

Exploring the hydrological response of greenhouse reservoirs

Master thesis

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Preface

This document was created as a graduation work (master thesis) for the master Water Management (track: Water Resources Management) at the faculty of civil engineering of the Delft University of Technology. After graduation the research will be continued to gather missing data and to publish the results.

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Friends & Family

Exploring the hydrological response of greenhouse reservoirs

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Abstract

The role of water storages at greenhouses will change in the future due to three trends in climate change, upscaling of greenhouses and changes in regulations. These three trends force the local water authority and the greenhouse sector to anticipate on future problems. First step in this process is to understand the hydrological response of greenhouse reservoirs.

In this research delays and losses of the precipitation collection system are measured in situ. With the knowledge gained a model is created to compute long term simulations of the storage in the reservoir to determine the volume of annual precipitation that is usable for irrigation.

In the long term simulations the amount of precipitation that is usable for irrigation varies only between 60% and 70% of the annual precipitation for reservoir-roof ratios of respectively between 500 m³/ha and 3000 m³/ha. However the use of additional water sources and overflows into the surface waters are strongly influenced by this ratio.

1. Introduction

In 2016 the Netherlands had approximately 9,300 hectares of greenhouses (CBS, 2017) which produced over \$8.3 milliard (CBS, 2017) worth of flowers, plants, fruits and vegetables in that year. “[Over the years], the sector gained a leading international position due to multiple innovations in energy- and labour-saving technologies and efficient production methods” (TNO, 2017). However, to maintain its leading position, the sector continuously needs to keep pushing its boundaries.

In this high-tech environment water is essential for photosynthesis and therefore for the development of crops. The main source of irrigation in the Dutch greenhouse sector is precipitation. The demand for most crops is rather constant, but precipitation varies over time, hence reservoirs are needed to intercept precipitation fluctuations.

Typical reservoirs consist of an angular basin enclosed by 2.5 meter high earthen embankments covered with pond foil. The size of these reservoirs varies per greenhouse

between 500 m³ and 3000 m³ per hectare of greenhouse roof. This corresponds to a storage capacity between 50 mm and 300 mm (minus the direct precipitation in the reservoir) in comparison to an annual precipitation of ±880 mm (KNMI, 2017). By law all greenhouses in the Netherlands are required to have a reservoir of at least 500 m³ per hectare of greenhouse (Nederlandse overheid, 2017). However in general reservoirs are bigger. The actual size is a choice of the horticulturist based on the type of crop, the availability of space and the desired independence of additional water sources. Additional water sources are ground water, surface water or the municipal drinking water system. Which before they can be used for irrigation all require purification by reversed osmosis (RO).

The following three trends indicate that the importance of greenhouse reservoirs will change in the future, both on the scale of individual greenhouses and regionally.

1. Due to climate change there will both be longer periods of dry spells and more

frequent and severe precipitation. (KNMI, 2017)

2. Greenhouses are growing larger and are placed more efficiently on building plots, increasing the density of the paved area. (Hordijk et al., 2014)
3. Regulations for reverse osmosis installations are changing. The Dutch government will completely ban the injection of the residual product of RO in deep aquifers on 1st of July 2022 (Rijkswaterstaat, 2017) forcing the horticulturist to invest in local waste water treatment facilities if they want to keep using RO.

These three trends force horticulturists to invest in new ways to overcome the increasing periods of water scarcity and to minimise losses during extreme precipitation events. Besides horticulturists, local water authorities are looking for solutions as well, as they fear more frequent and severe flooding.

Both horticulturists and local water authorities will benefit from improved insight in the hydrological response of precipitation collection systems for greenhouses. There is a particularly great need to determine the relationship between precipitation and the overflows into the surface water. The greenhouse sector is mostly interested in the amount of water that is currently lost, but could be used for irrigation. With detailed information about these losses, horticulturists can determine whether investing in larger storages or more efficient collection systems is profitable. The local water authorities are, besides the overflow volumes, also interested in the diversity of delays and tail effects of different reservoirs after a precipitation event to properly manage the water levels in the regional area.

Currently the knowledge on the hydrological response of precipitation collection systems is lacking. This means that there is insufficient insight in the delays, tail effects and losses that typically determine the hydrological response as illustrated in figure 1.

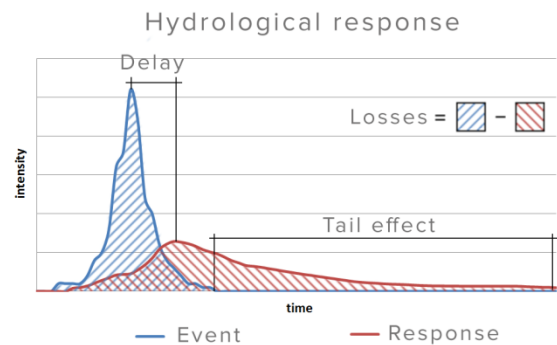


Figure 1: Concept of hydrological response

The goal of this paper is threefold: to determine the hydrological response of greenhouse reservoirs, investigate under which circumstances the system fails and generalise the findings to determine the influence of the reservoir size on the volume of annual precipitation that is usable for irrigation.

In the second chapter of this paper a general introduction to the greenhouse industry is given describing trends and key figures. The third chapter provides an overview of a typical greenhouse precipitation collection system.

In chapter four and five the research is reported in two parts. In the first part the delays and losses between the roof and the reservoir are determined on event scale. For this purpose in-situ measurements are conducted at a test-site. In the second part the knowledge gained is used to create a model to perform long term simulations to determine the annual use of RO-installation and the frequency and volumes of overflows to the surface water.

In the remainder of the paper the outcomes of both the measurements and the model simulations are presented and discussed.

2. The greenhouse environment

The growth conditions in the greenhouse are as controlled as possible to be less dependent on environmental conditions. To optimise the crop growth the horticulturist actively controls amounts of nutrients, (artificial) light, CO₂ and water.

2.1 Sources of water in greenhouses

The main source of water in the greenhouse sector in the Netherlands is precipitation. To use the collected precipitation as efficiently as possible drip irrigation is used. Any surplus of irrigated water is collected with drains, cleaned and re-used. The same goes for water that condensates against the inside of the greenhouse roof. Despite this efficient use of water the horticulturists cannot solely rely on precipitation, because for the majority of greenhouse crops the yearly water consumption is larger than the yearly precipitation due to the excellent growing conditions in the greenhouse. As additional water sources horticulturists typically use ground water, surface water in combination with a reversed osmosis (RO) installation and drinking water.

Drinking water is the most expensive additional water source with a price of € 1,10 /m³ (Dunea, 2017) and contains nutrients that plants absorb only slightly or not at all (e.g. Natrium). These nutrients accumulate in the system and can cause damage to the crops over time. Therefore unfiltered drinking water can only be used temporarily in small amounts.

Non-purified ground water is unusable due to high concentrations of chloride and iron. Non-purified surface water is unusable for the majority of crops due to the almost certain presence of fungi and viruses.

If purified with a RO-installation, water can directly be used in large quantities. The price of purified ground water from a reverse osmosis installation is € 0,75 /m³ (Lenntech, 2017). Cheaper than drinking water and therefore most horticulturists have a RO-installation as additional water source.

Although a RO-installation is a reliable source of water it is still relatively expensive compared to a precipitation collection system. The horticulturists will therefore own an undersized RO-installation (and use it

reservedly) and will always optimise the use of cheap precipitation.

2.2 Water storage at greenhouses

The reservoir volume is a compromise between the type of crop, the availability of space on the plot and the desired independence of additional water sources. When designing a new greenhouse the priority of the horticulturist is to maximise a rectangular on the plot of land. After the size of the greenhouse is designed the remaining area on the plot is filled up with the water reservoir, buildings, parking spaces, etc.

The most common way to store water is in a basin. A basin is basically a hole in the ground (approximately 1 meter) surrounded by a dirt wall (approximately 2,5 meter). The inside of the basin is covered with a watertight canvas. Some horticulturists cover the top of the basin with an additional canvas to limit water from evaporating.

On plots where less space is available the water will be stored in silos. Silos are usually higher (up to approximately 6 meter) than basins and require for the same volume less ground surface. However silos are more expensive to build.

Recent developments are storing water in an aquifer (Zuurbier et al., 2014) and building greenhouses on top of shallow reservoirs (Glastuinbouw waterproof, 2014) on plots where insufficient space is available for conventional basins or silos.

2.3 Design intensity for precipitation collection systems

The last decades show a clear increasing trend in the designed capacity of precipitation collection systems. Around the year 2000 the drainage systems were designed to handle a stationary discharge intensity of 25 mm/hour.

After increasing to 30 mm/hour in 2010, the design intensity is currently (2017) at 35 mm/hour. Expected is that this trend will continue towards design intensities of 40 mm/hour in the coming decade (BOM group, 2017). This trend is mainly caused by the combined effect of increasing greenhouse sizes and more extreme variations in precipitation, raising the risk of water shortage in the reservoir.

3. The greenhouse precipitation collection system

The majority of large greenhouses in the Netherlands have a similar precipitation collection system. An overview of such a system is given in figure 2.

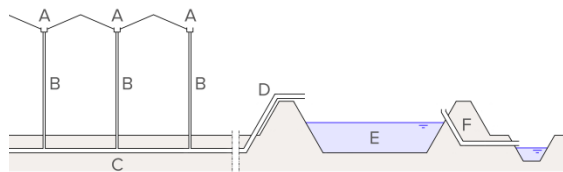


Figure 2: The precipitation collection system

Precipitation on the roof accumulates in small gutters. Through these gutters, and partly over the glass roof, the water flows to the edge of the roof to a collection bucket (A). From here, the water is guided through vertical drains (B) towards underground horizontal drains (C). At the basin (D), the horizontal drains rise above the basin wall to let the water flow into the basin (E). When the basin is filled up any surpluses of collected precipitation overflow into nearby surface water (F).

As stated before, it is desirable to minimize the losses in the system. Generally, losses occur in four ways (1) evaporation on the roof, *interception*, (2) losses within the collection system, e.g. leakages and spills at the collection buckets, (3) open water evaporation from the reservoir and (4) overflows from the reservoir. Experiences of horticulturists and the local water authority confirm that in cases of extreme precipitation spills at the collection bucket occur. Although this phenomenon is known, information about frequencies and volumes has not yet been quantified.

3.1 Spills at collection bucket

Two processes can result into spill at the collection buckets: an insufficient capacity of the drainage system or an inadequate collection bucket. These processes will further on be called respectively type I spills (full system) and type II spills (small bucket).

Type I spills occur when the resistance in the drainage system becomes too high. With increasing precipitation intensities the flow velocities in the system increase and therefore the head losses due to friction, valves, bends and such in the system increase. In cases of type I spills the head loss in the drainage system is bigger than the height of the vertical drains (figure 3). Because of this the vertical drains fill up entirely and will eventually overflow.

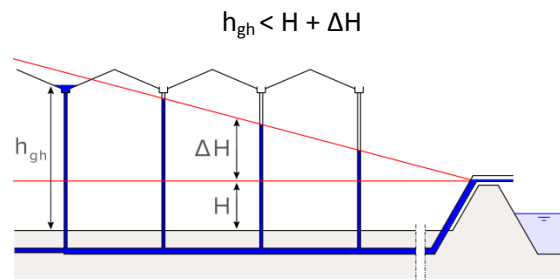


Figure 3: Schematisation of type I spills

To avoid type I spills the ISSO, Institute for installation engineering, states in its guidelines that “the maximum water level in all vertical drains must remain at least 100mm underneath the collection bucket for a stationary discharge of 35 mm/hour”(ISSO, 2015).

Figure 3 shows that the head loss increases with distance from the reservoir. Therefore the drains furthest away will overflow first. Drains near the reservoir are expected to overflow rarely.

Type II spills occur in cases of extreme precipitation when the width of the stream in the gutter and on the glass roof exceeds the opening of the collection bucket as shown with the red arrows in figure 4. During these events water will flow past the collection bucket directly on the ground next to the greenhouse.

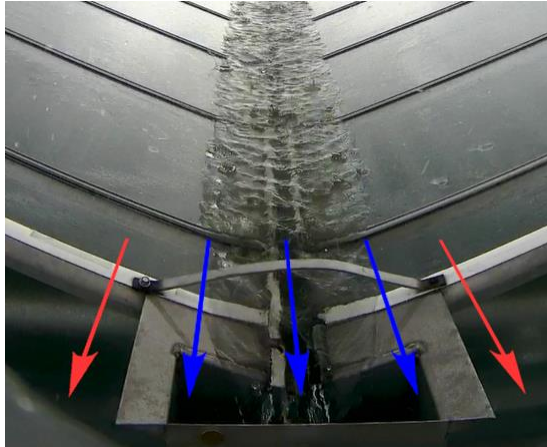


Figure 4: Explanation of type II spills

The ISSO accepts type II spills and states that “the width of the collection bucket must be at least equal to the width of the stream on the roof for 35 mm/hour”. Moreover it states that “for large amounts of precipitation it is tolerated for a collection bucket to spill” (ISSO, 2015).

Assuming little areal variation in precipitation intensity type II spills occur on all of the collection buckets at the same time.

4. Measuring in situ

Measurements are done on a test-location to gain knowledge about practical functioning of a precipitation collection system of a typical greenhouse system. All precipitation events during the measuring period are analysed and the results are combined to determine the delays, tail effect and losses in the system.

4.1 Test site – Holstein Flowers Bastille

To find a suitable test location, criteria such as a single system (only one roof, one drainage system and one basin) and a simple geometry were drafted to approach a 'standard' greenhouse. Specifications of the selected greenhouse are given in table 1.

	Test site
Name	Holstein Flowers Bastille
Cultivation	Gerbera
Location	51°59'07.7" N 04°15'17.9" E

Dimensions	Length	288 m
	Width	200 m
	Height	6 m
Reservoir	Area	3500 m ²
	Volume	10000 m ³

Table 1: Test site specifications

In figure 5 an aerial view of the greenhouse is shown. The roof area of the greenhouse can be divided into six sections with similar drainage systems. The precipitation flows from the middle of the greenhouse roof to the side of the greenhouse. From there the water flows towards the middle of each section. Collected precipitation from the three sections on the west side is transported through three large drains underneath the greenhouse to the basin on the east side. The flow of water of the mid-west section is given in blue in figure 5.

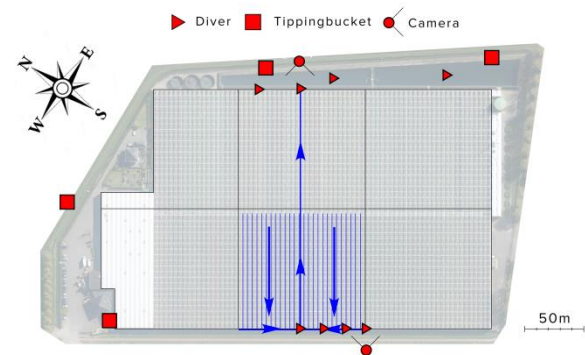


Figure 5: aerial overview of test location

For the experiment the water levels in several drains as well as the water levels in the basins were measured using divers. Anticipating differences in the areal distribution of precipitation (Berndtsson et al., 1988) and variations between different measurement locations (Molini A. et al., 2005) four tipping buckets are installed around the greenhouse. Detailed information about the location of the tipping buckets can be found in Appendix A. Furthermore two time lapse cameras (one picture every five seconds) are installed to get visual input of what is happening on the roof and at the inflow to the basin. The exact locations of all measuring equipment can be found in figure 5.

Over a period of 8 months, March 2017 – October 2017, measurements were conducted. Table 2 shows long term average

precipitation and the measured precipitation from March till July 2017.

	Measured [mm]	Average [mm]
April	43	40 - 45
May	17	60 - 65
June	35	65 - 70
July	132	85 - 90

Table 2: Overview of precipitation

Unfortunately the period April-June 2017 was one of the driest periods in years. Water levels in the reservoirs dropped to extreme lows. From March 21st to the end of August the reservoir did not overflow. Serious precipitation events only started in the second half of July.

4.2 Example analysis: Event - 9th of June 2017

During the precipitation event on the 9th of June the 10 mm precipitation was logged in 1.5 hour. During the event the measured differences between the four tipping buckets across the site were minimal. An analysis of the differences between the different tipping buckets can be found in Appendix B. Because of the small variations an average intensity is used in further calculations.

The precipitation started at 7h36, had a small double peak at 8h11 & 8h22 and a large peak at 9h00. From 8h58 till 9h03 the average precipitation was >25 mm/hour for 5 minutes corresponding to a volume of 2.4 mm/5min.

When the precipitation, water levels of the different vertical drains and water level in the reservoir are plotted in the same graph the responses are clearly visible (figure 6).

The graph shows that there is a clear difference between the drains near the basin in blue and the drains on the far side (west side) of the greenhouse in red. The 200 meter horizontal drain that transports the precipitation underneath the greenhouse clearly causes a large head loss.

For this graph the reaction in the reservoir is expressed in mm/hour (Volume difference divided by the contributing area, viz. the greenhouse, barn and office roofs plus the area of the basin). The peak delay after the precipitation is around 3 minutes.

The total volume of the event is calculated by integrating the precipitation over time, the same hold for the rise in water level in the reservoir. Differences in volume indicate losses due to interception and spills. In this case the total volume calculated from the tipping buckets is 688 m³ (10.2 mm) and the total volume calculated from the water levels in the reservoir is 696 m³ (10.3 mm). The difference of 8 m³ (0.1 mm) is within the measuring error, but indicates that any losses during this event were minimal.

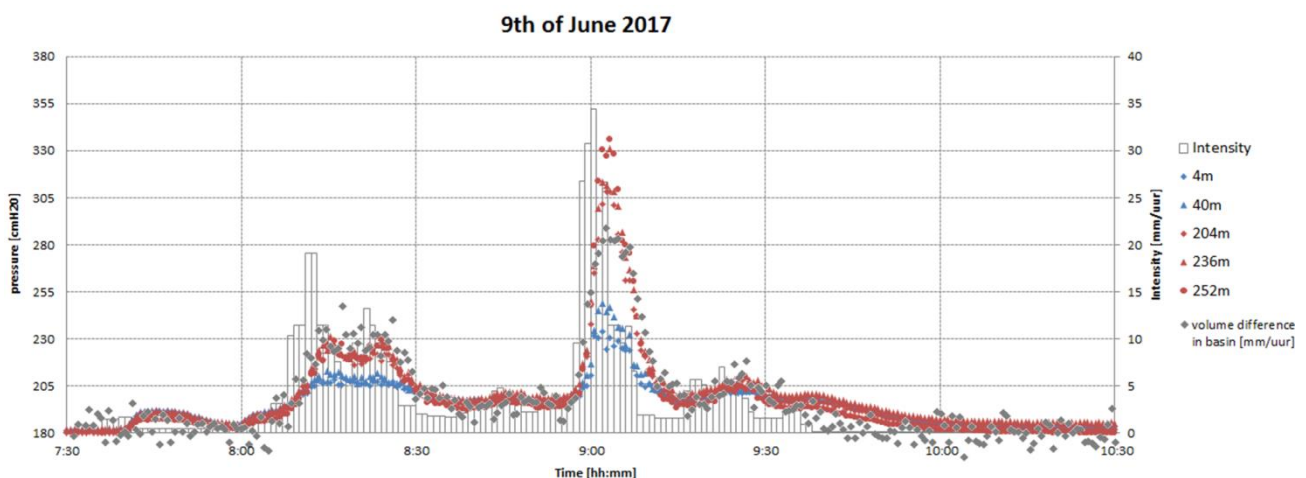


Figure 6: Event on the 9th of June

4.3 Results: Delays & Tail effect

By combining the results of all measured precipitation events, the delays and tail effect are determined.

The delays between precipitation peak and discharge peak are in the range of 3 to 7 minutes (figure 7). The delays are dependent on the antecedent conditions and intensity of the event: the response times tend to decrease when intensities increase. Responses to the same intensity peaks will be minutes faster on a wet roof compared to a dry roof.

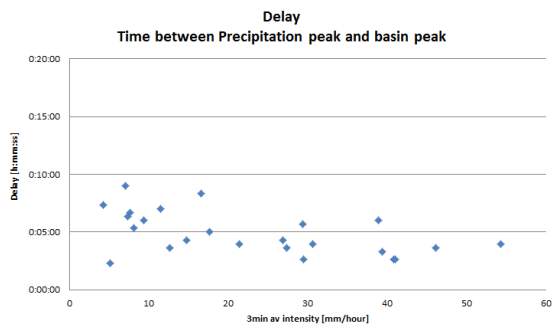


Figure 7: Delays between roof- and reservoir peaks

The time that it takes the drainage system to discharge a precipitation event is dependent on the shape of the event. In general it takes longer to discharge larger volumes. However for most events it takes between 25 and 35 minutes to discharge all precipitation from the roof to the reservoir after an event stops.

4.4 Results: Losses

Besides the delays and tail effect, the losses in the system have been analysed for all measured events as well.

4.4.1 Type I spill

To analyse type I spills averages were taken from the peak precipitation intensity and the maximum water level in the vertical drains. Averaging the precipitation is done because no information about return periods of events is available for minute scale. Averaging the water levels in the vertical drains is done to minimise any measuring errors due to the highly turbulent flow in the drains during events.

A plot of the precipitation intensity against the maximum water level in the vertical drain is plotted in figure 8.

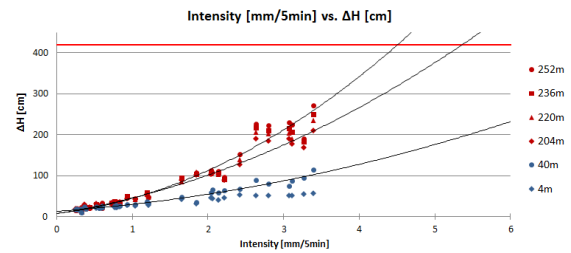


Figure 8: Results: type I spills

In the graph the blue dots represent the water levels in the vertical drains on the reservoir side of the greenhouse. The red dots represent the drains on the other side, 200m from the reservoir. As expected, as drains are further away from the reservoir, their water levels are higher.

Type I spills will occur at a water level of $h_{\text{Type I spill}} = h_{\text{greenhouse}} - h_{\text{reservoir wall}} = 600\text{cm} - 180\text{cm} = 420\text{cm}$. Extrapolating this data gives an estimate of approximately 4.5 mm/5min before the first type I spill occurs and at approximately 5.3 mm/5 min the whole far side will spill. In the Netherlands events with 5 mm/5min have a return period of once a year (KNMI, 2017). Therefore although no type I spill event was observed in the period of measurements, it is a scenario to reckon with.

4.4.2 Type II spill

Because no type II spill extreme high intensity took place during the measuring period from March to August a lab experiment was conducted. A 1:1 model of the gutter, glass roof and collection bucket was created in the laboratory. In this test setup the inflow of water can accurately be controlled and measured.

Results from the experiment are shown in figure 9.

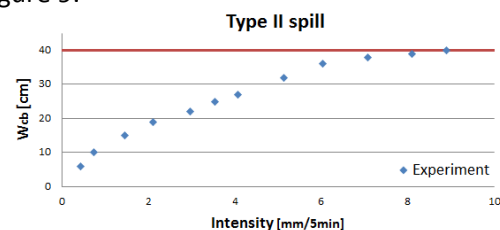


Figure 9: Results: type II spills

Based on these measurements type II spills are estimated to occur for events larger than 9 mm/5min. Such an event has a return period of once in 5 years. (KNMI, 2017).

4.4.3 Interception

In all analysed events the low intensity (< 4 mm/5min) allows us to discard type I and II spills. For all events the averaged tipping buckets differed slightly from the volume calculated from the water level rise in the reservoirs. However there was no constant deviation. In most cases the difference is only 1 or 2 tips (plus or minus 0.2 or 0.4 mm). This means that a measured difference is probably caused by the limits of the measuring devices and that the interception and possible leakages are minimal. Since the interception cannot be zero the findings above require further analysis.

Because this first analysis did not deliver conclusive results, an alternative method was required to estimate the interception. The footage from the camera is compared with the registered tips by the tipping buckets. Before the small precipitation event of the 24th of April 2017 from 03u54 to 04u07 the roof was dry and after the event the first drops discharge from the roof. During the same time period one out of the four tipping buckets registered one tip. Considering that one tip signifies 0.2 mm of precipitation, the most accurate approximation for the interception equals these 0.2 mm. More accurate measuring instruments are needed to determine the real interception.

5. Model simulation

With the insights gained from the in-situ measurements and the lab experiment, a model is created to determine the annual use of RO-installation and the frequency and volumes of overflows to the surface water. The structure of the model is based on three reservoirs; the first represents the greenhouse roof, the second represents the drainage system and the third represents the reservoir (figure 10).

Because only hourly weather data is available a one hour timestep is used for the simulations (station 330 – Hoek van Holland, KNMI, 2017). Although all processes on the roof and in the drainage system are in minute scale, the limitation of the timescale of the data forces to simplify the model by hourly averages of the precipitation. This means that general assumptions need to be made with regard to precipitation intensity, which are explained in section 5.1.

What remains is a model based on one reservoir. The created model for the reservoir can be understood by the simplified equation (eq 1).

$$\frac{d}{dt} S_b = P_{col} + Q_{add} - Q_{out} - E - Q_{overflow} \quad (\text{eq.1})$$

With

S_b	= Storage in reservoir	[m ³]
P_{col}	= Collected precipitation	[m ³ /h]
Q_{add}	= Additional water source	[m ³ /h]
Q_{out}	= Discharge from the reservoir	[m ³ /h]
E	= Open water evaporation	[m ³ /h]
$Q_{overflow}$	= Overflow to surface water	[m ³ /h]

In this equation overflows to the surface water will only occur when the reservoir is completely filled up ($S_b > S_{b,max}$). Furthermore it is important to realise that the Q_{out} is dominated by irrigation.

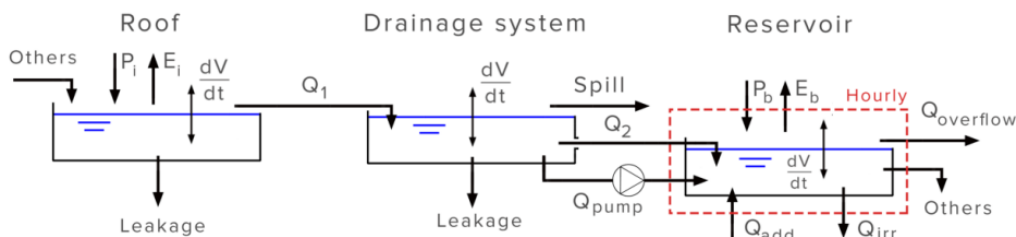


Figure 10: Schematisation of the greenhouse precipitation collection system

5.1 General assumptions

The model dimensions of the modelled greenhouse precipitation collection system are based on the dimensions of the test site. For the reservoir a conventional basin is assumed.

The annual interception is calculated with weather data from the nearby KNMI weather station - Hoek van Holland (ref). For this calculation assumed is that all intensities of less than 0.2 mm/hour and every first 0.2 mm precipitation after a dry hour are intercepted. This results in a total of 13 % of annual precipitation that is intercepted.

On an annual scale the maximum spill at the collection bucket can be calculated based on duration-intensity-frequency curves for the Netherlands (KNMI). It is calculated that for a precipitation collection system that is designed according to the ISSO-88 norm, but that fully accepts type II spills (spills of the collection bucket) the annual loss due to failure of the drainage system (both type I & II) is 0,3 %. The percentage is low because high intensity events (>3 mm/5min) occur seldom. The calculations and information about which events are collected can be found in Appendix C.

The efficiency of precipitation collection system can be characterised by the *roof run-off coefficient*. The roof run-off coefficient is defined as the amount of precipitation that falls on the roof divided by the amount of precipitation that ends up in the reservoir. The combined losses give a total loss of approximately 13% of the annual precipitation. This corresponds to an annual run-off coefficient of 0.87. This means that the current precipitation collection systems are capable of collecting 87 % of precipitation that falls on the roof.

For this model an irrigation discharge between 50 m³/day and 250 m³/day is assumed dependent on the transpiration of the crops based on temperature, incoming solar energy and humidity. Combined with the collected water from the drains in the greenhouse the

total irrigation gift is between 200 m³/day and 500 m³/day.

When storages in the reservoirs are running low an additional water source is used to secure the water supply. The use of the RO-installation (7 m³/hour at test location) is a choice of the horticulturist based on the current water level, the demand of the crops and the weather forecast. This is simulated with 4 regimes dependent on the storage in the reservoir (table 3).

Storage	Regime
> 60 %	No RO
40 - 60 %	RO 8h at night
20 - 40 %	RO 24h
< 20 %	RO 24h & add drinking water

Table 3: RO regimes

To calculate the open water evaporation the method of Penman is used (Penman, 1948).

5.2 Model

By calibrating over measured time series the model parameters are determined. Validation is done on the limited data of overflows. As an example a period of 10 days is given in figure 11. The figure shows both the measured data and the modeled data. The first 5 days of this period were rainy. During these days surpluses of collected precipitation overflow into the surface water. The last 5 days were dry. Therefore the level in the reservoir drops due to irrigation and evaporation.

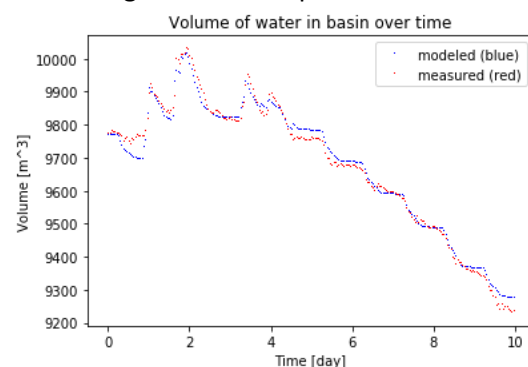


Figure 11: Model validation

5.3 Results

Figure 12 gives the results of a simulation of the stored water volume in the reservoir for a wet period and the maximum reservoir capacity. In this graph the maximum volume in the reservoir can be imagined by a line (red). The irrigation dominated outflow can be visualised as the gradient of the volume decrease during dry periods. To examine the influence of the size of a reservoir the red line can be shifted; upward for larger reservoirs, downward for smaller reservoirs.

5.3.1 Influence of reservoir size on frequency of overflows

The volume of storage is simulated for different roof-reservoir ratios (1000 m³/ha, 2000 m³/ha and 3000 m³/ha). For a relative dry and a wet winter the storages are shown in figure 13 as a percentage of the maximum storage.

In these graphs one can see that the reservoir size clearly has an influence on frequency of the overflows to the surface water during a dry period; The bigger the reservoir-roof ratio the less likely the reservoir overflows. However in wet periods the reservoir size has

little influence on the frequency and volume of overflows since the reservoir remains near its maximum storage capacity. The result is that any major precipitation event will cause the reservoir to overflow.

5.3.2 Influence of reservoir size on volume of overflows

From the simulation it is determined that the highest overflow peaks are hardly influenced by the size of the reservoir. This is because the majority of these spills occur during wet periods when the water level in the reservoir is close to the maximum. So from the simulation can be concluded that the maximum overflows to the surface water are equal for all greenhouses regardless the size of the reservoir.

However on a yearly basis the volumes of overflows do differ, mainly because of the difference in open water evaporation from the reservoir. The volume of storage is simulated for different roof-reservoir ratios in combination with the different irrigation factors. Results are shown in figure 14.

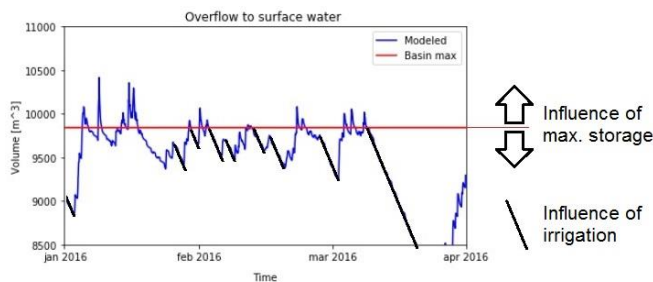


Figure 12: General model analysis

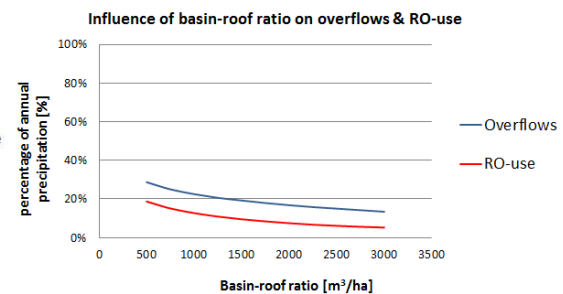


Figure 14: Overflows & RO-use

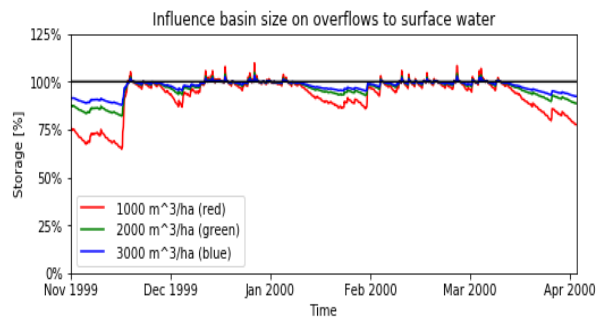
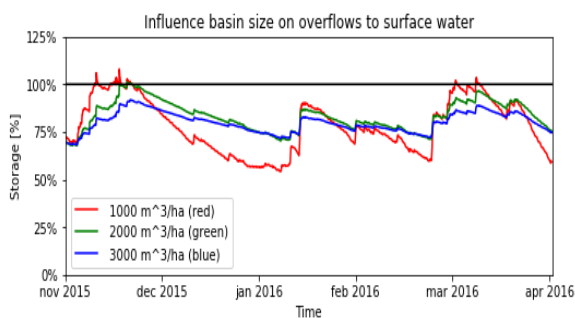


Figure 13: Model simulation during a dry (left) and wet winter (right)

5.4 Overview of results

If the potential annual precipitation (all precipitation that falls on the roof and direct in the reservoir) is set to be 100 %, then the distribution of the losses, the volume of the usable water and the required additional water can be expressed in percentages. For the smallest and largest reservoir-roof ratio these percentages are given in figure 15.

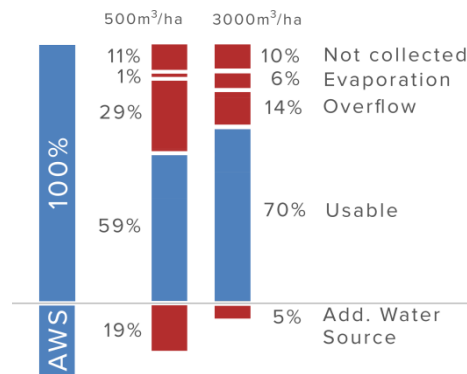


Figure 15: Overview of precipitation distribution

From the potential annual precipitation a percentage directly falls into the reservoir and is therefore fully collected. From the remaining percentage that falls on the roof 10-11 % is not collected due to interception and spills. There is 1% to 6% open water evaporation directly from the reservoir and depending on the reservoir-roof ratio 29% to 13% overflows into the surface water as can be seen from figure 13 in chapter 5.3.2. This implies that for a reservoir-roof ratio of 500 m³/ha 59 % of annual precipitation is usable and for a reservoir-roof ratio of 3000 m³/ha 70 %. Furthermore the use of additional water sources in times of water shortages decreases from 19% to 5 % of annual precipitation for a bigger reservoir.

6. Discussion

6.1 Response to surface water

The model shows the behaviour of the reservoir until overflow, but the way this water reaches the surface water was not observed. Hence it does not describe the delay and tail effect of overflows to the surface water.

6.2 Interception

The loss due to interception on annual scale is significant. However due to the limited accuracy of the tipping buckets the interception is assumed to be 0,2 mm. Table x gives an overview of the influence of this assumption.

Interception [mm]	Percentage of annual precipitation [%]
0.15	10%
0.2	13%
0.25	15%

6.3 No information on the shape of precipitation

The nearest KNMI weather station is station 330 - Hoek van Holland, about 9 km from the test location. For this weather station the hourly precipitation is available from 1970. However no minute scale information is available and peaks in intensity are averaged (figure 16).

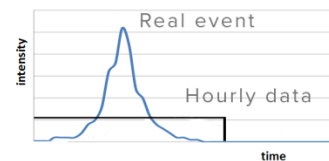


Figure 16: Lack of data

For information this paper used precipitation statistics in the form of duration-intensity-frequency curves (KNMI, 2017). To determine exact amount of spill precipitation data on minute scale is needed.

6.4 Large spills on event scale

Although small on annual scale the spills can be significant on event scale. Considering a minimal designed collection system collecting 3 mm/5min spills can be extremely high. For example the amount of precipitation that does not end up in the reservoir during a 1 in 20 year event of 12 mm/5min is 9mm/5min!

6.5 Design intensities

In this study a minimum design intensity of 35 mm/hour \approx 3 mm/5min is assumed. For older greenhouses the design intensity is probably lower (20 mm/hour \approx 2 mm/5min when constructed in the year 2000) resulting in

higher volumes of spills from the roof. For direct applicability of the outcomes of this study to a different greenhouse, dimensions need to be verified.

6.6 influence of irrigation

In the simulations done with the model the influence of irrigation is not investigated. In reality it is safe to assume that in general the reservoir-roof ratio is related to the irrigation. Horticulturists with large reservoirs will generally also use more water for irrigation.

7. Conclusions

The goal of this paper is threefold: to determine the hydrological response of greenhouse reservoirs, investigate under which circumstances the system fails and generalise the findings to determine the influence of the reservoir size on the volume of annual precipitation that is usable for irrigation.

The delays between the roof and the reservoir are between 3 and 7 minutes dependent on antecedent conditions and the event intensity. During wet periods the reservoir is typically completely filled up, which means that the overflows to the surface waters will also start within minutes. Since it takes more than minutes to lower the water level of the surface waters, the local water authority has to anticipate with lowering the water level, hours in advance of precipitation events.

The current precipitation collection systems are designed to handle a max. intensity of 35 mm/hour \sim 3 mm/5min. Above this design intensity the shape of the collection bucket is the dominating factor for how much precipitation is collected. For intensities above 3 mm/5min, but below the intensity at which the collection bucket becomes insufficient, the drainage system is in a state at which it will start to fail at the vertical drain furthest from the reservoir, whereas the other drains remain operational.

The maximum amount of precipitation spilled is approximately 0.3% of the annual precipitation. Although this figure is small on

annual scale the spills are significant on event scale. Considering a collection system that only meets minimum design criteria, spills during a 1 in 20 year event of 12 mm/5min can become more than 75% of the total precipitation during these 5 minutes. So 9 mm/5min does not end up in the reservoir!

For smaller reservoir sizes the annual percentage of precipitation that leads to overflows is significantly higher than for larger reservoirs. Whereas on event scale this cannot be strictly concluded, since overflows on event scales are dominated by antecedent conditions (mainly the water level in the reservoir), instead of by reservoir size.

Typically overflows will occur during wet periods only and are not to be expected from a single precipitation event in an overall dryer period. Furthermore it can be concluded that during wet periods both the frequency and the volumes of overflows are independent of reservoir size.

The size of the reservoir is found to have slight influence on the percentage of the precipitation that is usable for irrigation. However, the influence on the required use of additional water sources is far more significant.

8. Recommendations

More data is needed to determine the delay & tail effect of overflows to surface water and to validate the intensities at which the system fails. Recommended is to continue measuring at the test-site till sufficient data is collected to determine the delay & tail effects (and hopefully at least one spill will be registered).

Since the influence of the interception is significant further research on this topic is recommended. Interesting research could be on the differences between different greenhouses, to determine what causes differences in interception and whether it is possible to influence the amount of interception.

For the model simulation it is recommended to investigate the influence of irrigation on reservoir storage. The irrigation could have a large influence on the frequency and volumes of overflows, however before this can be taken into account research has to be done on the range of irrigation between different crop types.

Sprinkler systems have large effects on the water use from the reservoir, since evaporation of reservoir water is used to cool down the greenhouse roof. This term is left out because it is a new development and the majority of horticulturists do currently not use such systems. If the use of sprinkler systems becomes a standard feature in the greenhouse sector research on this topic is recommended.

This research is based on findings at one test-site. However the findings are generalised it is recommended that similar research is done at a different test location. Especially interesting is to investigate the influence of location of reservoir on spills.

For the analysis of the influence of the shape of precipitation detailed precipitation data on minute scale is needed. The meteorological institutes currently do not release data on minute scale. However for researches like this it is recommended that they do to allow for more accurate simulations.

Want to build a villa in a dry place? Consider De Lier!

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Appendix A – Location of tipping buckets

Ideally a tipping bucket would have been installed on every corner of the plot. However to exclude influences from the surroundings on measurements the tipping buckets are preferably located in open areas. Because a row of large trees on the south side of greenhouse and a road directly on the west side of the greenhouse no tipping buckets could be installed there. The exact locations of the tipping buckets can be found in table 4.

	Coordinates	Remark
A	51°59'10.7"N 4°15'09.2"E	In shrubbery
B	51°59'13.0"N 4°15'11.6"E	On reservoir wall
D	51°59'09.3"N 4°15'24.1"E	On reservoir wall
E	51°59'06.1"N 4°15'28.0"E	On office roof

Table 4: Coordinates of tipping buckets

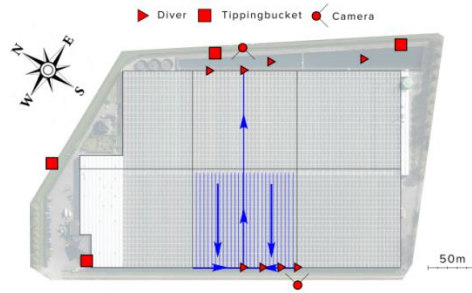


Figure 17: Tipping bucket A



Figure 18: Tipping bucket B



Figure 19: Tipping bucket D



Figure 20: Tipping bucket E

Appendix B – Tipping bucket differences

Although located in on different spots (Appendix A) the four tipping bucket registered very similar results. Figure 21 shows the raw data. Although the differences between the different already are pretty similar, these differences decrease even more when the volume is calculated (figure 22). The volume is calculated by multiplying the amount of tips with the volume per tip (calibrated in the lab).

To calculate the average intensity the average volume per minute is determined. Multiplying the minute average with 60 minutes gives the intensity in mm/hour for every minute (figure 23).

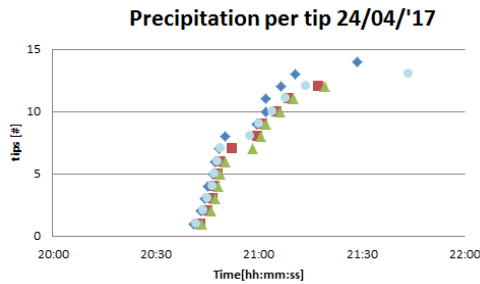


Figure 21: Tips over time

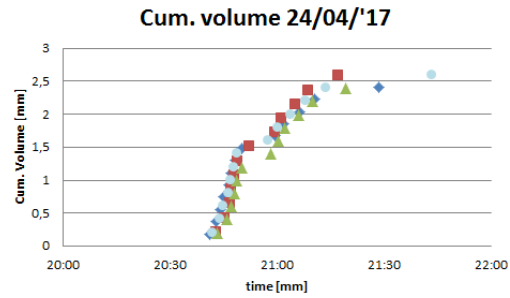


Figure 22: Volume over time

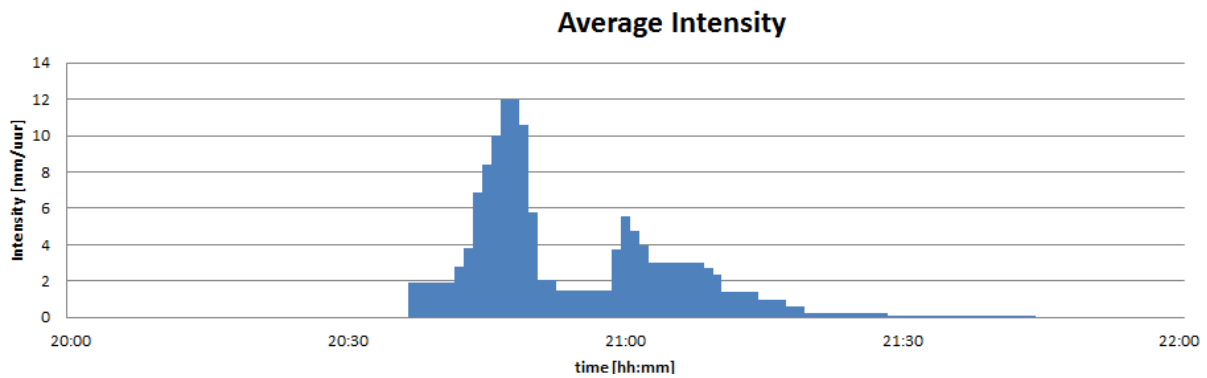


Figure 23: Averaged intensity

Appendix C – Losses due to type I and II spills

The losses of type I and II spills are based on the duration-intensity-frequency curves of the KNMI (KNMI, 2017). A sample period of 100 years is analysed. For every event the volume that is spilled is determined. This volume is multiplied by the amount of the event in 100 years and summed. Averaging the gained volume over 100 years gives the annual loss due to type I & II spills. Figure 24 & 25 show this calculation for a minimal design collection system and the system at the test site.

Losses due type I & II - 35 mm/hour collected																			
		volumes per timestep				volume collected				events in 100 year		spilled for events							
						2,9	8,8	17,5	35,0										
		5	15	30	60	volume spilled						#	# single	5	15	30	60		
					5	15	30	60											
10 x per	1 year		3	4	5	0	0	0	0	1000	500	0	0	0	0				
5 x per	1 year		4	6	7	0	0	0	0	500	300	0	0	0	0				
2 x per	1 year	4	6	8	10	1	0	0	0	200	100	27	0	0	0				
1 x per	1 year	5	9	11	14	2	0	0	0	100	50	26	3	0	0				
1 x per	2 year	7	11	14	18	4	2	0	0	50	30	31	17	0	0				
1 x per	5 year	9	15	19	23	6	6	2	0	20	10	15	16	4	0				
1 x per	10 year	11	18	23	27	8	9	6	0	10	5	10	12	7	0				
1 x per	20 year	12	21	27	32	9	12	10	0	5	3	7	9	7	0				
1 x per	50 year	15	26	32	38	12	17	15	3	2	1	3	4	4	1				
1 x per	100 year	17	29	37	43	14	20	20	8	1	1	4	5	5	2				
												122		66		26		3	
total spilled												217 mm				2,2 average mm per year			
												0,27% of annual precipitation (800 mm)							

Figure 24: calculation of type I and II spills for a minimal designed collection system

Losses due type I & II - Holstein															
		volumes per timestep				volume collected				events in 100 year		spilled for events			
						5,9	17,6	35,2	70,3						
		5	15	30	60	volume spilled						#	# single	5	15
5	15	30	60	5	15	30	60								
10 x per	1 year		3	4	5	0	0	0	0	1000	500	0	0	0	0
5 x per	1 year		4	6	7	0	0	0	0	500	300	0	0	0	0
2 x per	1 year	4	6	8	10	0	0	0	0	200	100	0	0	0	0
1 x per	1 year	5	9	11	14	0	0	0	0	100	50	0	0	0	0
1 x per	2 year	7	11	14	18	1	0	0	0	50	30	9	0	0	0
1 x per	5 year	9	15	19	23	3	0	0	0	20	10	8	0	0	0
1 x per	10 year	11	18	23	27	5	0	0	0	10	5	6	1	0	0
1 x per	20 year	12	21	27	32	6	3	0	0	5	3	5	3	0	0
1 x per	50 year	15	26	32	38	9	8	0	0	2	1	2	2	0	0
1 x per	100 year	17	29	37	43	11	11	2	0	1	1	3	3	0	0
												33	8	0	0
												total spilled			
												41 mm			
												0,4 average mm per year			
												0,05% of annual precipitation (800 mm)			

Figure 25: calculation of type I and II spills for the test site of Holstein Flowers