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# Into the air: a freestanding vertical greenery system (VGS) for evapotranspiration (ET) of roof runoff

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## ABSTRACT

In the search for space-efficient nature-based solutions (NBS) for stormwater management, we designed a vertical greenery system (VGS) for enhanced evapotranspiration (ET). After assessing a range of construction options, an 80 m long and 3.2 m high freestanding stormwater-VGS, referred to as the Green Climate Screen (GCS), was constructed in 2019 in Copenhagen. The GCS receives runoff from 240 m$^2$ of roof top and has a high ratio of surface-to-ground area to allow for the clothesline effect to enhance ET. The conveyance of runoff to the top of the GCS is based on gravitational force. It is estimated that 24 h events with return periods up to the 0.1 y (13.9 mm) are managed by ET, from 0.1 to 15 y (48.5 mm) by infiltration beneath the screen, and from 15 to >100 y by overflow to an adjacent area allowing for aboveground storage (167 mm), in total 229 mm. With the fulfillment of most performance criteria and successful inclusion of selected co-benefits ET-based stormwater, NBS could become future standard elements. To reduce CO$_2$ and resource footprint, steel, concrete, and mineral wool must be replaced with renewable materials. Adaptation to more spatial contexts is encouraged.

**Key words:** clothesline effect, gravity-driven conveyance, Green Climate Screen, nature-based solutions, performance criteria, stormwater-VGS

## HIGHLIGHTS

- Climate adaptation calls for innovative nature-based solutions for stormwater management in dense city areas.
- Vertical greenery systems (VGS) can be optimized to serve as a stormwater management element for roof runoff.
- Stormwater management based on ET can help re-establish natural urban water balance.
- The Green Climate Screen is a full-scale demonstration of a freestanding, ET-based stormwater-VGS sized to manage a 15 y event.

## 1. INTRODUCTION

Nature-based solutions (NBS) for stormwater management such as rain gardens, swales, and permeable pavements are increasingly used as a supplement to conventional pipe-based urban drainage infrastructure which is under pressure from climate change, urban densification, and urban expansion (Fletcher *et al.* 2015; Leng *et al.* 2020; Oral *et al.* 2020). Stormwater-NBS designs have evolved during the past decades, since at least the 1970s, when where German frontrunners developed the modern green roof and swale-trench infiltration systems (Grotehusmann *et al.* 1994) to enhance evapotranspiration (ET) and soil infiltration thereby reducing the direct runoff, overall aiming to re-establish the pre-urban water balance (Henrichs *et al.* 2016; Uhl *et al.* 2016; Berland *et al.* 2017; Zölch *et al.* 2017). Although green roofs play a positive role in urban stormwater management (Francis & Jensen 2017), they rarely provide a standalone solution due to limited capacity of their most popular form – the extensive green roof, e.g. in the case of Denmark a volume reduction of only 18–28% for 0.1–1 y return periods has been found (Locatelli *et al.* 2014). Accordingly, the majority of stormwater-NBS are based on terrain depressions and cavities, since infiltration seems to be the only mechanism that can match the discharge capacity of the conventional grey solutions, typically targeting 2–10 y events, in this way reducing ET to a curiosity in stormwater management. Acknowledging the original ambition of improving the ET-component of the urban water balance and realizing that infiltration-based stormwater-NBS have downsides in terms of land area

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requirement and soil excavation works and further may be obstructed by low hydraulic conductivity, high-standing groundwater, or soil contamination, our goal was to develop an ET-based stormwater-NBS with a small environmental footprint, capable of managing at least the 5 y events. Our idea was to modify the concept of vertical greenery systems (VGS) to provide sufficient storage and ET capacity to qualify as a standalone stormwater-NBS, referred to as a stormwater-VGS.

In recent decades, numerous examples of VGS have emerged (Manso & Castro-Gomes 2015; Bustami *et al.* 2018; Brković Dodig *et al.* 2019; Prodanovic *et al.* 2019b; Ascione *et al.* 2020; Manso *et al.* 2021), however, none with the primary goal of managing stormwater, but rather with a range of goals including urban cooling, greywater treatment, insulation of buildings, biodiversity support, and beautification through greenery, where contribution to stormwater management may be a part (Bustami *et al.* 2018; Perini & Roccotiello 2018; Eriksen 2019; Prodanovic *et al.* 2019a; Ascione *et al.* 2020). The problem with using VGS as a stormwater management element is the same as that of extensive green roofs mentioned above: the ET rate will in many regions be too low to ensure that storage capacity is regained before the next significant storm event may occur (Locatelli *et al.* 2014; Stovin Dunnett & Yuan 2017; Pearlmutter *et al.* 2021). According to the Food and Agriculture Organization of the United Nations (FAO), the maximum daily ET-rates from a lush short-cut well-watered grass field, referred to as a reference crop against which other crops may be compared, range from 1 mm in cold humid climates to 2–4 mm in temperate humid climates and 9 mm in warm arid climates (Allen *et al.* 1998).

In a temperate humid climate such as that of Northern Europe, the depths of critical rainstorms range from 40–70 mm for the 5–10 y events (Madsen *et al.* 2009b; Sørup *et al.* 2016) illustrating that many square meters of ET-surfaces are needed if stormwater runoff is to be removed in a reasonable time (1–3 days) (Jensen *et al.* 2020). Thus to maximize ET in VGS, a more promising approach may be to go from one-sided systems adjacent to buildings to two-sided freestanding systems, allowing for ET to take place unhindered from both sides, thereby doubling the ET surface area, and at the same time activating the ‘clothesline’ effect, where protruding vegetation due to more turbulence and edge effects has a higher ET rate than that of a same-height closed population, e.g. for single stands of trees ET-rates 1.2 to 1.4 times higher than that of a forest stand have been observed (Allen *et al.* 1998). Inspiration for design of two-sided freestanding VGS can be found in vegetated noise reduction barriers, including systems made from planter boxes as well as systems with ground-rooted vegetation, the latter typically being the narrower, and thus the more space efficient (Bendtsen 2010).

Another challenge in converting VGS into freestanding stormwater-VGS is the conveyance of the stormwater from the surface where it is generated to the freestanding VGS. Since pumping of stormwater should generally be avoided due to the increase in $CO_2$ footprint and system complexity, the more obvious approach to conveyance is to use the potential energy of stormwater originating from roof tops. This points to a preferential link between ET-based stormwater-NBS and runoff from buildings, while ET of road runoff is more challenging if pumps are not to be used. Gravity-driven conveyance is in principle simple, but in a climate with winter temperatures below zero the risk of freezing water in the conveyance tubes must be addressed.

Apart from stormwater-related factors, a number of additional aspects need consideration for a freestanding stormwater-VGS to be integrated into the urban spatial context, including safety, maintenance conditions, costs, $CO_2$, and resource footprint, as well as aspects related to neighborhood attractiveness and local stakeholders’ perception of the new structure which inevitably will change the local landscape (Lausen *et al.* 2022). By aiming at providing more services to society, in the form of site-relevant environmental co-benefits, e.g. biodiversity support, health, and amenity values, the chances of providing an acceptable stormwater-VGS increases (Backhaus & Fryd 2013; Frantzeskaki 2019; Sørup *et al.* 2019).

The objective of this study was to document the key experiences and understandings gained through the process of developing and implementing a new form of VGS with specified stormwater performance goals, site-relevant co-benefits and considerations of safety, lifetime of operation, $CO_2$, and resource footprints.

With the GCS now in operation in Copenhagen, it is demonstrated that stormwater management can be based on ET from freestanding VGS without the use of pumps. To our knowledge, this is the first VGS construction designed to perform at a specified storm return period. Furthermore, by describing the implementation challenges, this study advances the knowledge on the development of well-integrated urban stormwater solutions that provide multiple benefits with focus on regaining and enhancing the ET-component of the water cycle in urban areas.

## 2. METHODS

### 2.1. Stakeholder process

Performance goals specification and identification of possible corresponding stormwater-VGS designs followed an iterative process, involving researchers and experts from the fields of landscape architecture, hydraulic and construction engineering, as well as companies providing solutions for stormwater management, urban plantings, and noise reduction. Also, stakeholders, e.g. the Danish Road Directorate, the Municipality of Copenhagen, the water utility company of Copenhagen (HOFOR), the social housing association KAB (Københavns Almindelige Boligselskab), and its residents who took part. The design process consisted of brainstorms, workshops, literature studies, surveys, physical tests, and mock-ups. From project initiation to the construction of the Copenhagen stormwater-VGS, named the 'Green Climate Screen' (GCS), it took 6 y, including an almost 2 y long negotiation and design adaptation period to obtain the construction permit from Municipality of Copenhagen, and a 3-month construction period.

In the iterative design process, many ideas appeared to be dead-ends and will not be reported here, however, a summary can be found in Supplementary Material 1, Additional Material 1: Rejected Ideas and Designs (AM 1). A full project description is available at: https://www2.mst.dk/Udgiv/publikationer/2020/gentagelse.pdf (in Danish).

### 2.2. Case location

The case site for the construction of the GCS was a three-storey residential building and its immediate surroundings consisting of a paved path and a vegetated area with shrubs and sparsely distributed trees (Figure 1). It is located in Valby, a suburb of Copenhagen, facing the Folehaven road, with an average daily traffic of 45,000 vehicles. The local terrain is flat. The GCS was constructed parallel to the building it is serving, at 6–8 m distance, at the cadastral boundary toward the public pavement (Figure 1).

### 2.3. Design considerations

The technical issues and possible design solutions that were considered in the GCS design process are presented in Table 1 together with reasons for adoption or rejection, as further elaborated in Supplementary Material 1, AM 1.

The associated assessment was guided by values relating to NBS research (Raymond *et al.* 2017; Frantzeskaki 2019; Sørup *et al.* 2019; Venkataramanan *et al.* 2020; Pearlmutter *et al.* 2021; Sowińska-Świerkosz & García 2021) and included $CO_2$ and resource footprint (e.g. low energy use in material production and VGS operation, minimum area footprint, minimum soil excavation), economic efficiency (e.g. long lifetime of operation), multifunctionality, local laws and regulations, and aesthetics and recreation (e.g. involvement of inhabitants to create socially acceptable solution). Those values were considered in addition to the primary criteria of stormwater management to a specified return period in a safe way. The definition of co-benefits was based on the framework presented by Raymond *et al.* (2017) and on the classification of services that stormwater-NBS projects can provide by Sørup *et al.* (2019).

## 3. RESULTS AND DISCUSSION

This paper presents the final design of a multi-service freestanding VGS for ET and infiltration of roof runoff, referred to as the GCS. An 80 m long version of this stormwater-VGS design has been in operation in Copenhagen since 2019 (Figure 1). The GCS dimensioning is elaborated in Supplementary Material 2, Additional Material 2: Stormwater Capacity (AM 2), while in Supplementary Material 3, Additional Material 3: Co-benefits (AM 3), the possible co-benefits that were considered in the GCS design process are described.

### 3.1. A stormwater-VGS: a standard solution for the future?

#### 3.1.1. A stormwater-VGS construction

The study resulted in a new type of stormwater-VGS, which is a freestanding vegetation-covered structure that receives runoff from an adjacent building through a gravity-driven conveyance system (Figure 2).

Relying on the principle of communicating vessels, the roof runoff is conveyed to the GCS through pressure tubings (ID 50 mm) mounted 4 m above ground level inside of the four existing downpipes; the tubings run

**Figure 1** | Above: Map of Copenhagen showing the location of the GCS (UTM 55.651, 12.504). Middle: Aerial photo showing the full length of the Folehaven road, with the position of the GCS marked with a red dot (Source: Google Earth Pro ver. 7.3.6.9285; Imagery date: 29 May 2021). Bottom: Aerial photo showing the implemented GCS between the housing area and the public pavement along Folehaven road (Source: Google Earth Pro ver. 7.3.6.9285; Imagery date: 29 May 2021).

below ground and up to the top of the screen (3 m above ground level), where the water is released into a perforated distribution gutter mounted above the screen (Figure 2(b)). The water percolates through the perforations and is absorbed into the vertical mineral wool wall beneath.

**Table 1** | Overview of the stormwater management performance criteria and design options considered for the development of a stormwater-VGS

| | Anticipated performance of a stormwater-VGS | Corresponding design option(s) | Reason for adoption or rejection in GCS |
|---|---|---|---|
| Hydraulic | 1. Provide a storage corresponding to a $T = 5$ y 24 h rain event | (a) Storage built into the VGS<br>(b) **Storage built into the VGS and into additional elements located on the ground**<br>(c) Above or below ground water tank placed at a distance from the stormwater-VGS | Although (a) would be the simplest, increasing the storage capacity in the mineral wool VGS involved increasing the height of the screen (see volume calculations in Supplementary Material 2, AM 2). By placing the mineral wool VGS storage on the top of a planter box, (**b**) adequate total storage capacity was reached. Despite (c) would allow for a narrower stormwater-VGS, the total land use and maintenance would increase and installation of a pump would be needed. |
| | 2. Distribute water evenly over the full length of VGS | (a) Perforated pipes running horizontally inside the VGS at multiple depths<br>**(b) Perforated pipes placed horizontally at the top of the VGS ('distribution gutter')** | Option (a) would allow for water to be supplied equally to vegetation rooted at different depths directly in the storage modules (living wall system), but it was impossible to ensure even distribution of water to pipes at different depths without pumps (Supplementary Material 1, AM 1; Figure 4). With the suggested distribution gutter design, (**b**) the full section of the served stormwater-VGS would receive water simultaneously, however, the top part will always receive the water first, causing restrictions on living wall vegetation schemes. |
| | 3. Convey water from the roof top to the VGS | (a) Pump the runoff from downpipe well to the top of VGS<br>(b) Exploit potential energy of rooftop runoff to transfer water to the top of VGS using gutters suspended in the air to connect roof gutter to top of VGS<br>**(c) Use a below-ground pressure pipe and connected vessels' principle** | With a pump placed in a well at frost-free depth, option (a) allows for stormwater to be pumped to VGS year-round, but at the cost of $CO_2$ and sensitivity to pump breakdown. Although option (b) is simple in construction, aboveground gutters could block-free access of firetrucks, and maintenance could be difficult at that height (Supplementary Material 1, AM 1; Figure 1). Option (**c**) creates an invisible conveyance system, without any restrictions on land-use. To avoid frost damage, drainage of underground parts is needed along with access points for cleansing. |
| | 4. Use transpiration and evaporation to regain storage capacity | (a) Use alive vegetation: trees, vegetated soil dykes, and willow hedges to create the VGS<br>(b) Use transpiration from a living wall type VGS<br>**(c) Use evaporation from mineral wool type noise barriers with planter boxes at the bottom for transpiration and plant establishment** | With a growing VGS, (a) a standard performance from day one could not be guaranteed (Supplementary Material 1, AM 1; Figure 2). Plants need to be of a certain size to obtain required ET potential. While living wall-VGS systems as suggested in (b) are available, they depend on irrigation systems, making a stormwater-VGS highly |

(*Continued.*)

**Table 1** | Continued

| | Anticipated performance of a stormwater-VGS | Corresponding design option(s) | Reason for adoption or rejection in GCS |
|---|---|---|---|
| | | | maintenance dependent. The choice of vegetation would be also difficult due to the required tolerance to shifting water content of substrate. By relying on evaporation **(c)** as the main emptying mechanism, full stormwater service can be guaranteed from day one. Planter boxes provide additional transpiration release but are not the main emptying mechanism. The boxes serve as extra storage and allow for infiltration, and for the establishment of ground-rooted vegetation. |
| Safety and lifetime | 5. Be a safe roadside construction, able to stand local wind loads, and to have a guaranteed lifetime of at least 10 y | (a) Stack planting boxes, made from polyethylene, fiberglass, or galvanized steel (gabions), placed in a galvanized steel frame<br>(b) Use galvanized steel beams with galvanized steel mesh to hold mineral wool in place<br>**(c) Use wooden beams in a steel footing, mounted on a concrete base, with mineral wool held in place by willow panels** | Since (a) required mounting of each box in a supporting frame in order to be stacked to several meters' height, this solution was too complex (Supplementary Material 1, AM 1; Figure 3). While the systems described in (b) and **(c)** are similar to common noise barrier systems, the replacement of steel beams and mesh with wooden beams and willow panels improved both the climate and resource footprints and the appearance of the construction. |

The construction options adopted in the build GCS are marked in bold, while some of the rejected options are described further in Supplementary Material 1, AM 1.

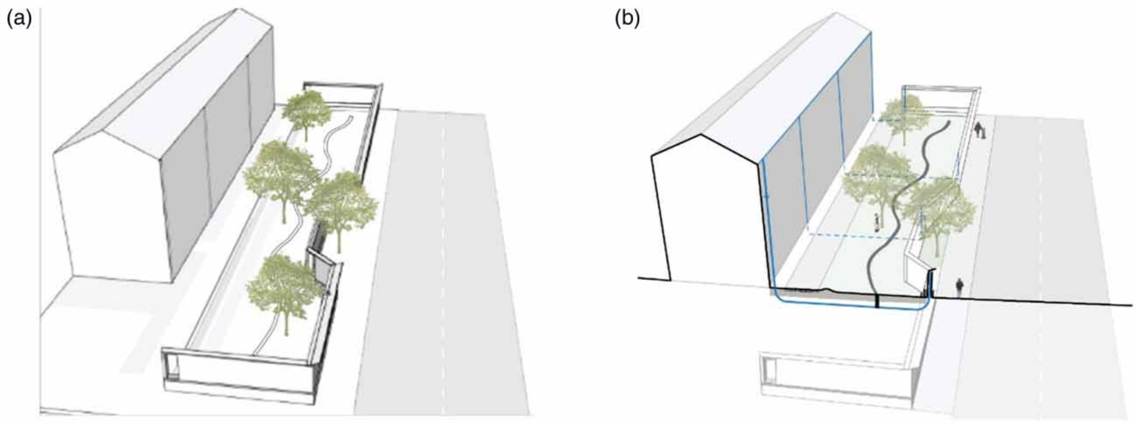

**Figure 2** | 3D drawings of the GCS on Folehaven. (a) The GCS is 3.2 m high and 80 m long, including 8 m of hydraulically inactive window sections. (b) Cross-section showing the water flow from the roof gutter to the GCS.

As seen from Figure 3, the GCS is built from three different types of modules: window modules, water storage modules, and water storage modules with a small green roof. All modules are carried by beams of hardwood (*Robinia pseudoacacia*) that are mounted on a steel footing inserted into a concrete block placed in the ground. Water storage is provided by slabs of mineral wool positioned between the beams, resting on a horizontal

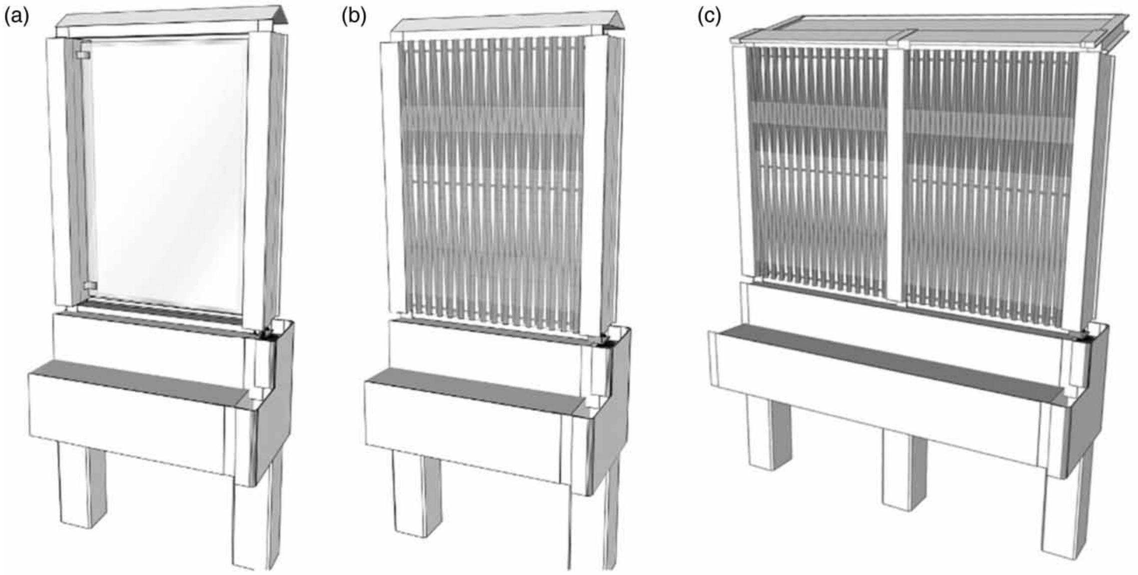

**Figure 3** | Drawings of the three module types used to construct the GCS. (a) Window module with see-through plates mounted directly on the beams, (b) mineral wool module, and (c) mineral wool with green roof module. Modules (a) and (b) are 1.5 m wide, while module (c) is 3 m wide. All three elements are equipped with a planter box at the bottom.

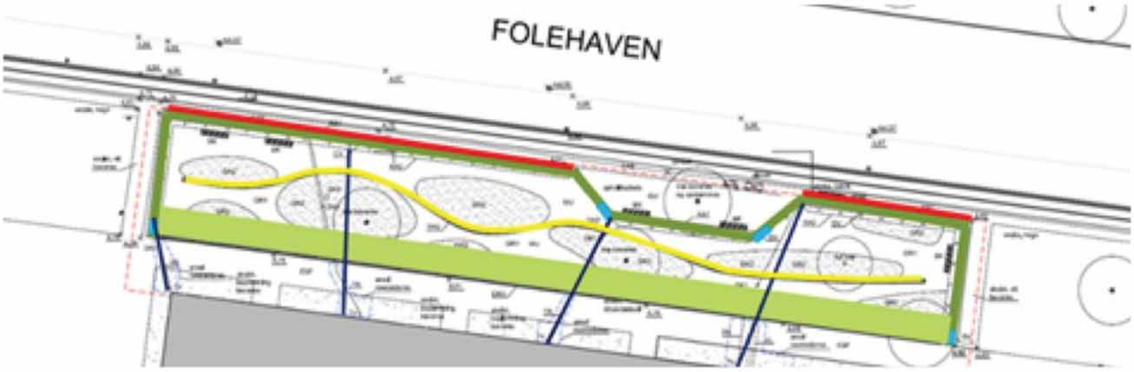

**Figure 4** | Plan view showing where the three modules are used. Blue: Window modules (see Figure 3(a)); Dark green without red line: Mineral wool modules (see Figure 3(b)); Dark green with red line: Mineral wool module with green roof (see Figure 3(c)). The light green area is a grass swale that receives runoff from the paved path next to the building. The yellow meandering line marks a gravel-filled infiltration trench in the green area. Circles mark trees and meadow vegetation as explained in Supplementary Material 3, AM 3.

steel bar, and covered by panels made from willow sticks. The wool used is a dual-density wool (Rockwool) delivered in slabs of $(L, W, H)$ $1.5\ \text{m} \times 0.16\ \text{m} \times 0.12\ \text{m}$, with the lower 0.02 m consisting of higher density wool, which is placed downwards (Supplementary Material 2, AM 2). The green roof is constructed from an iron mesh equipped with a plastic plate, with substrate and sedum on top.

Furthermore, at the bottom of each module, there is an additional storage element in form of a planter box, open at the bottom. The planter box is made from 3 mm iron plates inserted vertically 0.1 m into the ground, mounted on the wooden beams and filled with a green roof substrate (Taghavejord® https://www.zinco.dk/media/Taghavejord.pdf) and planted with different species (Supplementary Material 3, AM 3). Placing of the modules can be seen in Figure 4.

### 3.1.2. Stormwater-VGS dimensioning

The GCS manages the stormwater in a mineral wool wall allowing for storage and evaporation, supported by a planter box for further storage, infiltration, and ET.

The initially targeted stormwater management return period, $T$, for the GCS was $T = 5$ y (Table 1), however, the final design is likely to exceed this service level significantly. Based on Danish rainfall statistics (Madsen *et al.* 2009a) with critical storms mainly occurring in the summer period, a maximum emptying time of 72 h, and a number of assumptions as explained below, it is expected that the GCS in Folehaven can manage all runoff from the 240 $m^2$ large roof area it is serving up to the $T = 15$ y 24 h event (corresponding to 62.4 mm), with the mineral wool wall storing and evaporating the first 12.5 mm rain depth ($T = 0.1$ y), and the planter box to additionally evapotranspire 1.4 mm and infiltrate 48.5 mm (details in Supplementary Material 2, AM 2). In this calculation, the following is assumed (as further explained in Supplementary Material 2, AM 2): a water storage capacity in the mineral wool of 0.13 ($m^3/m^3$), a summer evaporation rate from the mineral wool wall of 10 L/$m^2$ per day (5 L/$m^2$ per day from each side), a water storage capacity of 0.40 ($m^3/m^3$) in the planter box, an ET rate from the planter box of 3 L/$m^2$ per day, and an infiltration rate into the soil beneath the planter box of $10^{-6}$ m/s.

In the specific case of Folehaven, the GCS has the option of overflowing to an aboveground basin (Figure 5(a)), made by circumventing the adjacent green area with a 0.3 m high dike (providing a storage volume of approximately 90 $m^3$) whereby another 167 mm of rain, including direct rainfall on the area, can be managed, lifting the total service level of the system to a hypothetical level exceeding $T = 100$ y. The gravel-filled trench (Figure 4) serves to enhance water distribution and infiltration when the aboveground basin is in use.

Although the constructed GCS meets the water storage requirement, the capacity of the mineral wool part in stormwater-VGS may be of concern, especially when stacked. In case of the GCS in Copenhagen, the main storage capacity is provided by the planter box (11.6 $m^3$) with only 3 $m^3$ provided by the 2 m high mineral wool wall. As explained in Supplementary Material 2, AM 2, the mineral wool seems to be susceptible to what may be referred to as a ‘stacking effect’, causing the storage capacity of mineral wool slabs to decrease with stack height. According to laboratory tests, this effect is responsible for the water holding capacity to drop from 6.4 g of water per g of dry wool in non-stacked wool to 2.9 g of water per g of dry wool when stacked to a height of 2 m, in both cases with high-density wool facing downwards and after 24 h of drainage (Supplementary Material 2, AM 2). Materials that can outcompete mineral wool in terms of water holding capacity, structural features, and durability, especially resistance to microbial mineralization in the moist aerobe environment of a stormwater-VGS, are not easy to identify. Côrtes *et al.* (2019) evaluated shredded cork insulation boards for use in VGS systems but found a water holding capacity of 20 kg/$m^3$ (Côrtes *et al.* 2019, 2021), which is much less than the 130 kg/$m^3$ observed for the mineral wool used in the GCS, and gave no estimates of lifetime.

Granting that most of the water holding capacity of the GCS is provided by the planter box, the impact of the ET mineral wool wall is still significant, both in terms of capacity (12.5 mm), and in terms of improvement of water balance since 24 h rainfall less than this depth comprises 90% of the annual precipitation, based on recorded daily rainfall from 1983 to 2012 (NOAA 2022). Thus, most of the roof runoff will evaporate, and infiltration beneath the planter box will only occur a few times per year. Furthermore, compared with the extensive green roof stormwater storage mentioned in the Introduction (max. 28% of 24 h duration event with 1 y return period, corresponding to 9 mm), the GCS can store six times more.

The capacity of the conveyance system was verified in a full mock-up prior to construction, mimicking the real heights and distances, and using a flow rate of 3.5 L/s, which exceeds the highest 10-min duration rain intensities in Denmark of 1.92–3.12 mm/min (corresponding to flow rates from 60 $m^2$ of roof of 1.92–3.12 L/s) observed in the period 1999–2019 (Cappelen 2020). To avoid frost damage of the conveyance system, each pressure tube is equipped with a valve (not shown in Figure 2) that allows for emptying of the tube at a slow rate (approximately 1/10 of the flow rate in the tube) into the gravel-filled infiltration trench (Figure 4).

### 3.2. ET as a hydraulic mechanism in stormwater-NBS

The removal of stormwater in the presented stormwater-VGS system is based partly on ET, which is a hydraulic mechanism not previously relied upon in stormwater management (Prenner *et al.* 2021). ET capacity is correlated with the size of the evapotranspiring surfaces. Compared with green roofs and VGS systems on building facades, a freestanding VGS allows for ET from both sides and thus to allow for clothesline effect to become active, as explained below. Surfaces for ET were incorporated in the GCS as the double-sided mineral wool wall and the surface of the planter box. Compared with the roof area that the GCS is serving (240 $m^2$), the ET surface area of the GCS is estimated to be 362 $m^2$ (the two sides of the mineral wool wall and the vegetated surface area of the planter box), while the GCS ground area footprint is 73.6 $m^2$. Thus, the ET surface area has been

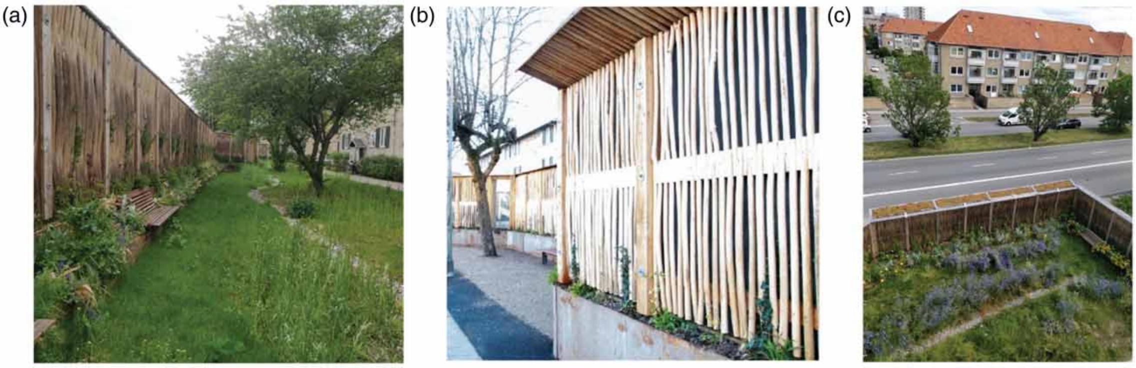

**Figure 5** | Photos of the GCS in Folehaven. (a) From the inside, 2 y after construction, showing the building and the GCS, and the recreational area (aboveground basin) in between. The gravel-filled infiltration trench is also seen. (b) From the roadside, a few months after construction, showing the willow panels, public resting place, and window panel. (c) From above, 2 y after construction, showing the corner side of the GCS placed next to the road, and one of the benches on the inside.

increased 4.9 times via use of the vertical dimension. In general, this surface-area-to-ground-area ratio of almost five in the present case may represent a useful indicator of ET efficiency in stormwater-VGS – the larger this ratio the better.

The mineral wool modules (Figure 3(b) and 3(c)) allowed not only for profiting of the vertical dimension but also double-sided ET from the freestanding element, which accommodates the 'clothesline' effect. An indication of the potential for the clothesline effect in case of stormwater management has earlier been mentioned by Brix & Arias (2011) in their study on wetlands, and by Stovin *et al.* (2017) in case of rain gardens, yet none of the studies provides observed values for the 'clothesline' effect. The estimations of ET potential of GCS in the current study used an ET rate of 5 mm/d (Supplementary Material 2, AM 2). This rate might seem high compared with the Danish yearly average of actual ET of 582 mm, or 1.6 mm/d, recorded during the years 1990–2000 (DMI). However, the highest ET-rates reported for Danish vegetation are 1,200–1,500 mm per year as documented for wind-exposed willow stands used for treatment of domestic wastewater, with maximum rates between August and October. Excluding the winter period, these values correspond to daily ET-rates of 5.6–7 mm, or 2–3 times as high as the FAO turf grass reference (Allen *et al.* 1998). Therefore, the ET rate used in calculations appears valid when acknowledging the clothesline effect. Furthermore, in case of stormwater-VGS, also the 'oasis effect' (Allen *et al.* 1998) may enhance ET compared with ET of neighboring surfaces. This effect is observed where vegetation has higher substrate moisture than surrounding vegetation, reflecting a better water supply, which will in general be the case of stormwater-VGS. The 'oasis effect' also can contribute to the larger consideration on the microclimatic changes that the vertical element can induce in the local environment including a cooling effect provided by ET and shading (Zölch *et al.* 2016).

According to the estimates presented in Supplementary Material 2, AM 2, the 72 h evaporation volume of the mineral wool wall exceeds its storage capacity, i.e. more could be evaporated if the storage was increased. For this reason, the process of infiltration into groundwaters remains the main hydraulic mechanism for higher return periods. The planter box contributes little to the ET but has a high storage and infiltration capacity as its calculated 72 h infiltration capacity exceeds its storage capacity (Supplementary Material 2, AM 2 paragraph 1.4). Also, there is uncertainty regarding this evaporation volume estimate since the ET rate depends on the amount of available water which will gradually be depleted as the wool dries up (Bougoul *et al.* 2005; van de Wouw *et al.* 2017; Pérez-Urrestarazu *et al.* 2019).

### 3.3. Considerations of safety, lifetime of operation, and climate and resource footprints

A freestanding stormwater-VGS placed in a streetscape must meet a high standard of safety to avoid accidents if collapsing. Multiphysics analysis using the Comsol Multiphysics® version 5.6 from Comsol AB simulation program was performed to ensure appropriate statics of the GCS assuming fully water saturated conditions and a maximum wind speed of 23 m/s.

To ensure a long operating lifetime, mineral wool was chosen as a structural storage material. It is mainly made from volcanic rock and practically non-degradable. The steel footings used to mount the wooden beams on concrete pillars (Figure 3) and other metal parts were galvanized (hot-dip zinc 60 my-m) preventing corrosion for at least 10 y. Wood decay was controlled by using hardwood *Robinia pseudoacacia* for beams and a willow (*Salix viminalis* × *Salix schwerinii*) panel construction method allowing the panel material made from 5 to 7 cm diameter poles to dry up after rain (no substrate contact) thereby preventing fungi attack, resulting in a lifetime of at least 37 y according to the provider.

As for many of the existing VGS (Manso *et al.* 2021), there are still considerations regarding cost of implementation and lifetime of operation, especially considering the use of heavy $CO_2$ footprint materials. The life cycle analysis (LCA) for VGS systems that were studied so far indicate that stainless steel used in support systems of VGS constructions have 10 times higher environmental burden than supporting structures constructed of recycled plastic or hardwood (Pearlmutter *et al.* 2021). Considering this, the GCS used steel elements only when necessary for safety reasons to provide enough static strength. Since the freestanding VGS element, especially when located next to the road, needs more support than building-attached VGS, this was considered as a compromise for providing more ET potential. The use of mineral wool as a storage component can be controversial from the sustainability standpoint as this material has been produced with high energy consumption (Beccali *et al.* 2003), hence having a high $CO_2$ footprint in the production process. Although organic materials like coconut fibers, seaweed, wooden chips, etc., would have the advantage of being renewable, their gradual degradation, and subsequent compaction would require regular refilling, making the maintenance challenging and costly (Pérez-Urrestarazu *et al.* 2019). A green-roof type substrate consisting of crushed tiles mixed with compost was tested in two types of living wall-VGS, made from either gabions or an A-shaped wooden structure, lined with geotextile for holding the substrate in place, and cut open to allow for greenery in the form of plug perennials (Supplementary Material 3, AM 3; Figure 2). In both configurations, significant compaction of substrate was observed. Compared with organic materials, mineral wool has a longer lifetime and a higher porosity, minimizing the required size of the storage compartment.

### 3.4. Stormwater-VGS applicability and co-benefits

The GCS now in operation in Copenhagen is one of a number of possible outcomes of the listed project criteria, local characteristics, and local requirements (Supplementary Material 3, AM 3), therefore with other pre-conditions the GCS could have reached another form. As such, some of the design choices that were made are not general but specific to local conditions, e.g. the 3 m height, or the length and shape of the screen, as well as the sizing of stormwater volume based on the disconnected rooftop size (Table 1). However, a strength of the presented solution lies precisely in its adaptability to the local conditions. The final construction is based on the modular technique of fixed-in-place panels that are mounted in the ground with minimal attachment points, resulting in minimal earth work. This allows for variability both in the vertical surface or lengthwise, e.g. the height of the panels can be lowered or heightened to required parameters, and modules can be easily reproduced and modified according to changing uses and functions. A modular approach is also an often-chosen solution within the research on innovations in living wall systems (Serra *et al.* 2017; Castellar *et al.* 2018). The adaptability of the design indicates a potential for stormwater-VGS based on ET to be placed not only in streetscapes but as stormwater elements next to buildings, in suburban gardens or in industrial sites.

To compensate for the loss of existing benefits such as degradation of habitats and spaces for recreation and to provide benefits that may easily be obtained in conjunction with the new structure, the GCS design targeted co-benefits related to socio-cultural values, enhanced biodiversity, and improved health through noise reduction, local cooling, and air quality improvement (Supplementary Material 3, AM 3). As detailed below, some of the co-benefits influenced the stormwater management component.

With a position next to a busy road (Figures 1 and 5(c)), the design target second to stormwater management was noise abatement. Simulations of noise reduction conducted with software SoundPlan, version 6.5 by Delta (Supplementary Material 3, AM 3) following a 3 or 4 m high VGS indicated that a 3 m high screen would be sufficient if equipped with a small green roof formed as a cap facing the noise source (Figure 5(b)) and serving purposes of aesthetic too. To ensure noise reduction, the VGS should have a bulk weight of at least 15–20 $kg/m^2$ (Miljøstyrelsen 2007), be free of voids or gaps, and preferably be made from sound absorptive rather than reflective materials which were the case (Supplementary Material 3, AM 3).

Another important influence on the hydraulic design of the VGS was the addition of the window modules (Figure 3) as a part of the cultural co-benefit (Supplementary Material 3, AM 3 paragraph 1.1). This modification reduced the total water storage capacity of the screen by 1.5 $m^3$, corresponding to 10% (Supplementary Material 2, AM 2).

By introducing the planter boxes, also as a cultural benefit increasing the aesthetic appearance of the screen, the overall stormwater storage capacity was tripled, from 3 to 14.6 $m^3$ (Supplementary Material 2, AM 2). The planter boxes further enabled a more diverse vegetation scheme with focus on native species to support biodiversity (Supplementary Material 3, AM 3). As the vegetation cover increases, ET and subsequently local cooling is expected to improve, as is air quality by deposition of particulate matter on the leaves (Supplementary Material 3, AM 3). Vegetation will also protect the willow construction from degradation due to blocking of direct sunlight.

The importance of this study lies in the fact that it describes not only the technical components of a multifunctional stormwater-VGS but focuses also on analyzing the real-life consideration on the integration of stormwater management into VGS and considers how the co-benefits influence the technical aspects and each other (Supplementary Material 3, AM 3). This is a novel approach that is in line with the current NBS development guidelines (European Commission *et al.* 2020). Despite that, the idea of using vertical surfaces for stormwater management is not new (Ascione *et al.* 2020), yet according to Prenner *et al.* (2021) even though the introductory concept of stormwater-VGS is often mentioned in the literature, only a handful of studies presents details on their practical implementation (Bustami *et al.* 2018; Brković Dodig *et al.* 2019; Prenner *et al.* 2021). In contrast to those cases, our study focused on the fact that the VGS are part of the urban structure and can be developed to service multiple benefits (Lähde *et al.* 2019; Venkataramanan *et al.* 2020; Pineda-Pinto *et al.* 2022).

The performance goals and the design options for the freestanding stormwater-VGS (Table 1 and Supplementary Material 3, AM 3) show how influential the human-related factors were on the final design and outlook. While the freestanding GCS avoided issues with fear of building damage caused by vegetation or water often mentioned in studies on VGS (Magliocco 2018), especially influential on the final design were the concerns regarding the height of the screen and its reference to the feeling of personal safety as well as shading of the surrounding area (Supplementary Material 3, AM 3). These concerns were not earlier addressed in VGS, mainly because they are usually considered as an attachment to the building and not a separate structure.

## 4. CONCLUSION

By reversing the stormwater storage orientation from horizontal to vertical, the spatial footprint and earth work of stormwater-NBS can be minimized, and similarly to other VGS, stormwater-VGS can offer a range of additional ecosystem services. In contrast to conventional NBS for stormwater management, the GCS presents the advantage of being applicable in cases where infiltration-based stormwater-NBS is not an option, e.g. due to low hydraulic conductivity, soil contamination, or shallow groundwater, and with the gravity-driven conveyance system, it operates at zero energy cost.

For practitioners, the GCS holds the potential of being modified to existing site conditions and a variety of design expressions can be developed depending on the local conditions, which makes the design a viable alternative to conventional NBS.

Further research should include an LCA focusing on the materials used for GCS construction, as well as an investigation of more climate and resource-friendly alternatives to concrete, steel, and mineral wool. Research on minimizing the 'stacking effect' of the mineral wool or identification of alternative materials for water storage is needed too. Additionally, the use of vegetation to add transpiration as a mechanism on the evaporative module should be further elaborated as should studies on the public perception of freestanding stormwater-VGS structures in urban landscapes.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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