RUR between 8% and 48% (C3 and B1- Figure 6). It can further be observed that the sensitivity of the RUR varies across the catchments (A, B, C scenarios). In particular RUR for roof harvesting is sensitive to doubling of the initial losses. Furthermore, a disparity of sensitivity between years can be observed. In years with fewer and low intensity rain events, the change in initial loss values has a higher impact on the RUR than in years with more rain (compare A scenarios with B and C). However, this effect is more pronounced for a decrease in the initial loss parameter, than for an increase.

3.4. Economic assessment

With the current, low water prices, firefighting is the only option with a return on investment period below 30 years, using the present storage at Schiphol. All other options result in a return on investment period of more than 30 years (Table 1). However, Table 1 shows that by doubling water prices, return on investment periods fall below 30 years. Higher water prices are very common around Europe (OECD, 2010). Especially options III and IV have low return on investment periods. A similar trend is observed for the ‘reservoir’ storage option. In contrast, storage in ‘concrete tank’ only becomes viable for option I and III with high water prices. These results suggest that at the current water price, water supply for firefighting is the only attractive option. Evidence for office buildings in the USA confirms that rainwater harvesting is not economically viable due to low water charges (Hicks, 2008; Wang & Zimmerman, 2015). However, in Frankfurt Airport rainwater harvesting has been implemented for firefighting purposes (Trautner, 2001). Furthermore, Neto et al. (2012a) found that at a water price of US$2.61/m^3 (=€2/m^3 at average yearly exchange rate of 0.8 in 2012), rainwater harvesting is economically viable for terminal application for an airport in Brazil. Indeed, at higher water prices a similar conclusion can be drawn for Schiphol (Table 1).

When the maximal negative sensitivity of the RUR (26% - Section 3.3) is applied to cost assessment, options III and IV

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Figure 5. Rainwater Utilization Rate (RUR) for all 9 scenarios with increasing storage depth and catchment size (i.e.1-3): R – Roof catchment, PL – paved landside catchment; PA – paved airside catchment. A refers to scenarios for the dry year, B the average year and C the wet year. 1 refers to scenarios with only rooftop harvesting, 2 for roof + paved landside, 3 for roofs, paved landside and paved airside.

provided the storage capacity is sufficient. For cases with roof catchments only, this requires 5 mm of storage depth. For roof and paved landside, a RUR of nearly 1 can already be achieved at a storage depth of 1.36 mm. For the storage currently available at Schiphol (storage depth = 0.34 mm), none of the scenarios achieve a RUR of 1.

All curves in Figure 5 show diminishing marginal returns to increased storage depth. Similarly, diminishing marginal returns are observed with increasing catchment size. Moving from a harvesting on roofs only to roofs + paved landside increases RUR from 0.48 to 0.68 (scenario B1 to B2). Increasing catchment size
Network infrastructure costs can be reduced when combined with maintenance or renewal activities, as the majority of costs for installation of pipe networks pertain to labour and trenching (between 50–75%) (Langdon, 2009). Finally, water treatment accounts for a small proportion of total asset investment (2–9%), and accounts for a third of operational costs. Therefore, if operational costs are kept low, water treatment for reuse on a large scale is no impediment to implementation of rainwater harvesting systems.

Investment cost breakdown shows that storage and network infrastructure are the most important cost items (Figure 7). Storage comprises between 30–50% of the total costs – except for option IV (Neto et al., 2012). Likewise, network infrastructure can account for more than 50% the total costs. Network infrastructure costs can be reduced when combined with maintenance or renewal activities, as the majority of costs for installation of pipe networks pertain to labour and trenching (between 50–75%) (Langdon, 2009). Finally, water treatment accounts for a small proportion of total asset investment (2–9%), and accounts for a third of operational costs. Therefore, if operational costs are kept low, water treatment for reuse on a large scale is no impediment to implementation of rainwater harvesting systems.

Table 1. Return of investment periods and realisation cost for all combinations of water prices and storage options. Values in brackets represent return on investment with RUR 26% down (highest observed sensitivity).

|                              | I Supply of all installations | II Supply terminal with roof runoff | III Supply terminal with roof and paved land runoff | IV Supply firefighting |
|------------------------------|------------------------------|-----------------------------------|----------------------------------------------------|------------------------|
| **Existing storage** Realisation costs | m€ 13 | 5 | 4.6 | 0.16 |
| €0.80/m³ years               | >30 (>30) | >30 (>30) | >30 (>30) | 14 (16) |
| €1.60/m³ years               | 28 (>30) | >30 (>30) | 10 (15) | 4 (5) |
| €2.50/m³ years               | 14 (20) | 21 (>) | 6 (8) | 3 (3) |
| **Concrete tank** Realisation costs | m€ 16.8 | 9.1 | 8.8 | 2.6 |
| €0.80/m³ years               | >30 (>30) | >30 (>30) | >30 (>30) | >30 (>30) |
| €1.60/m³ years               | >30 (>30) | >30 (>30) | 25 (>30) | >30 (>30) |
| €2.50/m³ years               | >30 (>30) | >30 (>30) | 12 (15) | >30 (>30) |
| **Reservoir** Realisation costs | m€ 9 | 5 | 4.5 | 0.3 |
| €0.80/m³ years               | >30 (>30) | >30 (>30) | 26 (>30) | 22 (22) |
| €1.60/m³ years               | >30 (>30) | >30 (>30) | 9 (13) | 8 (8) |
| €2.50/m³ years               | >30 (>30) | >30 (>30) | 5 (7) | 5 (5) |

Figure 6. Sensitivity of RUR to changes to parameter values of initial losses (ii).

Table 1. Return of investment periods and realisation cost for all combinations of water prices and storage options. Values in brackets represent return on investment with RUR 26% down (highest observed sensitivity).

Figure 7. Distribution of system investment costs across the different storage alternatives in combination with different catchment sizes and uses: (I) supply of all installations, (II) supply terminal with roof runoff, (III) supply terminal with roof and paved land runoff and (IV) supply firefighting.
4. Conclusions

Quantitative scenario analysis was combined with dynamic modelling to assess the potential for rainwater harvesting to supply the non-potable demand on a large scale for Amsterdam Airport Schiphol. It was found that, although rainwater harvesting could supply all non-potable demand and reduce total drinking water demand by 58%, application on this large scale is not economically viable.

It is demonstrated that Schiphol can become self-sufficient in its non-potable water demand. However, the quantitative scenario analysis performed in this study shows that full replacement of non-potable water demand with rainwater supply is inefficient, as diminishing marginal returns are observed for both increasing catchment area and storage capacity.

Economic viability evaluation indicates that supplying all non-potable water demand in Schiphol has a return on investment period of over 30 years at the current water price, and is thus not economically viable. Indeed, at current water prices the only viable option for rainwater harvesting is from roofs and paved landside when deployed for firefighting. However, with the higher water prices prevalent in many European countries, rainwater harvesting from both roofs and paved surfaces becomes viable for the supply of non-potable water demand in terminal buildings. Therefore, water prices are a critical factor in the viability of rainwater harvesting systems at this scale.

Notes

1. For the purpose of this paper, large scale refers to the scale of a suburban precinct within a city.
2. A 30 year return on investment period was chosen to evaluate economic viability, because it is the approximate life of water treatment assets and public buildings in the Netherlands.

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References

Agudelo-Vera, C.M., 2012. Dynamic water resource management for achieving self-sufficiency of cities of tomorrow (PhD Dissertation). Wageningen: Wageningen University.

Ambjerg-Nielsen, K. and Harremoës, P., 1996. The importance of inherent uncertainties in state-of-the-art urban storm drainage modelling for ungauged small catchments. *Journal of Hydrology*, 179 (1–4), 305–319.

Blokker, E., et al., 2011. Simulating nonresidential water demand with a stochastic end-use model. *Journal of Water Resources Planning and Management*, 137 (6), 511–520.

Butler, D. and Davies, J., 2000. *Urban drainage*. London: E & FN Spon Publishing.

Campisano, A. and Modica, C., 2012. Regional scale analysis for the design of storage tanks for domestic rainwater harvesting systems. *Water Science and Technology*, 66 (1), 1–8.

Chiew, F.H.S. and McMahon, T.A., 1999. Modelling runoff and diffuse pollution loads in urban areas. *Water Science and Technology*, 39 (12), 241–248.

Deng, S.M. and Burnett, J., 2002. Water use in hotels in Hong Kong. *International Journal of Hospitality Management*, 21 (1), 57–66.

Furumai, H., 2012. Significance of rainwater and reclaimed water as urban water resource for sustainable use. Paper presented at the Japan-China-Korea Green Technology Forum, Tokyo, Japan, 14 March, 2012.

Göbel, P., Dierkes, C., and Coldewey, W.G., 2007. Storm water runoff concentration matrix for urban areas (Issues in urban hydrology: the emerging field of urban contaminant hydrology). *Journal of Contaminant Hydrology*, 91 (1–2), 26–42.

Grotengast, G.J., et al., 1988. *Cultuurtectnisch Vademecum. Agricultural engineering handbook*. Utrecht, The Netherlands: Cultuurtectnische Vereniging.

Hicks, B., 2008. A cost-benefit analysis of rainwater harvesting at commercial facilities in Arlington County, VA. *VA: Master projects Nicholas School of the Environment and Earth Sciences, Duke University, Durham, NC, USA.*

House-Peters, L.A. and Chang, H., 2011. Urban water demand modeling: review of concepts, methods, and organizing principles. *Water Resources Research*, 47 (5), 1–15.

Kim, J., and Furumai, H., 2012. Assessment of rainwater availability by building type and water use through GIS-based scenario analysis. *Water Resources Management*, 26 (6), 1499–1511.

KNMI, 2012. *Uurgegevens van het weer in Nederland. Hourly data for the weather in the Netherlands*. Koninklijk Nederlands Meteorologisch Instituut. Retrieved from http://www.knmi.nl/klimatologie/uurgegevens/#n0 (Accessed 11 October 2013).

KNMI, 2015. *Klimaatatlas*. Royal Dutch Meteorological Institute. Retrieved from http://www.klimaatatlas.nl/klimaatatlas.php?wel=neerslag&ws=kaart&wom= Gemiddelde%20hoeveelheid%20verdamping (Accessed 3 March 2015).

Langdon, D., 2009. *Spon's civil engineering and highway works price book*. London: Taylor & Francis.

Lazarova, V., Hills, S., and Birks, R., 2003. Using recycled water for non-potable, urban uses: a review with particular reference to toilet flushing. *Water Science & Technology*, 3, 69–77.

Leung, R., et al., 2012. Integration of seawater and grey water reuse to maximize alternative water resource for coastal areas: the case of the Hong Kong International Airport. *Water Science & Technology*, 65 (3), 410–417.

Liaw, C.-H. and Chiang, Y.-C., 2014. Dimensionless analysis for designing domestic rainwater harvesting systems at the regional level in Northern Taiwan. *Water*, 6 (12), 3913–3933.

Loucks, D.P., et al., 1986. *Water resources systems planning and management an introduction to methods. Models and applications. Studies and Reports in Hydrology*. Paris: UNESCO.

May, S. and Prado, R.T.A., 2006. Experimental evaluation of rainwater quality for non-potable applications in the city of Sao Paulo, Brazil. *Urban Water Journal*, 3 (3), 145–151.

Neto, R.F.M., et al., 2012a. Rainwater treatment in airports using slow sand filtration followed by chlorination: efficiency and costs. *Resources, Conservation and Recycling*, 65, 124–129.

Neto, R.F.M., et al., 2012b. Rainwater use in airports: A case study in Brazil. *Resources, Conservation and Recycling*, 68, 36–43.

OECD, 2010. *Pricing water resources and water and sanitation services*. OECD Studies on Water. Paris: OECD Publishing.

Proença, L.C. and Ghisi, E., 2010. Water end-uses in Brazilian office buildings. *Resources, Conservation and Recycling*, 54 (8), 489–500.

Rajala, R., et al., 2003. Removal of microbes from municipal wastewater effluent by rapid sand filtration and subsequent UV irradiation. *Water Science & Technology*, 47 (3), 157–162.

Rathnayaka, K., et al., 2011. Review of residential urban water end-use modelling. In *19th International Congress on Modelling and Simulation*, Perth, Australia, 12–16 December 2011.

RHDHV, 2015. *Cost standard calculator*. Amersfoort, The Netherlands: Royal HaskoningDHV.
Wang, R. and Zimmerman, J.B., 2015. Economic and environmental assessment of office building rainwater harvesting systems in various U.S. Cities. *Environmental Science & Technology*, 49 (3), 1768–1778.

Ward, S., Memon, F.A., and Butler, D., 2010. Rainwater harvesting: Model-based design evaluation. *Water Science & Technology*, 61, 85–96.

Waternet, 2013. *Vaststelling Tariefbepalingen 2013*. Retrieved from www.waternet.nl (Accessed March 2013).

RIoNED, 2015. *Leidraad riolerings*. National centre of expertise in sewer management and urban drainage in the Netherlands. Retrieved from www.rioned.com (Accessed 4 March 2015).

Schiphol group, 2015. *Schiphol Statistics*. Retrieved from http://www.schiphol.nl/SchipholGroup/Company1/Statistics.htm (Accessed 3 March 2015).

Trautner, H.J., 2001. Rainwater utilization at the Frankfurt Airport. *World Pumps*, 2001 (414), 42–43.

Van de Ven, F.H.M., 1989. *Van neerslag tot rioolinloop in vlak gebied. From precipitation to sewer inflow in low lands* (PhD Dissertation), TU Delft, Delft.