Performance of different solutions for local water retention

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Abstract

Due to urbanisation and climate change, peak discharges have increased both in size and in frequency. Over the last few years heavy rainfall has shown the necessity of action, with water nuisance and flooding e.g. in the low lying polder areas in the Netherlands, Rhine, Elbe and Danube river basins. To mitigate the effects of urbanisation and climate change, local retention of water is an obvious measure to combat high peak discharges. Retention at the local level is the most effective. While in urbanised areas space typically is scarce and expensive, space designated for retention like ponds are of little economic value.

In Western Europe, most research in the field of rainfall run-off and retention focuses on housing areas. In contrast, this study evaluates different possibilities for water storage at large buildings like factories, office buildings and greenhouses. Roof sizes up to several hectares lead to different technical solutions compared to solutions suited for housing areas, where individual roof sizes are much smaller. Different technological solutions for water storage have different hydrological characteristics. Systematically, water storage possibilities at different places relative to the building (e.g. in, on top of, under and next to) are evaluated as alternatives to surface water storage. Subsequently, the most promising possibilities are compared on technical, cost and legal aspects. Hydrological performance is simulated using a mathematical model. This paper investigates differences, identifies (dis)advantages and proposes solutions for implementation, taking these disadvantages into account. As an example, a case study of a new greenhouse area (about 400 ha) in the west of the Netherlands is used.

Keywords: hydrology, water retention, peak rainfall, surface water, robust, benchmark, greenhouse area, synthetic bag.
1 Introduction

Over recent years, large parts of Europe in e.g. Great Britain, the Netherlands, Germany and Czech Republic suffered from water nuisance and flooding caused by heavy rainfall locally or upstream. Due to climate change [7], rainfall patterns are changing, with an increase of heavy rainfall both in depth and frequency. Moreover, urbanisation and cultivation generally lead to faster run-off processes and an increase in peak discharges. To prevent water nuisance and flooding retention is the most effective locally. In urbanised areas typically space is scarce and expensive. Ponds, canals and other space designated for retention are of little economic value compared to commercial plots. In housing areas local water retention through so-called Sustainable Urban Drainage Systems or SUDS [9], is applied. Large surface waters and infiltration swales offer architectural and environmental values. In commercial zones where water primarily has retention purposes, other values are less important. Alternative forms of water retention may bring efficient solutions to both water nuisance and space usage.

2 Method

In this study [10], local water storage possibilities were reviewed systematically. First, information necessary was gathered resulting in terms of reference: present situation, wishes and demands (e.g. about water quantity and quality). Further, information was gathered on similar projects for benchmarking purposes. Subsequently, locations relative to a theoretical construction site for local water retention were reviewed. In a quick scan, these theoretical possibilities were assessed. The three most promising possibilities were selected for elaboration in a case study. The elaboration consisted of analysis of space use and hydrologic performance review of financial and legal aspects. Finally, performance and possibilities for application of local water retention in general are discussed. This paper concludes with some recommendations.

3 Locations for local water retention

Local water retention facilities should store rainfall temporarily to prevent peak discharge downstream. Water retained will gradually discharge from local water retention facilities. Basically, water can be stored on top of, next to, under or in buildings (see figure 1).

![Figure 1: Locations for local water retention.](image)
1. Water retention in surface waters. Retention in local surface water through limiting discharge capacity causes water level rise. To provide the storage capacity necessary, surface waters including banks and maintenance zones take up substantial space. Excavation and ground transport are relatively costly. Retention in surface water is robust as this principle has a low risk of failure.

2. Water retention beneath buildings. Run-off from impervious surfaces can be stored directly under buildings more spatially efficient than in surface waters. Water retention can be either (2a) open (as an extension of surface waters) or (2b) closed. Closed water retention can be part of building foundations.

3. Water retention in aquifers. Superfluous water is stored underground in an aquifer [1] using pumps. While extreme peak rainfall can be stored in the aquifer, rainfall with a more common intensity has to be stored in surface water or retention facilities. The system cannot be used very frequently to prevent blockage of the injection system. As a consequence, the spatial gain is small in comparison to retention in surface water.

4. Water retention on top of buildings. Through the use of vegetation roofs [8] water can be retained on top of buildings. The retention of peak rainfall requires large storage capacities leading to major constructional consequences, however. Moreover, water retention facilities on roofs can increase damages caused by leakage, increasing risk. In green house areas retention on roofs is not an option.

5. Water retention next to buildings. Two types of water retention facilities next to buildings can be distinguished, water storage basins [11] e.g. applied in greenhouse areas and field retention such as ditches and infiltration fields or ponds. The rainfall stored in basins typically is used for watering crops. The spatial gain of basin-like retention facilities can be significant in comparison to retention in surface waters due to the relatively high storage depths possible. Spatial gain of swales is relatively small; storage depths in these SUDS are comparable to those in surface waters, leading to a comparable use of space.

6. Water retention in buildings. Water retention facilities can be placed inside buildings. Reduction of water retention on the plot implies a more efficient space use. However, in buildings activities have to be adjusted that makes buildings less flexible. Water nuisance caused by system failure is a risk.

Main objective for local water retention in built up areas is to realise sufficient water retention that is space efficient, sustainable, robust and affordable. Surface water is robust and sustainable but relatively space inefficient. Building over water can compensate this disadvantage. Floating buildings are the ultimate form of building over water. Unless a lake already exists however, realising suitable infrastructure takes large investments. Water retention in aquifers is less space efficient than retention in surface water because peak retention in aquifers is designed for peak rainfall with a 10-year return period. The surface water still has to store less extreme rainfall. Retention of peak rainfall in and on top of buildings cannot be combined with commercial activities very well because of flexibility and potential risk of water nuisance. Three locations for local water retention appear the most promising and are elaborated.
3.1 Open water retention beneath buildings

Buildings can be realised over surface water, either fully or partially. Run-off from impervious surfaces is discharged to the surface water. Because of water quality standards only half of the surface water can be built over. Combining functions provides space gains without reducing the necessary water retention capacity. Slopes and maintenance zones partly lie beneath buildings. This layout requires maintenance by boat. Space beneath buildings can be realised as open water or as dry zones that flood with a small water level rise (like a flood plain).

3.2 Closed water retention beneath buildings

Closed water retention facilities can be pervious to infiltrate water into the subsoil or impervious to prevent uncontrolled flow from or towards groundwater. Preventing uncontrolled water flow is necessary when the water stored is to be used in the production process e.g. in greenhouses. Superfluous water is discharged to nearby surface water. A closed water retention facility can be part of the foundation of buildings like concrete basements or located beneath fixed floors using plastic water storage crates or synthetic bags. Water storage crates are plastic building block-like elements that can be easily combined. Flexible synthetic bags typically are used for retention at combined sewer overflows.

3.3 Peak retention in water retention facilities next to buildings

Run-off from impervious surfaces can also be stored in water retention facilities like ponds, basins or tanks next to buildings. To be used space-efficiently, large water level fluctuations inside these facilities should be possible. Peak retention facilities should be available for peak rainfall at all times. Superfluous water is discharged slowly to nearby surface water.

4 Case Rijsenhout: modelling and analysis

4.1 Case greenhouse area Rijsenhout

The greenhouse area Rijsenhout is situated in the west of the Netherlands just south of Schiphol Airport Amsterdam (see figure 2). The total project area is approximately 500 ha, 1 by 5 km, of which a part is reserved for other purposes such as present land use, valuable culture historical objects and broadening of the bordering highway. A total of 326 ha is available for greenhouse development [6]. Plot size varies from 4 to 10 ha. The greenhouse area will be use predominantly for the production of flowers. This means greenhouses will have a solid floor. The design of future greenhouse area Rijsenhout [5] is used as a reference for the water retention designs elaborated. Run-off from greenhouses is
directed to water storage basins that overflow into the surface water system. The basins are located on the plots next to the greenhouses. The land use of the reference design is presented in table 1.

4.2 Benchmarking case Rijsenhout

To position the case study, Rijsenhout compared to seven projects of different types: greenhouse areas, housing areas and commercial zones. The projects vary in size and are located in the lower part of the Netherlands (see figure 2). In table 1 the projects land use and hydrological features are compared.

Figure 2: Location of projects used for benchmark.

Cluster Bergschenhoek [4]. Cluster Bergschenhoek consists of six horticultural companies that share resources and installations. They retain water in basins, tanks and in the aquifer. Superfluous rainfall is pumped into the aquifer to be used in dry periods.

Greenhouse area Rundedal [14]. All greenhouse companies in this project discharge run-off to central water reservoirs. A water company purifies the water and returns the water to a buffer. Each company receives water from the buffer. The purification capacity is about 1.5 million m$^3$ per year.

Greenhouse area Bergerden [12]. The rainfall run-off from the greenhouses is collected in a central water buffer of 4 ha from which all greenhouses draw water. No additional groundwater abstraction is necessary.

Housing area Leidsche Rijn [13]. This large housing area of 30,000 houses is to have a sustainable character. This is pursued a/o through various types of local water retention such as in vegetation roofs, swales and surface water. The Leidsche Rijn water system is designed to be self-supporting in its water need.

Housing area Vathorst [15]. Water has a prominent presence in Vathorst, through superficial run-off and water retention facilities. Water is infiltrated for retention in shallow groundwater.

Commercial zone Robbenplaat [3]. The commercial zone contains swales and ponds for local water retention. The sustainable character is expressed in (a/o) storm water retention and infiltration fields.
Commercial zone Oudeland [2]. This commercial zone is situated between newly developed housing areas and an existing commercial zone. The plan contains much surface water to solve retention shortages in the existing commercial zone.

<table>
<thead>
<tr>
<th>Project</th>
<th>Type</th>
<th>Total surface [ha]</th>
<th>Plots surface [ha]</th>
<th>Percentage open water [%]</th>
<th>Type of soil</th>
<th>Ground water flow [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rijsenhout</td>
<td>greenhouse</td>
<td>470</td>
<td>326</td>
<td>69%</td>
<td>clay</td>
<td>seepage</td>
</tr>
<tr>
<td>Bergschenhoek</td>
<td>greenhouse</td>
<td>24</td>
<td>20</td>
<td>83%</td>
<td>clay</td>
<td>seepage</td>
</tr>
<tr>
<td>Rundedal</td>
<td>greenhouse</td>
<td>300</td>
<td>180</td>
<td>60%</td>
<td>sand</td>
<td>infiltration</td>
</tr>
<tr>
<td>Bergerden</td>
<td>greenhouse</td>
<td>335</td>
<td>217</td>
<td>65%</td>
<td>sand</td>
<td>infiltration</td>
</tr>
<tr>
<td>Leidsche Rijn</td>
<td>housing</td>
<td>2.560</td>
<td>unknown</td>
<td>8%</td>
<td>sand/ clay</td>
<td>both infiltration</td>
</tr>
<tr>
<td>Vathorst</td>
<td>housing</td>
<td>561</td>
<td>unknown</td>
<td>7%</td>
<td>sand/ peat</td>
<td>seepage</td>
</tr>
<tr>
<td>Robbenplaat</td>
<td>commercial</td>
<td>64</td>
<td>46</td>
<td>71%</td>
<td>clay</td>
<td>seepage</td>
</tr>
<tr>
<td>Oudeland</td>
<td>commercial</td>
<td>120</td>
<td>75</td>
<td>63%</td>
<td>clay</td>
<td>seepage</td>
</tr>
</tbody>
</table>

### 4.3 Schematisation

The water system of greenhouse area Rijsenhout is part of a Dutch polder system. Such a polder system exists of one or more controlled water systems. Each water system has a target water level. Pumping stations discharge superfluous water to a retention and transport water system, called ‘boezem’, which eventually discharges the water to sea. During droughts water is supplied from this retention water system. Typically low water levels result in seepage.

With the model, water level rise during peak rainfall is simulated. Rainfall duration curves are used as rainfall input data, evaporation during peak rainfall events is neglected. Due to climate change peak rainfall events increase in size and frequency. To compensate for climate change, the historic rainfall duration curve is increased with 10%. Duration curves have limitations for designing water systems. Considering these limitations, using rainfall duration curves provide a quick-and-dirty solution fitting the general exploratory level of this study. Using rainfall duration curves works well in Dutch practise. The standard for water level rise in the case study is 0.6 m with a 25 years return period, which is about 40% of the difference between average surface water level and field level. Furthermore, water level rise should not increase.

The schematisation of the water system of Rijsenhout in the model is represented in figure 3.
4.4 Hydrological analysis

Model calculations provide insight into water level rise in peak rainfall events. The corresponding land use and surface water is shown in table 2. The surface water system takes up at least 5 ha. The designs with separate water retention facilities show a stronger water level rise than those with retention in surface waters. Figure 4 shows the water level rise for all four designs using the rainfall duration curve (T = 25 years). Calculation of water level rise for the polder water system shows maximum water levels are lower than in the present situation.

Table 2: Input data for model.

<table>
<thead>
<tr>
<th></th>
<th>Impervious</th>
<th>Pervious</th>
<th>Water</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>218.7 ha</td>
<td>78.0 ha</td>
<td>29.3 ha</td>
<td>326 ha</td>
</tr>
<tr>
<td>Open retention beneath buildings</td>
<td>228.5 ha</td>
<td>68.2 ha</td>
<td>29.3 ha</td>
<td>326 ha</td>
</tr>
<tr>
<td>Closed retention beneath buildings</td>
<td>248.9 ha</td>
<td>72.1 ha</td>
<td>5.0 ha</td>
<td>326 ha</td>
</tr>
<tr>
<td>Retention facilities next to buildings</td>
<td>248.9 ha</td>
<td>72.1 ha</td>
<td>5.0 ha</td>
<td>326 ha</td>
</tr>
</tbody>
</table>

The retention behaviours of surface water and retention facilities shown in figure 4 are clearly different. The water level in the case of retention in surface water rises sooner, but total water level rise is than that with retention in facilities. The water surface area increases with water level rise because of the slope of banks. As a consequence surface water contains extra retention capacity on the slopes. In this case the total retention capacity below ground level in the design with retention in surface waters is approximately 390,000 m³ and about 230,000 m³ in the designs with retention facilities.

The minimum required retention capacity is approximately 112,500 m³ at a water level rise of max. 0.6 m. Maximum water levels occur 16 hours after start of the peak rainfall. This matches with a rainfall depth of 60 mm in those 16 hours.

For Dutch polder systems, peak rainfall should be discharged within three days. The necessary pumping capacity for discharging 112,500 m³ in three days is 26.0 m³/min. This is smaller than the installed capacity of 26.7 m³/min. Additionally, discharge from the retention facilities is limited. The local standard
corresponds to 23.5 m$^3$/min. The stricter discharge standards for retention facilities provide an additional safety in the design.

![Figure 4: Water level rise through rainfall that occurs once every 25 years.](image)

An advantage of retention facilities is storage of the first rainfall. In figure 4 the water retention facilities curve initially demonstrates a more or less flat water level in the first hour after start of the rainfall event. During the first hour the retention facilities store run-off from impervious surfaces. Therefore, water level rise is only caused by rainfall directly on surface water. This is the small rise in the first minutes and results in a start of the pumping station. Discharge of the pumping station causes a slight decrease in water level in the second half of the first hour. After approximately one hour the water facilities are filled to capacity and overflow into the surface waters. The strong increase in water level is a result of the relative small surface water area in this design. Retention facilities can solve potential nuisance by reducing peak discharge.

Water use in greenhouses varies with crops, seasons, water quality and so on. Average annual water use in Dutch greenhouses [11] is 7,500 m$^3$/ha or about 20 m$^3$/ha daily. Peak daily water use varies from 60 to 70 m$^3$/ha per day. Average daily water use varies from 20 m$^3$/ha to 70 m$^3$/ha. The foreseen capacity of water retention facilities is 450 m$^3$/ha. Considering the fact that this storage capacity should be available 3 days after an extreme rainfall event, 13% to 47% of the storage volume can be used in the greenhouses in this case study, reducing the discharge from retention facilities to surface water.

### 4.5 Space use analysis

In the case study, locating peak water retention facilities underneath buildings increases the space available for production purposes with approximately 35% compared to the reference situation. The gain in production space is achieved on
one hand through an efficient layout of the area to be developed. The surface water system takes up less space. On the other hand the individual plot can be used more efficiently. A larger percentage of the project area can be sold, which is favourable to both developer and user. A more efficient use of the plot is profitable to future companies. For the other designs evaluated, the gain is smaller but substantial varying from 15% for facilities next to buildings to 20% for open retention beneath buildings. Compared to conventional retention in surface water much space can be gained by using different retention locations instead. The use of retention facilities beneath buildings performs particularly well.

### 4.6 Financial and legal aspects

In the case study, conventional realisation of the greenhouse area according to the reference design has the minimum total investment including all costs. The cost consists mainly of excavations and construction work. The differences in excavation cost between the designs are caused by differences in the surface water system design. Construction costs on the other hand are determined by the total greenhouse surface. The foundation type is not a distinguishing factor. All greenhouses need fixed flours. Different constructions have a similar cost level. The retention facility underneath the floor of the greenhouse, e.g. a synthetic bag, is more expensive.

Considering cost effectiveness, more expensive designs with larger production space perform best. Efficient layouts result in lower costs per m² production space. For industry and commercial zones that do not use water storage basins space and cost gain is probably less. However, synthetic bags beneath buildings with a fixed floor perform best on cost effectiveness. Larger production space results in potential larger revenues.

In the Netherlands water retention at private plots can be registered in different legal documents. The different designs mentioned are comparable legally except for the reference situation. The reference situation has the lowest legal risk. It is possible however, to attain the legal security required through a combination of different legal possibilities.

### 5 Conclusions and discussion

Water retention facilities beneath buildings perform well for peak retention. The more efficient use of space particularly offers possibilities in urban areas with high ground prices. Application of flexible synthetic bags for water storage underneath a floor construction instead of concrete water retention basements is more cost effective. Disadvantage of water retention facilities is their reduced robustness: strong surface water level rises can occur when the retention facility is filled to capacity. Further research using long term observed rainfall data instead of the rainfall duration curves used in this study into the hydrological performance of this solution before practical application is advised. The robustness of the surface water system can be improved outside the water
retention facilities e.g. by increasing the available retention facility volume or by creating relatively low lying areas with a low invested value, like green areas to be flooded first, creating additional water storage capacity below the level where high damages would occur.

References