Knowledge for Climate

Rainwater harvesting, a sustainable solution for urban climate adaptation?

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Rainwater harvesting, a sustainable solution for urban climate adaptation?

Authors
Dr.ir. J.A.M.H. Hofman [(1)], Dr.ir. M. Paalman [(1)]

[(1)] KWR Watercycle Research Institute, PO Box 1072, 3430 BB Nieuwegein, The Netherlands

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Content

1 Summary

Rainwater harvesting (RWH) is a climate adaptation strategy of all times and was applied by many civilisations in history of mankind. The system is especially found during eras with long dry periods. Rainwater harvesting is gaining interest again worldwide, not only to store water for dry periods, but also as a measure to cope with extreme rainfall. This report has evaluated recent literature on rainwater harvesting. Focus has been on design principles, application scale, water quality and public acceptance. It was concluded that rainwater harvesting can have a significant effect on the water management during extreme precipitation. In general the water quality of harvested rainwater is good, although some microbiological contamination may be present.

Application of small individual size RWH systems are not economically viable if they are considered as an alternative source for drinking water in low grade applications. In that case pay-back times are very long (>60 years). Larger scale systems seem to be economically viable.

The possibilities for application in Dutch urban areas is explored in the final chapter. In principle rainwater harvesting can be applied in the Netherlands as well and in fact several installations and projects exist. RWH can have a significant impact on urban water management. To introduce it on large scale a clear incentive has to be created and demonstration projects are required to investigate and demonstrate the possibilities.

2 Samenvatting

Opvang van regenwater – rainwater harvesting – is een strategie die al sinds mensenheugenis wordt toegepast. Regenwater opvangsystemen zijn vooral gebruikt in tijdperken waar langdurige droogte voorkwam. De laatste jaren neemt de belangstelling van regenwateropvang toe, niet alleen vanwege de belangstelling om het water in droge periodes te kunnen inzetten, maar ook om overlast bij extreme neerslag te helpen voorkomen. In dit rapport is recente literatuur over regenwateropvang geëvalueerd. Daarbij is vooral gekeken naar de ontwerpprincipes, het effect van schaalgrootte, waterkwaliteit en maatschappelijke acceptatie. Geconcludeerd is dat regenwateropvang een belangrijke invloed heeft op de afvoer van water tijdens extreme neerslag. In het algemeen blijkt de waterkwaliteit van het opgevangen regenwater goed te zijn, hoewel soms nog wel sprake is van enige microbiologische verontreiniging.

Individuele regenwateropvangsystemen lijken economisch gezien niet levensvatbaar, in het bijzonder als ze worden toegepast als een alternatieve bron voor drinkwater bij de inzet voor laagwaardige toepassingen. Als de kosten worden vergeleken met de inzet van drinkwater, zijn de terugverdientijden voor een opvangsysteem extreem lang (> 60 jaar). Toepassing van systemen met een grotere schaalgrootte lijken wel economisch haalbaar te zijn.

De toepassingsmogelijkheden in de Nederlandse stedelijke omgeving is in het laatste hoofdstuk verder uitgewerkt. In principe is regenwateropvang in Nederland goed mogelijk en het wordt op beperkte schaal zelfs al toegepast. Regenwateropvang kan een belangrijk onderdeel vormen van stedelijk waterbeheer, maar om het op grote schaal te introduceren zal een “drijvende kracht” moeten worden gecreëerd. Om de toepassingsmogelijkheden en effecten voor het stedelijk waterbeheer te onderzoeken en te demonstreren zullen ook demonstratieprojecten nodig zijn.

3 Extended summary

Climate is expected to change in the coming decades. As a consequence, precipitation may increase in frequency and intensity and it is likely that the balance between dry and wet periods will change. Existing urban drainage systems are based on a centralised approach consisting of piped networks that provide drinking water to consumers and drainage networks that transport wastewater and stormwater runoff away from the populated areas. It is expected that a lacking capacity to remove the excess water from the city, especially during short and extreme precipitation peaks, will become apparent. This will result in more frequent water at the street level and associated nuisance and damage. Also health risks may increase. Moreover, periods of drought and heat may increase due to climatic changes. These periods may be characterised by water shortage. Cities need to adapt to cope with the effects of climate change. One of the adaptation measures is to store the excess rainwater (in tanks or aquifers) and use it for low water quality application within the city (RWH).

Research questions
In this report a literature review on rainwater harvesting is given. The results are used to give an outlook for the possibilities of application in The Netherlands. The following research questions are addressed in this report:

- What are the technical conditions (collection and storage, treatment, demand matching)?
- What are the costs and benefits in a broader context?
- What are the health risks involved?
- Can RWH be applied as an climate adaptation measure in cities in The Netherlands?

Rainwater harvesting
Rainwater harvesting is used as a climate adaptation strategy that has been in use during many eras of mankind. Archaeological studies and historical information showed that the technology was in use for more than 10,000 years on all continents. In most cases it was mainly used as an alternative water source in dry periods and it was a survival strategy for ancient civilisations.

Rainwater harvesting can not only be used as an adaptation measure against periodic water scarcity and reduction of drinking water use. It can be seen as a strategy to be included in urban water cycle management. It may reduce the city’s external water demand, alleviate water stress on the area, reduce non-point source pollution, reduce treatable urban runoff volume, prevent flooding and help to alleviate climate change. Studies have shown that application of RWH results in a reduction of stormwater runoff volume between 20 to 50 %.

In the Netherlands, urban drainage is a policy field of the municipalities. In many cities, urban drainage is done by mixed sewers, transporting excess water via the sewers and the sewage treatment plant (STP) to the receiving surface water. Because this often results in bad performance of the STP during rainfall, and worse, direct sewer overflows to surface water, more and more municipalities are changing to separate sewer systems for wastewater and rainwater. Currently, 72 % of the sewers in the Netherlands is mixed. In some cities, urban drainage takes place over hard paved surface and sometimes infiltration systems are installed to replenish the local groundwater.

In the current situation, extreme precipitation may already bring damage and nuisance to cities. Future climate scenarios have been developed for the Netherlands. In all scenarios precipitation intensities increase: depending on the scenario this can be during summer or during winter. The scenarios that predict increased precipitation levels in winter also predict rainfall frequencies to increase.

Design

Traditionally rainwater harvesting (RWH) has been used on small scale. Driving force is mainly to find sustainable solutions to supply lower grade water in water scarce areas. Most common applications are garden or landscape irrigation, toilet flushing or laundry washing. In the Dutch situation the driving force for application of RWH is to cope with climate change within cities, primarily to solve extreme precipitation situations, but the stored rainwater can be used in periods of drought.

Many systems and publications look at individual systems for a single house. Sometimes larger systems like sport arenas, apartment blocks and office buildings are described. A typical RWH system contains a rainwater catchment (mostly roof tops), a storage tank and some treatment options (filters, disinfection). The design of RWH systems depend on many factors such as total precipitation, precipitation frequency and duration, duration of dry periods, catchment efficiency and the application of the harvested water. Water use is a key success factor, because it is necessary to empty the storage facilities before the next extreme rain event.

Different models exist to predict the performance of RWH systems. Often simple mass balance approaches or 'rule-of-thumb' design based on annual precipitation volumes is used. These tools however don't have sufficient accuracy and detail to properly size RWH systems. More detailed designs can be made with the so-called behavioural (stochastic) models. These models lead to storage tanks that are substantially smaller than simple mass balance simulations.

Economic factors

An important factor in utilising rainwater is the economic viability of the system. Although RWH may bring more sustainability to a city, it should also be a cost-effective solution. Economic evaluations have been made by using many different approaches in the water sector, including cost-benefit analysis, net present value, internal rate of return, or payback time.

Research also confirms that economy of scale is an important factor. Though most systems are designed for individual houses, calculations have shown that these systems are not economically viable. However, for large scale systems economic viability has been proved. Most systems use tanks for storage, but subsurface storage can be an interesting alternative.

In most cases in the economic benefits analysis of RWH, the costs of RWH are compared to the reduction of the costs of drinking water use. However if RWH is used as climate adaptations strategy, it can also lead to cost reduction for stormwater management and prevent costs from damage by flooding. This means that a societal cost-benefit analysis is required.

Water quality

Water quality is an important issue when considering application of rainwater harvesting. Depending on the application, the water quality requirements may vary, but also the water quality of the harvested water may vary in space and time.

The water quality of the harvested rainwater depends on many factors. Three types of contaminants can be distinguished: (a) chemical, (b) microbiological, and (c) physical. The uptake of contaminants occurs from the moment the raindrops leave the clouds, either as particulate matter or as solutes. A second important source for pollutants is the roof surface. Water harvested at the rooftop can be influenced by the rooftop material and the deposits on the rooftop. Finally, water quality may change during storage.

For water quality assessment, the chemical water quality and the microbiological water quality have to be distinguished. The chemical water quality is in general very good and approximates drinking water quality, but in most situations faecal contamination and regrowth of bacteria can be observed. Depending on the application of the harvested water, an additional disinfection step, e.g. with filtration and/or UV-disinfection may be required.

Application in The Netherlands

Currently application of harvested rainwater in the Netherlands is only allowed for toilet flushing. It is used occasionally in larger office buildings. Nevertheless, if rainwater harvesting is applied in an urban area and it is designed well, i.e. there is sufficient storage capacity for the water and the water discharge to the storage can be done at high rate, such a system has a big potential to create a sustainable solution for climate adaptation in urban areas. On average about 50% of the hard surface in an urban area are roof tops. If an infrastructure can be created to harvest water from roof tops, while the existing storm water infrastructure is used for the other 50% of roads and paved surfaces, a large capacity increase to deal with increasing precipitation levels can be realised, while also a new water source is created that can be used for water applications that do not need drinking water quality, such as toilet flushing, laundry washing, garden watering, or cooling purposes. However, a change of legislation is required for this.

For the cases and hotspots involved in Climate Proof Cities a rough estimate on the applicability of RWH on different scales was made. The options are summarised in the table below. They are not validated. Further research is required to determine the real viability of these options.

Area	Individual systems	Office Buildings	Neighbourhood
Amsterdam, Watergraafsmeer Deep polder (-5.5 m MSL), varying urban density, residential areas, large road and railway infrastructure, office buildings	Possible	Existing	Possible with storage in ponds or aquifer
Rotterdam, Het oude Noorden Very high urban density, over 70% hard surface	Difficult	Not present	Possible, storage in aquifer
Tilburg	Possible	Possible	Difficult; low grade water project terminated
Arnhem-Nijmegen Cities partly built at push moraines, sandy soils and clay soils in river bed	Possible	Possible	Possible, storage in aquifer

Conclusions

With respect to the research questions the following conclusions were drawn:

- What are the technical conditions (collection and storage, treatment, demand matching)?
  - RWH is of all times and is an ancient climate adaptation strategy
  - Rainwater harvesting infrastructure consists of a catchment (mostly roof surfaces), a storage (tank or aquifer), a small treatment system and an application for water use
  - RWH can reduce stormwater load on (existing) sewer system significantly if designed well. It is expected that a well-designed system can keep at least 40% water “out of the sewer”.
  - Storage is possible in storage tanks and in the subsoil.

- What are the costs and benefits in a broader context?
  - The availability of water utilisation is a key issue
  - RWH on small scale (individual systems) is not economically viable when used as an alternative water source.

- ▽ If applied on large scale and the costs are weighted against costs for capacity expansion of a sewer network and costs by damage caused by flooding, the societal costs may be less.
- ▽ Large scale systems (collective systems on neighbourhood scale, large office buildings etc.) can be economically viable

- ∆ What are the health risks involved?
  - ▽ Physico-chemical water quality of roof harvested is in general good, if a first flush is diverted.
  - ▽ Roof water contains in general low levels of pathogens, depending on the application some disinfection treatment may be required
  - ▽ Health risks of RWH are low.

- ∆ Can RWH be applied as an climate adaptation measure in cities in The Netherlands?
  - ∆ Application in The Netherlands depends strongly on the local situation. Large scale RWH with aquifer storage can be effective, even in urban areas with high urban density. This has already be demonstrated in for horticulture, but may also be applicable in urban areas.
  - ∆ In many area's individual systems can be used, but they are only effective if many of them are installed and they have sufficient storage capacity. In this case governance and the creation of an incentive to install systems is an important issue.

4 Introduction

Climate is expected to change in the coming decades. As a consequence, precipitation may increase in frequency and intensity and it is likely that the balance between dry and wet periods will change. Existing urban drainage systems are based on a centralised approach (Younos 2011) consisting of piped networks that provide drinking water to consumers and drainage networks that transport wastewater and stormwater runoff away from the populated areas. Younos (2011) expects that a lacking capacity to remove the excess water from the city, especially during short and extreme precipitation peaks, will become apparent. This will result in more frequent water at the street level and associated nuisance and damage. Also health risks may increase. Moreover, periods of drought and heat may increase due to climatic changes. These periods may be characterised by water shortage. Cities need to adapt to cope with climate change. Several possibilities exist:

- Increase the urban drainage capacity;
- Store the excess water (in tanks or aquifers) and use it for low water quality application within the city (rainwater harvesting).

Figure 1: Water nuisance around Velperweg and Huijgenslaan in Arnhem (Photo: Jan Hofman)

In a holistic view on sustainable urban water management decentralized water infrastructures should be designed in the water management system. These infrastructures include small to medium-scale local use and re-use systems for rainwater, stormwater runoff and wastewater. According to Younos (2011) rooftop rainwater harvesting is a critical component to develop a sustainable urban water management system and is supplemental to other measures such as retention basins, infiltration trenches and basins, vegetated filter strips, swales, constructed wetlands and porous pavement systems.

Rainwater harvesting (RWH) seems to be a climate adaptation strategy of all times. Pandey *et al.* (2003) have studied archaeological and historical information of civilisations during the Holocene period (9000 BC until now). In general, cultures remain settled in their homeland until all options for survival have exhausted. In their study, Pandey *et al.* (2003) reviewed paleoclimatological data and matched them with the historical data. They found evidence that abrupt changes in climate conditions such as increased aridity or drought correlates well with the appearance of the construction of RWH systems. In Mexico the Mayan culture responded to climate variations by constructing rainwater storage systems. Similar systems have been have been found in other regions in South America, North America and the Arabian Peninsula. Some structures date back to a period between 11,000 and 3,000 BC.

Many studies from literature describe RWH from a perspective of water saving and alternative water supply for potable and non-potable use (Farreny *et al.* 2011a, Fewkes 2012, Mendez *et al.* 2011, Morales-Pinzón *et al.* 2012, Palla *et al.* 2011, Palla *et al.* 2012, Roebuck *et al.* 2011, Vialle *et al.* 2011, Villarreal en Dixon 2005, Ward *et al.* 2012b).

RWH can not only be used as an adaptation measure against periodic water scarcity and reduction of drinking water use. Farreny *et al.* (2011a) label it as a sustainable strategy to be included in urban water cycle management. It may reduce the city's external water demand, alleviate water stress on the area, reduce non-point source pollution, reduce treatable urban runoff volume, prevent flooding and help to alleviate climate change. Domènech en Saurí (2011) take it a step further as they mention that rainwater harvesting may turn hazards into local resources. And although RWH has been ignored too much in the past, a development of new regulations and incentives for RWH can now be observed worldwide (Rygaard *et al.* 2011). Steffen *et al.* (2013) conclude from their results that rainwater harvesting can reduce stormwater runoff volume up to 20% in semiarid regions, and less in regions receiving greater rainfall amounts for a long-term simulation. Overall, the results suggest that U.S. cities and individual residents can benefit from implementing rainwater harvesting as a stormwater control measure and as an alternative source of water. Also in Nanjing, China, the utilisation of RWH to reduce waterlogging was investigated (Zhang *et al.* 2012). It was concluded that problems can be effectively reduced through rainwater harvesting by 13.9 %, 30.2 % and 57.7 % of runoff volume reduction in three cases of the maximum daily rainfall (207.2 mm), the average annual maximum daily rainfall (95.5 mm) and the critical rainfall of rainstorm (50 mm).

Some countries stimulate RWH through national policy, while in others regional or local governments are taking the lead. Policies range from obliging to install RWH systems to subsidy programs or exemption of paying taxes. In the UK, the driving forces for RWH are the Government's water strategy 'Future Water', the Flood and Water Management Act, and the European Water Framework Directive. These encourage the use of other water sources such as rainwater (Ward *et al.* 2012a).

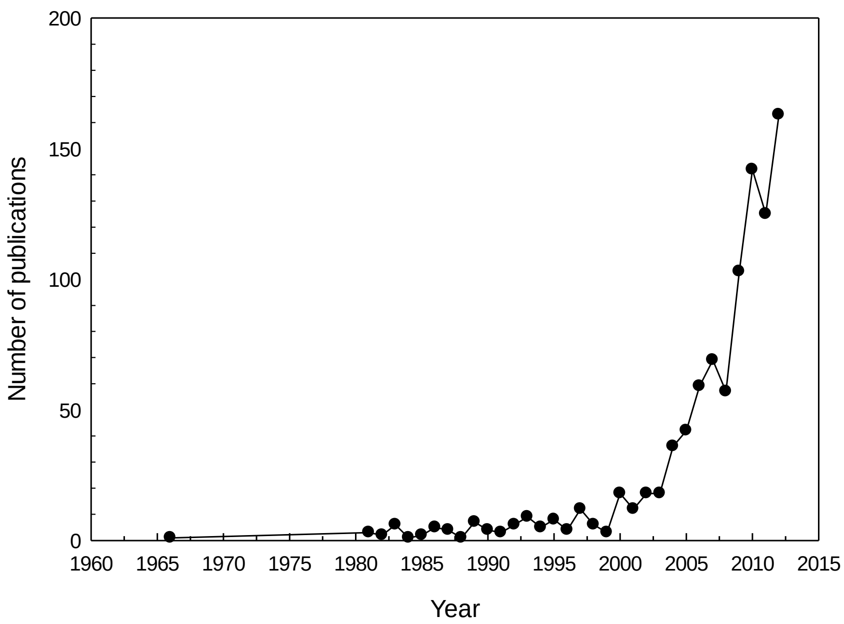
A determining factor for the feasibility of RWH systems is finding the right applications for the harvested rainwater. Larger demand volumes will increase the economic feasibility. Morales-Pinzón *et al.* (2012) have studied this scale effect. They use a holistic view to analyse the economic and environmental feasibility of RWH systems in Spain at several scale levels ranging from single houses to groups of apartment buildings. They conclude that RWH systems from a financial point have an optimal scale at large scale and high-density developments. Furthermore they conclude that systems that are more financially viable are not necessarily the best in terms of environmental impact.

The decentralised and often privately owned character of RWH means that the involvement of the owners is large. Consequently the control of central authorities and water supply companies will reduce. This means that a successful implementation of decentralised systems needs also policy and management innovations (Partzsch 2009) and the development of new business models (Van Der Hoek *et al.* 2011).

In many cases described in literature, the utilisation of harvested rainwater is limited to only one or two applications, e.g. toilet flushing, landscape or garden irrigation or laundry washing, which is logical considering the single-family building approach. Increasing size and scale to building block or neighbourhood level, may render in a more cost-effective system and will open doors for other applications, like cooling, street flushing or application in energy systems.

Scientific literature on RWH is growing exponentially. Figure 2 shows a graph on the number of publications in Scopus. In this report, a literature survey on RWH is presented. Furthermore, the use of RWH for climate adaptation in the Dutch cities will be explored.

Figure 2: Growth of the number of publications on “Rainwater Harvesting” in Scopus.



Research questions

The following research questions are addressed in this report:

- What are the technical conditions (collection and storage, treatment, demand matching)?
- What are the costs and benefits in a broader context?
- What are the health risks involved?
- Can RWH be applied as an climate adaptation measure in cities in The Netherlands?

5 Rainwater utilisation in the urban environment

5.1 Urban drainage in The Netherlands

The current policy is to remove excess rainwater from the city as rapid as possible. Sewers are designed to prevent water on the street during intensive rain showers with a repetition time of 2 years (Luijtelaar 2006). During more extreme precipitation, water on the street can result. Three levels are distinguished concerning water on the street:

- Some nuisance: small amounts of water on the street during short period (15 – 30 minutes)
- Severe nuisance: large amounts of water on the street, flooded tunnels, floating manhole covers duration 30 – 120 minutes
- Impediment: longer periods of water on the street on a large scale, flooded buildings, material damage, traffic and economic obstruction

In the Netherlands, urban drainage is a policy field of the municipalities. In many cities, urban drainage is done by mixed sewers, transporting excess water via the sewers and the sewage treatment plant (STP) to the receiving surface water. Because this results in bad performance of the STP during rainfall, and worse, direct sewer overflows to surface water, more and more municipalities are changing to separate sewer systems for wastewater and rainwater. Currently, 72 % of the sewers in the Netherlands is still mixed (Oosterom en Hermans 2011). In some cities, urban drainage takes place over hard paved surface and sometimes infiltration systems are installed to replenish the local groundwater.

In the current situation, extreme precipitation may already bring damage and nuisance to cities. Future climate scenarios (Hurk *et al.* 2006) have been developed for the Netherlands (Figure 3). These scenarios predict a change in precipitation pattern over the summer and winter season. Two scenario's assume the effect of global warming (W, G) and two scenario's include the effect of changed air circulation patterns (W+, G+).

Table 1 summarizes the predicted changes in temperature and precipitation regimes for the four scenarios. The W+ and G+ scenarios predict on average dryer summers and wetter winter periods. In summertime the wet day frequency is reduced, but the wet day precipitation rate increases slightly. For the winter period both the wet day frequency and precipitation on a wet day increase.

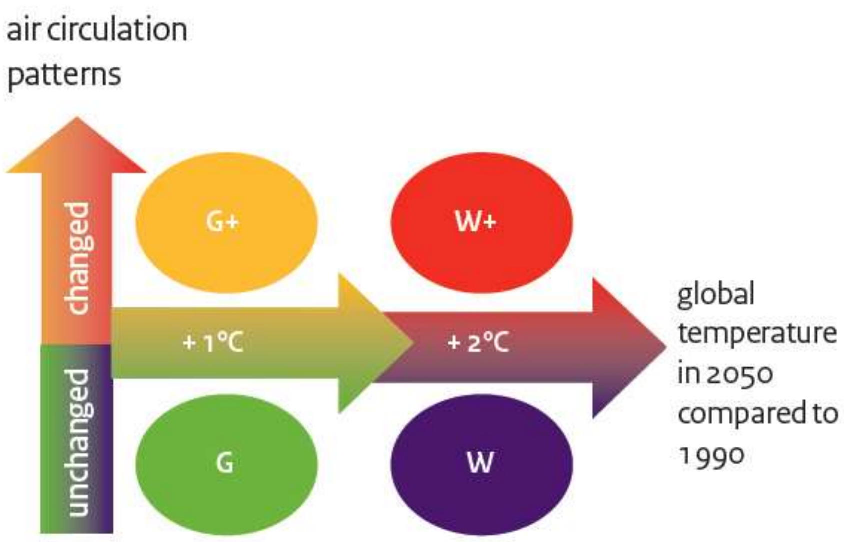


Figure 3: KNMI'06 climate change scenarios for the Netherlands (Hurk *et al.* 2006).

Table 1: Summary of KNMI'06 climate change scenarios (Hurk *et al.* 2006).

Variable	**G**	**G+**	**W**	**W+**
Summertime values				
Mean temperature (K)	+0.9	+1.4	+1.7	+2.8
Yearly warmest day (K)	+1.0	+1.9	+2.1	+3.8
Mean precipitation (%)	+2.8	-9.5	+5.5	-19.0
Wet day frequency (%)	-1.6	-9.6	-3.3	-19.3
Precipitation on a wet day (%)	+4.6	+0.1	+9.1	+0.3
10 yr return level daily precipitation (%)	13	+5	+27	+10
Potential evaporation (%)	3.4	+7.6	+6.8	+15.2
Wintertime values				
Mean temperature (K)	+0.9	+1.1	+1.8	+2.3
Yearly warmest day (K)	+1.0	+1.5	+2.1	+2.9
Mean precipitation (%)	+3.6	+7.0	+7.3	+14.2
Wet day frequency (%)	+0.1	+0.9	+0.2	+1.9
Precipitation on a wet day (%)	+3.6	+6.0	+7.1	+12.1
10 yr return level daily precipitation (%)	+4	+6	+8	+12
Potential evaporation (%)	0	+2	-1	+4

For the G and W scenarios the average summer precipitation increases, but the wet day frequency decreases. This means that in these scenarios more short and heavy rain showers will occur. For the winter season in the G and W scenario, the average precipitation increases while the wet day frequency only slightly increases. This means that showers will become more severe.

So in summary, in all scenarios precipitation intensities increase: G and W during summer, G+ and W+ during winter. In the latter also frequencies increase.

The current municipal policy to cope with water nuisance during heavy rainfall is to accept water on the street for a short time. Furthermore, storage and drainage at the surface are unavoidable and subsurface storage and designing the sewerage system for extreme precipitation peaks is believed to be physically and financially impossible (Oosterom en Hermans 2011).

A RIONED study in 2007 showed that most (92%) Dutch municipalities are already adapting. The majority of the measures is to drain wastewater and rainwater in separate systems (decoupling). Other measures include increasing storage and drainage capacity and modifications at the surface to guide stormwater away from places that can cause nuisance or damage (e.g. road profiles, lowering urban green etc.). This is illustrated in the view on the future water cycle developed by the Dutch ministry of VROM (now I en M)(see Figure 4).

Figure 4: Future vision on the urban water cycle. Concave road pavement, separate sewers, cisterns for rainwater harvesting (Fokké *et al.* 2009).

5.2 Rainwater utilisation

Rainwater harvesting is mostly used as a decentralised system. Driving force is mainly to find sustainable solutions to supply lower grade water in water scarce areas. Most common applications are garden or landscape irrigation, toilet flushing or laundry washing (Roebuck *et al.* 2010). In many cases rainwater is used for just one of these, sometimes because there is ‘competition’ by e.g. grey water use (Farreny *et al.* 2011a). In the Dutch situation, at least in this project, the driving force for application of RWH is to cope with climate change within cities, primarily to solve extreme precipitation situations, but the stored rainwater can be used in periods of drought. It is our primary goal to investigate whether RWH can be used to solve problems with extreme precipitation or stormwater.

As already mentioned in the previous paragraph, designing storage and drainage capacity for (increasing) precipitation peaks is often believed to be too expensive and physically impossible. On the other hand if storage capacity is created the collected rainwater can be used for many applications that require a water quality less than that of drinking water. Furthermore, costs can be evaluated in a broader perspective by considering (financial) benefits at other water applications. Other studies have shown the cost effectiveness of RWH on regional and local scale (Coombes *et al.* 2002).

Table 2 shows an overview of a possible applications for rainwater in an urban environment. The applications range from local application at home to more centralized applications. The list will probably not be exhaustive. Moreover, it is possible that not all mentioned applications can be implemented in practical situations. Implementation will depend on local conditions (space available, building types present etc.). Karakoçak *et al.* (2013) describe a special pilot case in an amusement park in Turkey.

Table 2: Possible options for rainwater utilisation in urban areas.

Cooling	Toilet flushing
Fire fighting	Landscape irrigation
Laundry	Industrial re-use
Street flushing	Zoo
Swimming pool	Fountains/water squares
Allotment gardens	Blue energy
Thermal energy storage	Infiltration/groundwater replenishment
Car washing	

5.3 Acceptance of rainwater harvesting

Ward *et al.* (2012a) conclude that reliance on piped infrastructure is declining, because its resilience and adaptability in the face of climate change is becoming increasingly questioned. They examined the social-technical aspects of RWH in the UK. Their conclusion is that RWH in the UK requires more support, especially for product development, capacity building and the development of support services.

In a more recent study Ward *et al.* (2013) surveyed UK householders to find out whether they are receptive, willing and able to implement RHW. They concluded that overall the receptivity to the idea of using RWH was positive for a wide range of uses. They also showed that the willingness to implement has potential to be compromised due to the commitment and costs associated with maintenance. However, financial incentives and receiving appropriate information from water companies were two factors that have unanimous support from the survey participants.

6 Design of RWH systems

6.1 Introduction

Traditionally Rainwater Harvesting (RWH) has been used on small scale. Many systems and publications look at individual systems for a single house. Sometimes larger systems like sport arenas, apartment blocks and office buildings are described. In most cases water scarcity, reduction drinking water use or general sustainability are the major driving forces reported. In many publications RWH is mentioned as an option to reduce stormwater runoff. However, the actual effect and possibilities for this application are rarely investigated.

A typical RWH system contains a rainwater catchment (mostly roof tops), a storage tank and some treatment options (filters, disinfection). The design of RWH systems depend on many factors such as total precipitation, precipitation frequency and duration, duration of dry periods, catchment efficiency and the application of the harvested water. More details can be found in Fewkes (2012).

The rainwater storage capacity is an important design factor. The size of the storage facility determines the water use efficiency and the economic viability of RWH systems. In most systems the storage facility is an underground tank, sometimes with an additional rooftop tank to provide pressure head for utilisation of the water. Other ways to store water are in storage lakes (e.g. Marina Barrage Singapore[1]) or in the subsurface.

6.2 RWH system design and dimensioning

The rainwater storage capacity is an important design factor. Both economic feasibility and operations will depend on the storage size. A simple domestic RWH system is shown in Figure 5.

Different models exist to predict the performance of RWH systems (Fewkes en Butler 2000, Ward *et al.* 2010b). Often simple mass balance approaches or ‘rule-of-thumb’ design based on annual precipitation volumes are used. These tools however don’t have sufficient accuracy and detail to properly sized RWH systems (Roebuck en Ashley 2006).

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[1] http://www.pub.gov.sg/Marina/Pages/default.aspx.

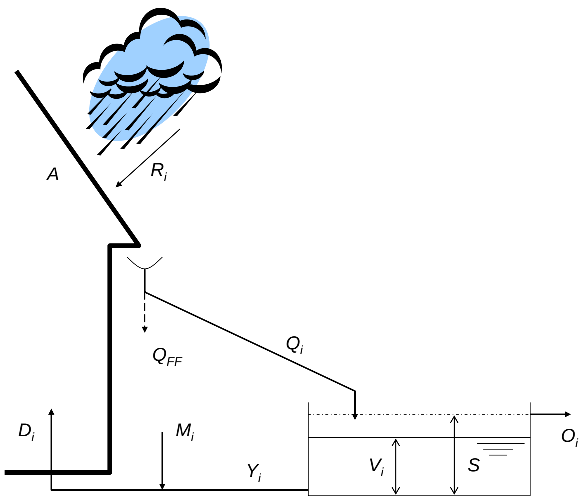

Figure 5: Basic RWH system for a single building. A = roof area (m^2), R_i = Rainfall (mm), Q_i = collected rainwater volume (m^3), S = Storage volume (m^3), V_i = stored volume (m^3), O = Overflow or spillage (m^3), Y_i = yield (m^3), M_i = drinking water suppletion (m^3), D_i = Rainwater demand (m^3), i = time step in behavioural model.

More detailed designs can be made with the so-called behavioural (stochastic) models. Ward *et al.* (2010b) show that these models lead to storage tanks that are substantially smaller than those based on simple mass balance simulations. The behavioural models simulate a (semi-) continuous mass balance from input (rainwater and suppletion), output (demand and overflow) and stored volume on a fixed time interval basis (Palla *et al.* 2011):

$$V_i = Q_i + V_{i-1} - Y_i - O_i \quad (1)$$

Here V_{i-1} is the stored volume in the previous time step of the model. The other symbols are defined in Figure 5.

Evaporation losses from the tank are neglected as we assume that it is covered. The inflow is calculated from the rainfall and the catchment surface area:

$$Q_i = \varphi \cdot R_i \cdot A \quad (2)$$

Here φ is the runoff coefficient describing the fraction of precipitation that can be collected on a roof . Behavioural models are relatively simple to develop and easy to understand. They are also easy to incorporate in other time series based models.

Rainfall is a stochastic process. Therefore, the behavioural models use rainfall time series of many years on e.g. an daily or hourly basis. In many models the output is seen as a more or less continuous flow. In practice, depending on the applications of the rainwater, this can also be seen as a stochastic process.

Two extreme models have been developed by Jenkins *et al.* (1978). The first model, called Yield After Storage (YAS) is a conservative model. The rainfall is added to the previous stored volume, discards the excess water when the tank capacity is full and then subtracts the yield (demand):

$$Y_i = \min\begin{cases} D_i \\ V_{i-1} \end{cases} \qquad (3)$$

$$V_i = \min\begin{cases} V_{i-1} + Q_i - Y_i \\ S - Y_i \end{cases} \qquad (4)$$

The second model, the Yield Before Spillage (YBS) model, adds the previous stored volume and the rainfall, subtracts the yield (demand) and then spills the excess above storage. This is a more liberal model.

$$Y_i = \min\begin{cases} D_i \\ V_{i-1} + Q_i \end{cases} \qquad (5)$$

$$V_i = \min\begin{cases} V_{i-1} + Q_i - Y_i \\ S \end{cases} \qquad (6)$$

Both models are illustrated in Figure 6.

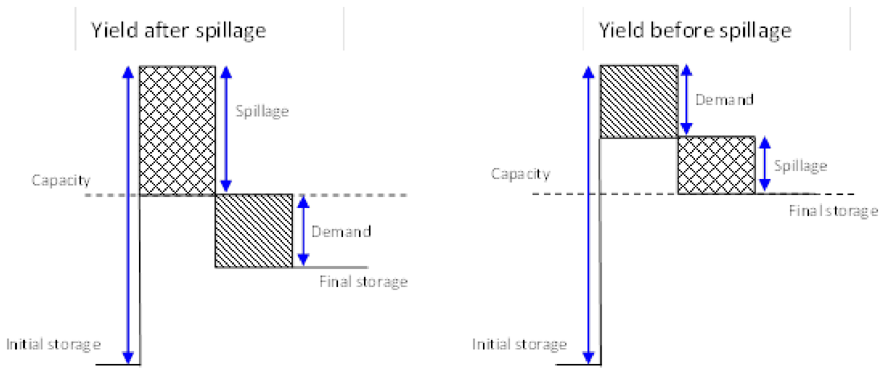

Figure 6: Schematic representation for YAS and YBS behavioural models.

Latham (1983) brings both models together in a more general form:

$$Y_i = \min\begin{cases} D_i \\ V_{i-1} + \theta Q_i \end{cases} \qquad (7)$$

$$V_i = \min\begin{cases} (V_{i-1} + Q_i - \theta Y_i) - (1-\theta) Y_i \\ S - (1-\theta) Y_i \end{cases} \qquad (8)$$

In this model the parameter θ can vary between 0 and 1. If θ = 0 then the YAS model is used, if θ = 1 then the YBS model is used. The used symbols are defined in Figure 5.

Fewkes (1999) and later Fewkes en Butler (2000) evaluated the use of these models for 5 different UK cities with different levels of rainfall. The models were used with daily and monthly time series and were tested against two dimensionless design parameters: the storage fraction (*S/AR*) and the demand fraction (*D/AR*) where *D* is the annual demand (m^3), *A* is the roof catchment area (m^2), *R* is the annual rainfall (mm) and *S* is the storage capacity (m^3). A wide range of operational conditions and storage capacities was evaluated. It was concluded that the YAS algorithm gives a conservative estimation of the system performance irrespective of the time step. From the data it was recommended that a daily time interval can be used for all storage capacities. Only for very small storage capacities (*S/AR*<0.01), the model on daily basis will deviate from reality. In Fewkes en Warm (2000) another 11 sites in the UK were simulated. Instead of the storage fraction the storage period (*S/d*) is used as parameter, with *d* the average daily demand (m^3/d). They concluded that the system performance was relatively insensitive to daily fluctuations in rainfall at each site. They derived a more general or average design curve for the UK.

An important design parameter is the water-saving efficiency. This is the overall drinking water saving that can be achieved by harvesting and using rainwater:

$$E_T = 100\% \times \frac{\sum_{i=1}^{T} Y_i}{\sum_{i=1}^{T} D_i} \tag{9}$$

where *T* is total time used in the model. More recently a new improved dimensionless design parameter has been derived and tested against 17 sites in Sicily (Italy) by Campisano en Modica (2012). However, the tests were only valid for constant rainfall during the year.

Palla *et al.* (2011) applied the YAS model to investigate the optimum performance of rainwater harvesting under different climatic conditions. Three different precipitation regimes in Italy are used as case studies: Genoa, Florence and Catania. From their study they conclude that the demand fraction (D/AR) is the most important design parameter. When this parameter is close to 1, the system can be improved further by increasing the storage ratio. Moreover it seems that the water-savings ratio is almost independent of the climatic conditions, which confirms the findings of Fewkes (1999), Fewkes en Butler (2000) and Fewkes en Warm (2000).

A more detailed model (RainCycle® 2.0), incorporating additional parameters, as initial loss at the catchment roof, filter losses and first flush was developed by Roebuck (2007). The model also included whole life cycle cost methodology to estimate the economics of RWH. The model is available on the internet (SudSolutions 2005).

Santos en Taveira-Pinto (2013) examined six different optimisation criteria for designing RWH systems. The conclude that 100% Efficiency and Maximum

Water Use scenario's lead to large storage tanks and high investment costs. The design needs to make a trade-off between investment costs and water savings. From the two case studies in their investigation they conclude that a 80 % Efficiency scenario is most appropriate.

6.3 Economic viability

An important factor in the utilising rainwater is the economic viability of the system. Although RWH may bring more sustainability to a city, it should also be a cost-effective solution. Economic evaluations have been done by many different approaches in the water sector, including cost-benefit analysis, net present value, internal rate of return, or payback time.

An elaborative cost model has been developed by Roebuck (2007). The software (RainCycle® 2.0, SudSolutions (2005)) is capable of making a detailed analysis of the water balance and economics of the system. It applies a YAS algorithm as explained in the previous paragraph and uses a whole life costing (WLC) method to assess the economics. WLC is believed to give robust results because it includes all costs for investment, operation and maintenance. Roebuck's model includes capital costs, decommissioning costs, water and sewerage charges, operating costs and maintenance. Capital costs were derived from installation costs given by system suppliers. Seven suppliers gave quotations for equipment and installation costs for systems with tank sizes ranging from 1.2 – 15 m^3. Operating costs include metered water charges and electricity charges mostly for pumping. Future operating costs are extrapolated by regression analysis of historic price data. Maintenance costs were estimated by best practices manuals and differentiated for all items of the RWH system. The tank was assumed to have a long life expectancy, pumps should be replaced every 10 years, solenoid valves every 7.5 years etc.

More recently Roebuck *et al.* (2010) described their WLC approach in more detail. A total of 3.840 domestic systems were assessed. It was found that harvesting rainwater was significantly less cost effective than relying on solely drinking water. Domestic RWH generally resulted in financial losses approximately equal to their capital costs; only 76 % was able to win back part of the capital costs. The predicted WLC of every single RWH system was greater than the WLC of the equivalent mains-only system. None of the RWH systems was able to demonstrate a return on investment. The assessment showed that the operation of RWH was cheaper than drinking water, but the periodic recurring costs for maintenance proved to be greater in magnitude than drinking water savings, resulting in a greater total rate.

Domènech en Saurí (2011) have evaluated the use of RWH systems in the Metropolitan Area of Barcelona, Spain. In their study they investigated social aspects, drinking water savings and costs of single and multi-family buildings. For the economic modelling they also used the RainCycle® model. For single family homes, the harvested rainwater was used for toilet flushing, cleaning, filling the swimming pool or washing the car. In multi-family buildings only garden irrigation was assumed. Again in this study long payback times were found, up to 60 years with as main cause the high capital costs. Subsidies may therefore encourage the use of RWH systems.

Farreny *et al.* (2011a) recently investigated RWH on a larger scale in dense Mediterranean urban neighbourhoods. No other studies on this aspect have been published before. The research compares cost-efficiency at two scales (single building and neighbourhood) and implementation (new construction areas and existing area retrofits). However the case study is limited to the use of rainwater for laundry washing only. Toilet flushing in the specific case study was done by grey water from showers and landscape irrigation was omitted because of the xerogardening[2] was used in the area. Farreny *et al.* (2011a) used the Water Balance Method (Krishna 2005) to design the RWH system and used the Life Cycle Costing (LLC) method (Sharma *et al.* 2009) for the economic assessment. The results were compared to the results from the RainCycle® program (SudSolutions 2005). The study of Farreny *et al.* (2011a) again conclude that cost-efficiency of RWH strategies may be put in doubt, as long as local water prices are low. Furthermore, they conclude that RWH systems should be preferably installed at neighbourhood level, because economy of scale will be enabled. Installations should be realised in new construction areas to be cost effective.

Morales-Pinzón *et al.* (2012) modelled both conventional financial indicators (NPV and IRR) and environmental impact indicators (Global Warming Potential and energy use). In their study they investigated 87 scenario's in a number of Spanish cities. The scenario's consisted of RWH systems of various sizes, ranging from two single houses to a group of apartment buildings connected to a single RWH system. They concluded that the material type for the storage tank is not a fundamental financial factor, but planning on a neighbourhood scale is. The costs per functional unit[3] ranged from 0.94 to 10.59 €/m^3 with the lowest cost for the category 'group of apartment buildings'. RWH systems have a better financial fit for large-scale and high-density constructions. The best strategy was implementation at a neighbourhood level. An example of such a system can be found in Ringdansen, Norrköping (Sweden) (Villarreal en Dixon 2005). Variability of rainfall is an important factor to be considered in detail during design because it has a direct impact on the RWH tank size.

6.4 RWH on large scale or neighbourhood level

Application of RWH on a larger scale is more economically viable. As indicated above individual domestic or small size systems have very long pay-back times. The examples from Spain (Morales-Pinzón *et al.* 2012), Sweden (Villarreal en

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[2] Gardening that reduces or eliminates the need for supplemental water from irrigation
[3] Collection, storage and supply of 1 m^3 rainwater to be used as non-potable water for a household washing machine with a constant demand of 56 liter per cycle (ISO14040)

Dixon 2005), UK (Ward *et al.* 2012b), Turkey (Karakoçak *et al.* 2013) and South Korea (Kim *et al.* 2012) illustrate this.

Large scale systems require larger storage facilities. Morales-Pinzón *et al.* (2012) studied systems with tank sizes ranging from 3 m^3 for single houses to 125 m^3 for apartment buildings. Materials used are polyester fibreglass, concrete, steel and high-density polyethylene. The Ringdansen project (Villarreal en Dixon 2005) concluded that a tank of 40 m^3 would save more than 60% drinking water for toilet flushing. A tank of 80 m^3 at each block would save almost 60% of the water needed for irrigation of the central garden area in the summer. The UK system in Exeter tested by (Ward *et al.* 2012b) used a tank of 25 m^3. In this study they concluded that behaviour based models are necessary to determine the tank size in large scale projects. Simple mass balance models overestimate the tank size, which leads to too high costs. The system tested at the Seoul National University (Kim *et al.* 2012) used a tank of 200 m^3.

Beside storage facilities, large scale systems also need a separate distribution system to deliver the rainwater to the point of use. For existing neighbourhoods and buildings, construction of rainwater storage facilities and a second distribution system is often difficult to realize. For new area's the construction of large scale systems can be incorporated from the initial design phase.

Petrucci *et al.* (2012) studied the application of small individual rainwater tanks a 23 ha neighbourhood in the East of Paris. Rainwater tanks were installed at 30 % of the premises and their effect to control stormwater runoff was estimated by model calculations. They concluded that in the specific situation the number and volume of the rainwater tanks was too small to prevent sewer overflows in the case of extreme rain events. Nevertheless they concluded that installing rainwater tanks can be an effective solution, if wisely planned and implemented, taking parcel and catchment scale into account.

Myers *et al.* (2012) have investigated the application of RWH in a broader perspective. They used model calculations to compare the effects of water savings and rainwater harvesting options for the water system benefits, but also for the energy and environmental benefits and consequences in the urban area. The model calculations are based on a neighbourhood in Southeast Asia where harvested rainwater is used for irrigation and toilet flushing. The simulations show that a significant reduction in peak flow of stormwater runoff can be achieved. Furthermore, the study has shown that the water conservation and rainwater harvesting lead to a significant reduction of the pollutants load to surface waters and energy consumption and greenhouse gas emissions in the neighbourhood.

6.5 Subsurface storage of excess water by deep vertical infiltration

In many areas in the Netherlands excess of water can easily be stored in sandy soils which are unsaturated with water. For this purpose a so called 'wadi system' is developed. In a wadi system the excess of rainwater is collected in a subsurface infiltration supply and transported through a porous layer (gravel, volcanic stones) by gravity to the groundwater. The advantages of such systems are avoiding of flooding, less diluted water to the sewage treatment plant and increase groundwater supply. For example in Utrecht wadis are built in the higher parts of the new district Leidsche Rijn.

Another relatively new possibility is to infiltrate the excess of rainwater directly in a deeper aquifer by vertical infiltration. For the municipality of Rhenen the company IF-Technology developed and installed such a system. The advantage of vertical infiltration is that less space is needed and that the system is relatively simple and cheap.

The principle of vertical infiltration or deep infiltration is simple. The subsoil in the Netherlands consists often of various horizontal layers of clay, peat or sand. By vertical infiltration excess water is infiltrated directly in a water saturated aquifer (sandy soil layer).

The principle is based on the law of Archimedes. By the infiltration an overpressure of infiltration water results in a flow of water in the aquifer. The water in the aquifer is pressed aside predominantly in lateral direction. By deep infiltration there could be effects of water seepage at the surface, but these effects are probably relatively small in comparison to the water excess problems and they will show up with a delay due to the soil resistance. Figure 7 shows the concept of vertical infiltration. When the aquifer at the top is covered by a less water permeable soil layer (e.g. clay layer, aquitart), water seepage will be reduced.

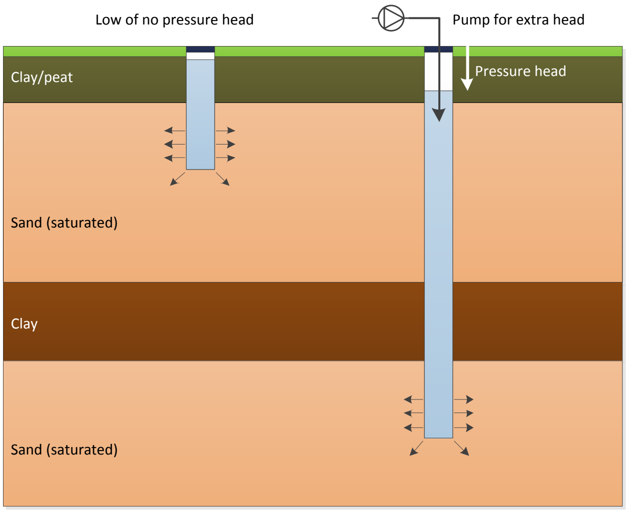


Figure 7: Schematic representation for YAS and YBS behavioural models.

For example for a cities like Amsterdam or Rotterdam, where the subsurface consists of various soil layers, the concept of vertical infiltration would be interesting and promising.

Important aspects to consider:

- Water quantity. At ground level the infiltration unit has to be installed on a place where excess rainwater aggregates. Moreover at ground level or directly below, the water has to be collected in a vessel or wadi system.
- Water quality aspects are important to consider in order to avoid
  - pollutants in groundwater. The European Framework Directive water sets water quality standards for pollutants. Rainwater can become polluted by air, by roof and by street (see paragraph 4.1). An important measure to prevent contamination of the groundwater is by organising a first flush and by using a properly designed storage tank;
  - well clogging. The infiltration capacity can be reduced over time by infiltration of small suspended particles. Therefore (sand)filtration is needed to prevent well blockage.

Deep vertical infiltration is a promising technique to avoid water nuisance problems and contribute to a more climate proof environment in urban regions. Further development of the concept of deep vertical infiltration of excess rainwater is recommended.

6.6 Summary

Validated design tools for RWH are available. The tools use precipitation data, catchment surface area and water demand as primary input. From these data the required storage capacity can be estimated. Another factor that determines the storage size is the purpose of RWH: if water efficiency is the main goal different tank sizes may be necessary. If the system is aiming at preventing water nuisance, other storage sizes will be required. In that case costs and benefits have to be evaluated in a broader perspective.

Research also confirms that economy of scale is an important factor. Though most systems are designed for individual houses, calculations show that these systems are not economically viable. For large scale systems economic viability has been proved. Most systems use tanks for storage, but subsurface storage can be an interesting alternative.

7 Water quality considerations

7.1 Water quality in RWH systems

Water quality is an important issue when considering application of harvested rainwater. Depending on the application, the water quality requirements may vary, but also the water quality of the harvested water may vary in space and time.

The water quality of the harvested rainwater depends on many factors. Abassi and Abassi (2011) recently gave a review on water quality aspects of rainwater. In their paper they focused on roof top harvesting systems and distinguished three types of contaminants: (a) chemical, (b) microbiological, and (c) physical. Furthermore, they analysed the pathways of these contaminants into the water. They concluded that the uptake of contaminants occurs from the moment the raindrops leave the clouds, either as particulate matter or as solutes.

Falling raindrops may pick up traces of sulphate, nitrite, nitrate and carbon dioxide, but also industrial air pollutants or sprayed pesticides may be caught. Concentrations of these parameters above drinking water limits are reported.

A second important source for pollutants is the roof surface. Water harvested at the rooftop can be influenced by the rooftop material and the deposits on the rooftop. Cupido *et al.* (2012) conclude that atmospheric deposition is the most important source of contamination. Compounds from the roof material can dissolve or leach into the water. Roof catchments in urban areas also receive dry deposition from traffic and industry. Furthermore, microbiological contamination occurs due to accumulation of soil and leafs, faecal material deposited by animals and insects, dead animals on the rooftop or in the storage tank, or airborne microorganisms. Abassi and Abassi (2011) evaluated in total 93 case studies from literature, documenting the water quality aspects of rooftop rainwater harvesting. Recommendations are given to control water quality. Crucial aspects are of course keeping the rooftop clean, using screens to protect the water against debris and animals, realising a first flush and using a properly designed storage tank.

7.2 Physico-chemical water quality

An overview of physico-chemical water quality parameters published in international literature on harvested rainwater is shown in Table 3. The data in this table is not exhaustive, but gives a good impression on the physico-chemical conditions. The harvested rainwater can be classified as soft water and the pH ranges roughly between 6 and 9. It can also be observed that water quality can vary largely. Important causes of variation are the roof material. In general the TOC content is also low, but in some cases like Ain in France very high values are reported. There is no clear explanation for this as the roof was made of clay tiles. The influence of the roof type is also demonstrated by the Seoul and Austin, TX.

Table 4 gives an overview of some inorganic compounds in rainwater as reported in literature. The data show that the inorganic content is also rather low. All data are far below the maximum levels for drinking water (Drinkwaterbesluit 2011) in the Netherlands.

In Table 5 concentrations for a number of metals in rainwater is given. These metals may occur from settling of aerosols on the roof and dissolution of roofing and water collection materials. For the cases reported most values were very low compared to the drinking water standards. The values for lead are an exception, because they exceed the drinking water standard from time to time.

7.3 Microbiological water quality

A large amount of data on microbiological water quality can be found in literature. Many papers deal with human consumption of rainwater in developing countries (Dean en Hunter 2012, Domènech *et al.* 2012, Gomes *et al.* 2012). The data generally show good water quality, but health risks are also reported, related to bad material selection and maintenance.

In our study we focused on non-potable applications of rainwater. Nevertheless microbiological water quality is important, because direct contact with the water exists. In Table 6 is a short overview of the data microbiological parameters in rainwater tanks after a first flush. When considering microbial contamination of rainwater, two sources of contamination have to be distinguished: 1) direct contamination of the harvesting surface (roof) and system and 2) regrowth of bacteria in the storage tank.

The roof can be contaminated with faecal bacteria by excreta of birds and small mammals. An important factor is also the time between wet periods. The longer these antecedent dry periods, the more contaminations may be accumulated at the roof. Multi-variate analysis however showed no significant effect (Farreny *et al.* 2011b)

Table 3: Physico-chemical parameters in harvested rainwater (min, max, median (min-max, mean±std.dev.) after first flush.

Location	pH	EC (µS/cm)	Turbidity (NTU)	TOC (mg/L)	TH (mmol/l)	Sample[1,2]	Reference
Seine Maritime, France	6.9-8.9 7.1-8.7	117-188 119-197	0.8-2.0 1.3	<0.03 <0.03	0.3-0.8 0.4-0.7	T PoU	**(De Gouvello et al. 2013)**
Ain, France	4.5-6.5 4.2-6.4	10-32 18-31	0.7-3.4 0.6-1.8	166-8800 170-3500	<0.08-0.1 <0.05-0.1	T PoU	**(De Gouvello et al. 2013)**
Île-de-France, France	1.2 1.2	32 24	1.7 1.2	1.5 0.1	0.04 0.04	T PoU	**(De Gouvello et al. 2013)**
Rual Village, France (SW)	6.5 (5.6-10.4)	56.2 (13.5-235)	2.4(0.5-6.1	2.3 (0.5-5.1)	0.16 (<0.01-0.58)	T	**Vialle et al. (2012), Vialle et al. (2011)**
Sidney (4 sties), Australia	6.60±0.50	62.2±54.5	2.96±6.16	No data	0.24±0.21	T	**Van Der Sterren et al. (2013)**
Seoul (3 tanks). Korea	7.04 (6.8-8.2) 8.71 (7.7-9.9) 8.56 (6.7-9.7)	45 (42-56) 88 (75-109) 286 (152-428)	3.4 (1.4-10.8) 5.7 (0.41-8.56) 4.90 (1.31-11)	No data	No data	T T T	**Amin en Han (2011)**
Seoul, Korea	6.5 (6.3-7.1) 7.3 (7.1-7.6) 7.1 (6.7-7.4) 6.0 (5.9-6.3)	No data	No data	16 (13-19) 10 (9-12) 10 (8-12) 2 (2-5)	No data	T,Wd T,Con T,Clay T,GSteel	**Lee et al. (2012)**
Greece NE (6 sites)	6.75±0.46 6.64±0.58 6.99±0.57 6.65±0.51 6.63±0.49 6.76±0.63	63±31 68±20 143±25 37±10 46±22 31±13	No data	No data	0.26±0.09 0.36±0.13 0.48±0.11 0.21±0.10 0.27±0.12 0.27±0.11	T T T T T T	**Gikas en Tsihrintzis (2012)**
Ballinabrannagh Ireland SE	7.21 (6.26-8.21)	No data	1.11 (0.0-4.60)	No data	0.35 (0.1-0.6)	T	**O'Hogain et al. (2011)**
Exeter,UK	7.6-10.4	43.5-261	0.3-2.8	No data	0.16-0.27	T	**Ward et al. (2010a)**
UAB University Barcelona, Spain	7.59±0.07	85.0±10.0	No data	11.6±1.7	No data	T, 4 roofs	**Farreny et al. (2011b)**
Austin, Texas USA	6.8 6.5 7.6 7.1 7.3	36.3 25.5 74.5 35.3 235.3	No data	11.7 4.8 6.1 6.5 25.5	No data	T,Asph T,AlZnStl T,ConT T,Bit T,Green	**Mendez et al. (2011)**

[1]T = Tank; PoU = Point of Use; T.Wd = Tank, water collected at wood tile roof, T.Con = Tank, water collected at Concrete roof; T.Clay = Tank, water collected at clay tile roof; T.GSteel = Tank, water collected at galvanised steel roof; T,Asph = Tank, water collected at asphalt shingle roof; T,AlZnStl = Tank, water collected at Aluminium-zinc coated steel, T.ConT = Tank, water collected at concrete tile roof; T,it = Tank, water collected from bituminous cool roof, T,Green = Tank, water collected at unfertilized green roof.

[2] All samples taken from water stored after first flush

Table 4: Inorganic parameters in harvested rainwater (min, max, median (min-max, mean±std.dev.) after first flush.

Location	Cl^- mg/L	SO_4^{2-} mg/L	NO_2^- mg N/L	NO_3^- mg N/L	Na^+ mg/L	Sample[1,2]	Reference
Seoul, Korea	No data	0.1-1.5 0.1-0.8 0.1-0.5 0.0-0.1	No data	0.06 0.06 0.02 0.00	No data	T,Wd T,Con T,Clay T,GSteel	Lee et al. (2012)
Greece NE (6 sites)	7.29±3.97 5.05±2.93 4.16±2.81 3.54±2.25 3.48±3.28 3.61±2.28	10.65±3.14 13.56±4.34 15.70±6.43 8.28±2.69 8.84±5.31 10.25±3.98	0.08±0.10 0.05±0.12 0.05±0.10 0.03±0.07 0.04±0.10 0.01±0.02	0.83±0.71 0.84±0.71 0.58±0.52 0.71±0.57 0.66±0.51 0.58±0.55	5.15±2.08 4.42±1.57 6.91±1.90 3.26±1.89 3.78±2.14 4.15±1.77	T T T T T T	Gikas en Tsihrintzis (2012)
Ballinabrannagh Ireland SE	5.06 (1.50-22.49)	7.50 (0.0-31.7)	0.01 (0.0-0.15)	0.33 (0.0-0.64)	4.60 (0.0-8.6)	T	O'Hogain et al. (2011)
Exeter,UK	3-28	No data	<0.01-0.22	1.32-17.74	2.8-4.3	T	Ward et al. (2010a)
UAB University Barcelona, Spain	8.86+2.38	3.54±0.39	0.040±0.015	0.395±0.059	No data	T, 4 roofs	Farreny et al. (2011b)
Austin, Texas USA	No data	No data	0.03 0.02 0.03 0.02 0.03	1.0 1.1 1.1 1.1 1.5	No data	T,Asph T,AlZnStl T,ConT T,Bit T,Green	Mendez et al. (2011)

[1]T = Tank; PoU = Point of Use; T.Wd = Tank, water collected at wood tile roof, T.Con = Tank, water collected at Concrete roof; T.Clay = Tank, water collected at clay tile roof; T.GSteel = Tank, water collected at galvanised steel roof; T,Asph = Tank, water collected at asphalt shingle roof; T,AlZnStl = Tank, water collected at Aluminium-zinc coated steel, T.ConT = Tank, water collected at concrete tile roof; T,Bit = Tank, water collected from bituminous cool roof, T,Green = Tank, water collected at unfertilized green roof.

[2] All samples taken from water stored after first flush

Table 5: Heavy metals in harvested rainwater (min, max, median (min-max, mean±std.dev.) after first flush.

Location	Aluminium mg/L	Copper mg/L	Lead mg N/L	Zinc mg N/L	Iron mg/L	Sample[1,2]	Reference
Sidney (4 sites) Australia	0.115±0.143	0.221±0.294	0.011±0.013	2.63±2.2	No data	T	Van Der Sterren et al. (2013)
Seoul, Korea	0.043 0.099 0.036 0.033	0.009 0.012 0.015 0.016	0.003 0.005 0.003 0.003	0.018 0.038 0.019 0.074	0.023 0.048 0.024 0.027	T,Wd T,Con T,Clay T,GSteel	Lee et al. (2012)
Ballinabrannagh Ireland SE	No data	No data	0.002(0.0-0.025	No data	0.022(0.0-0.095)	T	O'Hogain et al. (2011)
Exeter,UK	0.080-0.108	0.218-0.290	0.026-0.064	0.193-0.480	0.009-0.027	T	Ward et al. (2010a)
Austin, Texas USA	0.36 0.31 0.48 0.46 0.21	0.035 0.0 0.0 0.0 0.0	0.001 0.001 0.003 0.001 0.004	0.045 0.186 0.135 0.105 0.345	0.262 0.244 0.349 0.349 0.070	T,Asph T,AlZnStl T,ConT T,Bit T,Green	Mendez et al. (2011)

[1]T = Tank; PoU = Point of Use; T.Wd = Tank, water collected at wood tile roof, T.Con = Tank, water collected at Concrete roof; T.Clay = Tank, water collected at clay tile roof; T.GSteel = Tank, water collected at galvanised steel roof; T,Asph = Tank, water collected at asphalt shingle roof; T,AlZnStl = Tank, water collected at Aluminium-zinc coated steel, T.ConT = Tank, water collected at concrete tile roof; T,Bit = Tank, water collected from bituminous cool roof, T,Green = Tank, water collected at unfertilized green roof.

[2] All samples taken from water stored after first flush

Table 6: Microbiological parameters in harvested rainwater (min, max, median (min-max, mean±std.dev.) after first flush.

Location	Total/Faecal Coliforms N/100ml	*E. Coli N/100ml*	Enterococci N/100ml	PC22°C/PC37°C N/ml	Sample[1,2]	Reference
Seine Maritime, France	30-1,800/— and illegilble results	No data	No data	56-480/40-450 and illegilble results	T PoU	(De Gouvello et al. 2013)
Ain, France	<30-230/— 12-92/—	No data	No data	133-8,800/3-10,400 170-3,500/6-5,000	T PoU	(De Gouvello et al. 2013)
Île-de-France, France	1200/— 1200/—	No data	No data	>100/400 >100/250	T PoU	(De Gouvello et al. 2013)
Rual Village, France (SW)	40 (<10->10,000)	2 (<10-5,500)	45(<10->10,000)	10-632,000/25-368,000	T	Vialle et al. (2012), Vialle
Sidney (4 sites), Australia	426/77	11	12	No data	T	Van Der Sterren et al.
Seoul, Korea	12/— 12/— 2/— <1/—	1 2 <1 0	Not detected Not detected Not detected Not detected	No data	T,Wd T,Con T,Clay T,GSteel	Lee et al. (2012)
Greece NE (6 sites)	0-7750/— 0-3250/— 0-2800/— 0-2050/— 0-1600/— 0-4700/—	5-200 0-3 0-2 — — —	No data	10^3-10^4/10^3-10^4 30-100/240-10^4 20-30/8-60 — — —	T T T T T T	Gikas en Tsihrintzis (2012)
Austin, Texas USA	540/28.1 440/1.9 780/4.7 530/10.8 50/4.7	No data	No data	No data	T,Asph T,AlZnStl T,ConT T,Bit T,Green	Mendez et al. (2011)

[1] T = Tank; PoU = Point of Use; T.Wd = Tank, water collected at wood tile roof, T.Con = Tank, water collected at Concrete roof; T.Clay = Tank, water collected at clay tile roof; T.GSteel = Tank, water collected at galvanised steel roof; T,Asph = Tank, water collected at asphalt shingle roof; T,AlZnStl = Tank, water collected at Aluminium-zinc coated steel, T.ConT = Tank, water collected at concrete tile roof; T,Bit = Tank, water collected from bituminous cool roof, T,Green = Tank, water collected at unfertilized green roof.

[2] All samples taken from water stored after first flush

7.4 First Flush

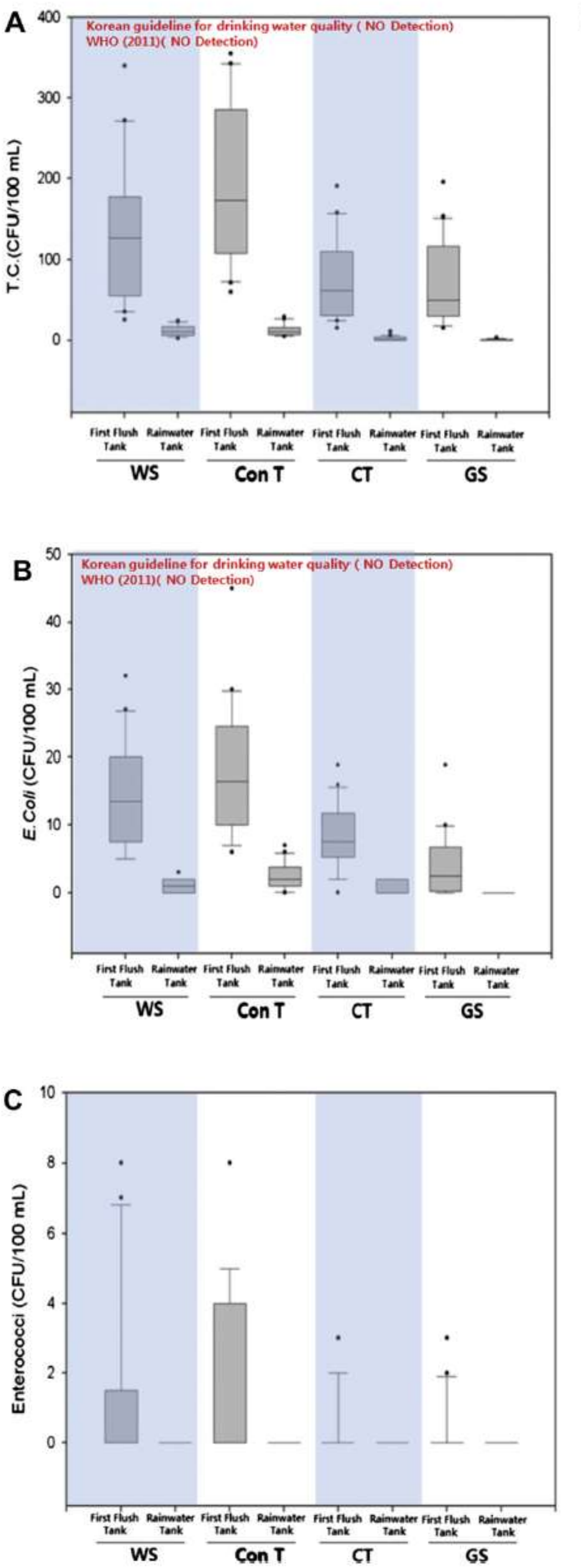
Contaminants from a roof are usually concentrated in the first runoff. After this runoff has passed and the roof is washed, the water is considerably safer (Abbasi en Abbasi 2011). Martinson (2007) has extensively reviewed this first flush phenomenon and the attempts made thus far to model it. Most substances follow this first flush phenomenon – their concentrations are the highest in the first minutes of a rain event, and decrease later toward a constant value.

The main cause of this phenomenon is the deposition and accumulation of pollutant material on the roof during dry periods. Exposure to UV, heat, and desiccation on the roof top inactivate many bacteria, while wind removes some heavy metals accumulated from atmospheric fallout. Pollutant additions to roof runoff include organic matter, inert solids, faecal deposits from animals and birds, trace amounts of metals, and even complex organic compounds. The longer the antecedent dry period, the greater the probability of a higher pollutant load in the first flush (Amin en Alazba 2011)

Several authors have published their results on the first flush water quality and compared it to water harvested after a first flush. Amin en Han (2011) sampled rainwater during first flush. The samples were highly contaminated in case of regular roof, green-roof and terrace intercepted samples. The quality improves considerably after first flush of rainfall in case of roof catchment samples. The roof-intercepted sample was almost free of contamination in terms of *E. coli* after first flush of rainwater (about 0.05mm of rainfall) and had acceptable turbidity with neutral pH. *E. coli* and heterotrophic plate counts (HPC) were found in the first flush samples representing contamination of catchment surfaces by human activities. The longer the dry period, the greater the probability of higher pollutant loads in the first flush is.

Diverting the first flush away from the storage tank can therefore improve the harvested water quality. Gikas en Tsihrintzis (2012) conclude that the installation and use of a first flush system improves the physico-chemical quality of collected rainwater, but it cannot avoid microbial contamination of stored rainwater because of regrowth during storage. Van Der Sterren *et al.* (2013) recently concluded too that the water from the tank overflow and the first flush was of a lower standard than the water from the storage tank. It was noted that proper maintenance and installation of a first flush device would improve the water quality of the rainwater harvesting tank and reduce potential associated health risks to the users.

Figure 8: Total coliforms (A), *E. Coli (B)* and Enteriococci (C) in first flush and harvested rainwater in Seoul, Korea. WS=wood shingles, ConT=concrete tiles, CT=clay tiles, GS=galvanised steel (Lee *et al.* 2012)



Lee *et al.* (2011) investigated the water quality and roof material in South Korea. Metal concentrations were within the permissible limits specified in the Korea drinking water standard. In addition, counts of coliform, E. *coli* and heterotrophic bacteria were higher in the first flush 5 minutes after the start of the rainfall event (see Figure 8). Principal component analysis and correlation analysis through 40 events in 2009 showed that the quality of stored rainwater depends on the conditions of the catchment and storage tank and the antecedent dry period.

Mendez *et al.* (2011) conducted research on water quality of harvested rainwater in Austen, Texas. Results from pilot-scale and full-scale roofs demonstrated that rainwater harvested from any of these roofing materials would require treatment if the consumer wanted to meet United States Environmental Protection Agency primary and secondary drinking water standards or non-potable water reuse guidelines; at a minimum, first flush diversion, filtration, and disinfection were recommended. For the shingle, tile, and cool (made of reflecting material) pilot-scale roofs, the total coliform concentration of the first flush was significantly higher than that of the rainwater harvested after the first flush (p-value < 0.024), but the total coliform concentration from the metal and green roofs did not change significantly from the first flush to the subsequent tanks (p-values = 0.131 and 0.179, respectively). For all of the roofs, the total coliform concentration of the rainwater harvested after the first flush was statistically indistinguishable from that in the ambient sampler (p-values > 0.131). In particular, the rainwater harvested after a first flush consisting of a minimum of 38 L for every 93m^2 of collection area from the asphalt fiberglass shingle, metal, concrete tile, and cool roofs, would need treatment for total coliforms, faecal coliforms and turbidity.

Recent studies by Kim *et al.* (2011a), (2011b) aimed to develop a technology for the treatment of first flush rainwater using new filters made of wood fibre mat, dental cotton, and feldspar. The removal of pollutants in first flush rainwater with each filter material was evaluated. Combinations of filter materials were found to have been effective in removing particles in the rainwater. New and used fibre filter media were compared in terms of their filterability and ion-exchange capability. The removal efficiency of particles by the used media was similar to that of the new media. Nevertheless, the removal efficiencies of nitrogen and phosphorous by the used media were substantially lower compared to the new media. This suggests that the fibre filter media should be periodically replaced to maintain high removals of nutrients.

7.5 Summary

In summary, water quality of harvested rainwater is generally good. It has a low content of organic and inorganic substances. Nevertheless some microbiological contaminations may be present, due to contaminations at the catchment surface (birds, rodents).

An important factor in the contamination load is the antecedent dry period. The longer this period, the more contamination may accumulate on the catchment surface. An important factor to keep the water quality at a high level is to divert the first flush before the water enters the storage tank.

Depending on the application of the harvested rainwater, some treatment (filtration or disinfection) may be required, but in general health risks of harvested rainwater are expected to be low.

8 Applications in The Netherlands

8.1 Where and when to apply?

For application in The Netherlands different aspects have to be considered: scale of use, integration with existing drainage infrastructure, the harvesting infrastructure itself, rainwater storage and the utilisation of the water. These aspects will be discussed below.

Scale

Different scales of application of rainwater harvesting have to be distinguished. RWH can be used on an individual home scale. In this case roof harvested water will be stored in a small rainwater tank. The system can be scaled-up to combined systems for (small) apartment blocks. The rainwater tank can be installed in the garden or basement of the building and rainwater can be used in the house (e.g. for toilet flushing).

The next scale can still be seen as individual systems, but their size is considerably larger. Typical characteristics of these systems is an integration in the building construction, with dedicated roofs and large cisterns to catch and store the rainwater, water treatment steps *et cetera.* These systems can be used for office buildings or large apartment buildings.

Finally, rainwater harvesting can be applied on a large neighbourhood scale. In this case rainwater is harvested from many homes and buildings in an urban neighbourhood or residential area.

Which of these specific scales can be applied in the urban areas in The Netherlands depends of course on the local situation. Factors as the soil type and groundwater conditions, urban density, and ground level (below or above sea level) play a decisive role.

RWH as a part of existing drainage infrastructure

Another aspect to consider is that rainwater harvesting is additional to the existing urban drainage infrastructure. Rainwater harvesting is not (necessarily) a replacement of existing infrastructure. An important factor when RWH is applied to a large extend is that rainwater falling on rooftops can be treated separately from rainwater falling at the street surface. Existing sewers can be used to drain street level precipitation. Often this water is unfit for use because of contamination. For the Netherlands, on average 50% of the hard surface in an urban area is considered to be roof tops. That means that is if a separation between roof and street level precipitation is made, the drainage capacity of existing sewer systems can be freed and their life time be extended, while high quality rainwater from roofs can be stored and applied in dry periods. An important restriction however is that storage capacity must be large enough to store water from roof tops during precipitation peaks.

Harvesting infrastructure

Depending on the application scale, the harvesting infrastructure becomes more complex for larger scale applications. When the scale increases, it means that a facility has to serve a larger roof area and therefore has to deal with larger volumes of water. Furthermore the transport distances increase as the application scale increases. Systems at neighbourhood level therefore need to be designed to deal with very large volumes of water that are transported from the catchment areas to a central point were the water can be stored. Integration with water squares, where an intermediate storage could be achieved, is an interesting option. Small scale systems with individual tanks at the premises, are less complicated. Maybe this is the main reason why so much international literature is available on these small systems.

When increasing to neighbourhood scale, there will be a point where the collection and transport infrastructure will have a close resemblance with a conventional sewer drainage system, except that the water is now locally stored instead of transported away from the urban area. In these cases it is very important to evaluate the benefits from local storage and possibilities for re-use of the harvested water.

Storage

The storage size is also an important factor. The system has to be designed in such a way that always sufficient free storage capacity is available. If the storage is full, rainwater harvesting will not function to create climate resilience. The design rules presented in Chapter 6 can be applied to estimate the required storage capacity of a system, assuming precipitation volumes and emptying rates by water utilisation.

Larger systems require larger storage sizes. Individual systems can suffice with a tank of a few m^3 while larger office buildings require tens to one hundred m^3. Scaling up to neighbourhood size, the use of storage tanks will most probably not be feasible. Aquifer storage is more likely in that situation. Water squares may be used as temporary storage if the infiltration rate into the aquifer is too slow to keep up with the high intensity precipitation peaks.

Whether or not storage tanks can be used depends on the available space in the urban environment. In the older inner cities with high urban density, tank placement is problematic. In the newer residential areas more space may be available and for new construction areas, rainwater harvesting can be integrated in the urban planning.

Water utilisation
Water harvesting is only one side of the system. On the other hand, harvested water utilisation is equally important, because it is crucial to empty the storage facilities before the next rain event.

Once collected water should find its destination. In individual and office building systems, this is quite easy. The harvested water can be used in and around the building. For larger systems it becomes more difficult. A secondary distribution system is required and, because of the bad experiences with cross connections in household water projects, it is difficult to realise (see paragraph 8.2). Furthermore, pilot projects to supply low grade water for industrial purposes and fire fighting have been cancelled because they were not economically viable due to insufficient water users. An example is the project "Samen Stromen" in Tilburg where low grade water was supplied to the industrial area Kraaiven.

8.2 Household water

Experiments with household water in the end of the 1990s until 2002 showed that dual distribution systems pose a significant health risk, caused by cross connections between the household water and drinking water mains (Oesterholt *et al.* 2007).

Household water was produced by limited treatment from a variety of sources and had a lower quality than drinking water. No water quality legislation for household water (including rainwater) existed at the time and the Dutch government appointed six of these estates as pilot projects. Four pilot projects were intensively monitored for toxicological and microbiological safety as well as microbiological stability during a period of almost 16 months.

Detection of viruses and pathogenic protozoa in treated water demonstrated that some of these systems were microbiologically unsafe. Furthermore certain household waters had a relatively high biofilm formation potential leading to growth of *Legionella sp.* and *Aeromonas* and complaints from customers about the smell and colour of the household water. In nearly all cases concentrations of heavy metals and organic pollutants were below drinking water standards, hence the toxicological risk caused by chemical substances was not significant.

Based on the results of this study the Dutch government decided to discourage the production and distribution of household water on a large scale. In 2003 the Secretary of State, Pieter van Geel, banned large scale household applications. Application of household water was only allowed in small scale applications for toilet flushing (Geel 2003). Recently the Dutch legislation limits the use of household water to roof harvested rainwater for toilet flushing (Drinkwaterbesluit 2011). At present all projects owned by water companies in the Netherlands have been terminated by replacing household water with drinking water.

8.3 Individual small scale systems

Individual small scale systems are commercially available in many countries; an example is given in Figure 9. In The Netherlands these systems are however very scarce, except for the simple old fashioned rain barrel. In many Dutch cities, individual systems could be applied as many dwellings have gardens that could give space to the storage tank. However, currently there is no incentive to use these systems. Individual systems have to be installed by the home owners. The systems are expensive and the rainwater may only be used for toilet flushing according to the Dutch Drinking Water Decree (Drinkwaterbesluit 2011). With the current drinking water price in The Netherlands rainwater harvesting will not pay back if used for this application. An incentive for use may be created by giving home owners additional financial benefits e.g. by reducing waste water taxes or a subsidy program. This could be a reasonable approach as societal costs for urban drainage may be lower when RWH is applied and the urban environment will be more resilient against severe precipitation. Another option to use individual systems is by legally enforcing the use as is done in Belgium[4]. In either case, it is necessary to investigate further and quantify the benefits for the individual users and society. An interesting option would be to set-up a demonstration project to investigate the use of these systems in practice.

Figure 9: Example of a small scale individual RWH system.

[4] Many people in Belgium don't use the water in their rain tanks. Therefore the tanks will often be completely filled and overflow into the sewer during rain showers.

8.4 Office buildings

As mentioned in Chapter 6, economy of scale is an important factor for individual systems. For office buildings, sufficiently large scale can be reached to make RWH economic viable. Especially for new to be constructed buildings, an additional incentive to utilise rainwater collection and reuse, is to create sustainability. Using collected rainwater will result in additional credit points on sustainability certificates as BREEAM®.[5] An example of a larger office building with a rainwater harvesting system installed, is the main office building of Waternet in Amsterdam. The water can be used for toilet flushing, but currently this system is out of use, because of maintenance problems and coloured water in the toilet bowls.

8.5 Neighbourhood or district scale level

When scaling up to the neighbourhood or even district level, the advantage is that the RWH system can relatively easy be integrated in the urban water management system (technically and policy wise)in a city. This will ease the management and control of the system by the municipality of the Water Authority. When RWH at the neighbourhood level is applied, it has to be decided whether only roof harvested water or all the rainwater collected at the hard urban surface should be collected. The advantage of only roof harvested water is that the water quality of that water will be better. On the other hand dividing between roof top water and water from the paved surface will lead to a more complex harvesting infrastructure, harvesting system and storage system. Subsurface storage provides a good opportunity. An important design factor remains the peak capacity of the system. This peak capacity needs to be sufficient to deal with peak loads in precipitation.

The total harvested water volume will be so large that centralised storage tanks would reach unreasonably large dimensions. Therefore other solutions like storage in surface water in the city or the sub-urban area, or by aquifer storage is more appropriate. In peak situations the transport of water into the central storage can be so high that it becomes limiting. In that case one or more intermediate storages, e.g. water squares may be required.

Rainwater harvesting at this scale is not yet tested, albeit that some elements are already operational on full scale e.g. water squares and aquifer storage. The latter will be discussed in more detail in the next paragraph.

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[5] Building Research Establishment Environmental Assessment Method; www.breeam.nl

8.6 Storage of rainwater in aquifers

Subsurface storage of freshwater in saline water regions

In the Western and Northern part of the Netherlands groundwater is predominantly brackish or salty. Figure 9 shows the depth in metres below surface level (BSL) where the boundary is between freshwater and brackish/salty water. The boundary depth is where groundwater exceeds 1000 mg Cl/L. In this coastal area the agriculture and horticulture sector needs freshwater especially in the growing season.

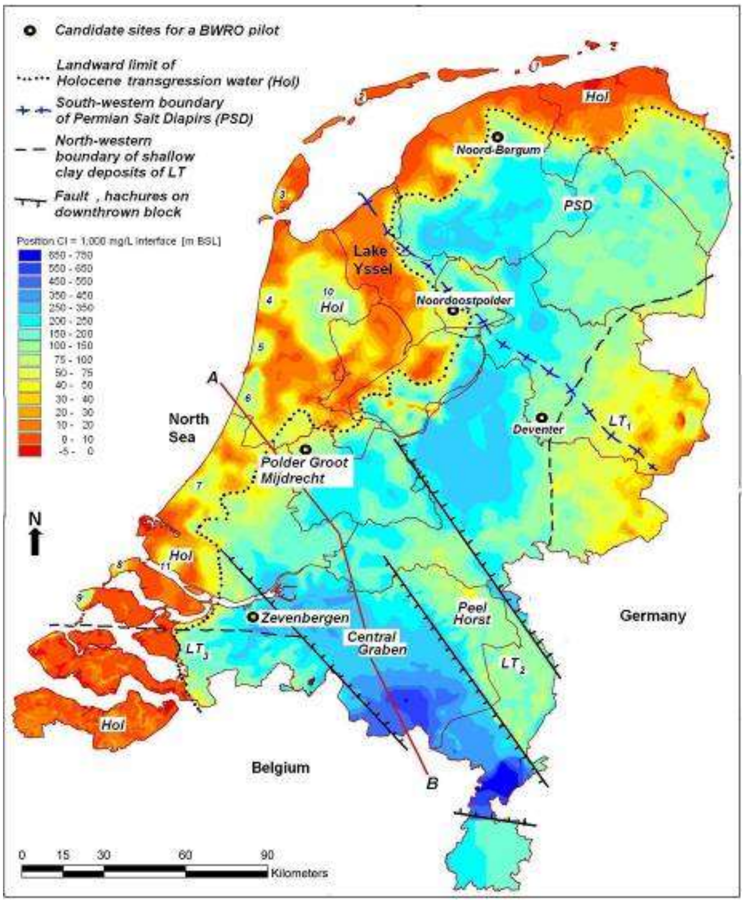

Figure 9: Depth below surface (m) where the boundary is between fresh water and brackish/saline water (Cl^- = 1000 mg/L).

In spring and summer the horticulture sector has often a shortage on freshwater. Figure 10 illustrates the shortage of water for the horticulture sector in the Westland area, which is situated approximately between Rotterdam and the North Sea. The horticulture sector needs freshwater of high quality which is low in sodium (< 20 mg Na/L). Rainwater is the only suitable freshwater source that meets the quality standards of good irrigation water. All other water sources in the region such as the surface water and groundwater are too salty and have to be desalinated before being used as irrigation water. Figure 10 shows that for example in 2003 the amount of rainwater in dry periods as is not sufficient to fulfil the water demand of the horticulture sector. Moreover, even in years with average or high rainfall a shortage of freshwater will occur. The main reason is the limited storage capacity of the freshwater basins which means that only a part of the rainwater is harvested effectively. Moreover, some crops as tomato or cucumber needs more water than the annual precipitation per surface unit (Paalman *et al.* 2011). In order to get sufficient irrigation water the horticulture companies make use of salty groundwater and desalinate this water through the process of reversed osmoses. However, by this process a brine solution arises which is discharged in deeper groundwater layers.

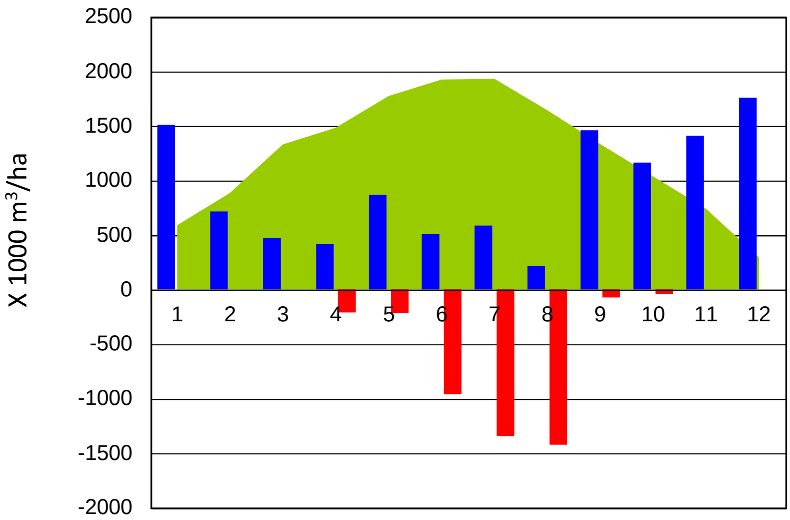

Figure 10: Water demand (green), rainwater distribution (blue), water shortage (red) in the horticulture sector of the Westland (Western Netherlands) in 2003

A future direction is to harvest rainwater more effectively. Because the water demand and water supply do mostly not match in time and place (Figure 10), the rainwater has to be stored. One solution is to store the freshwater in the groundwater aquifers. In Figure 11 the concept of rainwater harvesting and aquifer storage is shown. Through infiltration fresh water replaces the (brackish) ground water which is pushed aside. On this way a fresh water lens arises in the brackish aquifer.

By infiltrating rainwater falling on roofs of houses and buildings in cities in aquifers, the amount of water for low grade applications in the urban environment (see 5.2) increases. In this way drinking water use can be reduced and capacity extension of existing drainage systems can be postponed or diminished.

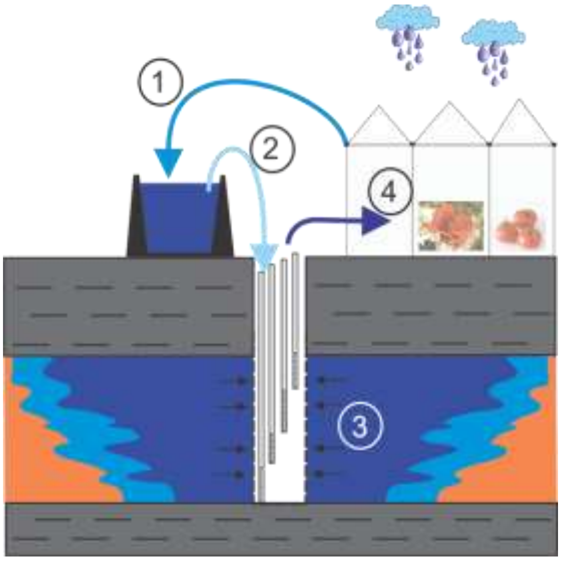

Figure 11: Schematic of rainwater harvesting and storage in basins and aquifers in the horticulture sector.

8.7 Opportunities for rainwater harvesting in Dutch cities

The results of this study have shown that rainwater harvesting is a system that has been practiced since the early ages of mankind. Ancient civilisations already applied RWH to cope with change in climatic conditions, mainly droughts. In the last decade, rainwater harvesting is gaining interest again in literature, related to finding sustainable water management solutions in urban areas. More and more RWH is seen as a sustainable method to overcome droughts and enable a reduction of water demand.

Recent studies also identify rainwater harvesting as a method to prevent or reduce nuisance and damage due to flooding during severe rain events. In existing urban areas, RWH can store excessive rainwater and therefore reduce the need to expand the existing sewer capacity, even when precipitation rates and frequencies increase. In future urban areas, RWH can be integrated with an optimum mix of storage and drainage capacity. The key question here is:

“What are the opportunities for Rainwater Harvesting in The Netherlands?“

For successful application of RWH as a climate adaptation measure in urban areas, a number of preconditions have to be met:

1. There should always be sufficient storage capacity available to store large amounts of precipitation in a short time.

2. The hydraulic design of the harvesting system needs sufficient capacity to transport the water in short time to the storage buffer.

3. Water re-use applications need to be installed to empty the storage capacity.

Beside these preconditions some choices have to be made about which fractions of the rain will go into the RWH system, and which fraction will go into the sewer. There are four options:

1. The total rainfall on hard surface is collected and split in a certain ratio between the sewer system and the RWH system.

2. Only rainfall in excess to drainage capacity of the (existing) sewer system is collected in the RWH-system. Normal rainfall will go into the sewer system ("peak-shaving")

3. All roof-top rain will go into a RWH system, while rain on other hard surfaces will be drained by the (existing) sewer

4. Only roof-top rain will go into the RWH system if the total drainage capacity of the sewer system is exceeded.

Storage and system design

For the Netherlands we have to consider that, on average, of hard surface in Dutch urban areas 50% is roof tops and the other 50 % is roads and pavements. Of course, in many situations and urban districts the actual ratio between roof and pavement will be different. Moreover the ratio between hard surface and green may vary locally.

To prevent water nuisance and flooding the storage capacity needs to be large. For the situation in the Netherlands, a system with many privately owned small systems will not be an effective measure because it is difficult to enforce and control the use of individual systems, and is probably not cost-effective. Based on the results of this study, a centralised approach on larger scale, e.g. in a neighbourhood or urban district, is expected to be more viable. A large scale system requires however a large storage capacity. In most cities in The Netherlands this is very difficult to achieve, because space for large storage facility is not available, especially in the most vulnerable parts with a high urban density. In these cases deep well infiltration and aquifer storage (ASR) may be a solution. Although not in a real urban area, the demonstration project in the Westland horticulture area in the Netherlands is a good example of such a system. In many places in The Netherlands the subsoil is suitable for application of ASR. Infiltration wells take only limited space and their construction in a dense urban area is relatively easy. The infiltrated water will push the water present in the aquifer in a horizontal direction. At large distances from the ASR well this may lead to some increased seepage.

The system design for a centralised urban RWH system is expected to be rather complex and dependant on the specific local situation. Important aspects will be the above choices on which part of the rain will be going into the RWH. To design a system, a stochastic approach as described in Chapter 6 has to be used. This modelling will give a good estimate on the volumes and flows of rainwater that needs to be stored and is drained via the existing sewers. Predicted future precipitation volumes and frequencies have to be taken into account, as well as water use scenarios.

Hydraulic design

In a centralised RWH system rainwater from relatively large surface areas are collected and brought together in one or a few points. At these the hydraulic capacity of the collection system has to be sufficient to deal with high peak flows in short time periods. If ASR is used, the infiltration rate should also be high enough to bring the water into the aquifer.

The size and hydraulic infiltration capacity of the ASR system determines the total surface area that can be used as catchment surface. It depends on the water quality whether an additional filter or screen is required. If this is the case, its capacity should match infiltration capacity of the ASR wells.

Once the hydraulic infiltration capacity and catchment area are known, the flow paths of the collection system can be designed. Depending on the choices of what part of the rainfall will go into the RWH system, the total hydraulic design can be made and integrated into the urban area.

An intermediate storage of the rainwater, e.g. on a water square can be included in the hydraulic design. This provides the opportunity to create a hydraulic design that decouples the catchment flow capacity from the ASR-infiltration capacity. Most probably the ASR capacity will be lower and less expensive than a direct coupling. On the other hand intermediate storage requires space in the urban environment. An example of a temporary storage of roof harvested rainwater is the Benthemplein in Rotterdam.

Water re-use applications

An important success factor for RWH is the water re-use application. Water re-use is important to empty the storage before the next event. On large size systems, the water re-use application has to use again relatively large volumes. Applications to be considered may be cooling systems, garden and park watering, and household water (toilet flushing, laundry). The latter requires of course to create a separate distribution system. As mentioned in paragraph 8.2 household water systems were banned in the 1990s. Nevertheless, in the broader context of climate change and advances in technology it would be worthwhile to reconsider this application

Application of RWH as a measure to create climate proof cities is of course only effective if it is applied on a large scale (neighbourhood or district level). This means that large storage volumes are required. In many cities and urban areas placement of such a large storage tanks is problematic. Alternatively, large scale rainwater harvesting combined with aquifer storage can be an interesting option to create climate proof cities.

Application of RWH in the cities involved in this project is evaluated. The results are shown in Table 7. As shown in this table large scale systems with ASR seem a feasible option.

Table 7: Option for RWH in some Dutch urban areas

Area	Individual systems	Office Buildings	Neighbourhood
Amsterdam, Watergraafsmeer Deep polder (-5.5 m MSL), varying urban density, residential areas, large road and railway infrastructure, office buildings	Possible, difficult to control, effects uncertain	Existing	Possible with storage in ponds or aquifer
Rotterdam, Het oude Noorden Very high urban density, over 70% hard surface	Difficult	No present	Possible, storage in aquifer
Tilburg	Possible, difficult to control, effects uncertain	Possible	Possible; however low grade water project terminated
Arnhem-Nijmegen Cities partly built at push moraines, sandy soils and clay soils in river bed	Possible, difficult to control, effects uncertain	Possible	Possible, storage in aquifer

9 Conclusions and recommendations

9.1 Conclusions

The following research questions were addressed in this report:

- What are the technical conditions (collection and storage, treatment, demand matching)?
    - RWH is of all times and is an ancient climate adaptation strategy
    - Rainwater harvesting infrastructure consists of a catchment (mostly roof surfaces), a storage (tank or aquifer), a small treatment system and an application for water use
    - RWH can reduce stormwater load on (existing) sewer system significantly if designed well. It is expected that a well-designed system can keep at least 40% water "out of the sewer".
    - Storage is possible in storage tanks and in the subsoil.

- What are the costs and benefits in a broader context?
    - The availability of water utilisation is a key issue
    - RWH on small scale (individual systems) is not economically viable when used as an alternative water source.
    - If applied on large scale and the costs are weighted against costs for capacity expansion of a sewer network and costs by damage caused by flooding, the societal costs may be less.
    - Large scale systems (collective systems on neighbourhood scale, large office buildings etc.) can be economically viable

- What are the health risks involved?
    - Physico-chemical water quality of roof harvested is in general good, if a first flush is diverted.
    - Roof water contains in general low levels of pathogens, depending on the application some disinfection treatment may be required
    - Health risks of RWH are low.

- Can RWH be applied as an climate adaptation measure in cities in The Netherlands?
    - Application in The Netherlands depends strongly on the local situation. Large scale RWH with aquifer storage can be effective, even in urban areas with high urban density. This has already be demonstrated in for horticulture, but may also be applicable in urban areas.

- In many area's individual systems can be used, but they are only effective if many of them are installed and they have sufficient storage capacity. In this case governance and the creation of an incentive to install systems is an important issue.

9.2 Recommendations

It is recommended to set-up a few research and demonstration projects

1. Application of small individual systems. The goal in this study would be to demonstrate the effect on water management and storm water drainage in an urban neighbourhood or district. Especially the prevented costs for a large should be compared to the societal costs.

2. Application of a neighbourhood scale project in urban environment, using aquifer storage. The main goal in this research would be to test en demonstrate the feasibility and to create and validate design rules for such a system.

10 Literature

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To develop the scientific and applied knowledge required for Climate-proofing the Netherlands and to create a sustainable Knowledge infrastructure for managing climate change

Contact information

Knowledge for Climate Programme Office

Secretariat:
c/o Utrecht University
P.O. Box 85337
3508 AH Utrecht
The Netherlands
T +31 88 335 7881
E office@kennisvoorklimaat.nl

Public Relations:
c/oAlterra (Wageningen UR)
P.O. Box 47
6700 AA Wageningen
The Netherlands
T +31 317 48 6540
E info@kennisvoorklimaat.nl

www.knowledgeforclimate.org