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Vertical Retention Bodies for Rainwater Retention and Microclimate Improvement — Proof of Concept

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Vertical Retention Bodies for Rainwater Retention and Microclimate Improvement — Proof of Concept

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Abstract

This study examines the use of vertical retention bodies for water retention in urban areas. The growing challenges of climate change and its impact on the hydrologic cycle are bringing increased attention to the management of heavy rainfall events and the reduction of the urban heat island effect. The "sponge city" concept offers solutions for local water storage in urban areas as a contribution to climate adaptation. This paper addresses the largely untapped potential of vertical systems and presents a proof of concept for a vertical water storage system. An experimental setup is presented to investigate the water storage capacity of vertical retention bodies using two storage substrates (perlite and vermiculite) with the aim of storing the water accumulating on the roof in the vertical retention body. Under heavy rainfall conditions, maximum water storage capacities of up to 194% for perlite and up to 250% for vermiculite were determined. The findings were then assessed to determine the potential for using retention bodies on building facades. This proof of concept demonstrates the application potential of vertical retention bodies as one component of the sponge city concept. The retention bodies contribute to water storage during heavy rainfall events, the cooling effect of water evaporation and the preservation of the local water cycle.

Keywords: vertical water sponge; urban water cycle; heavy rainfall; sponge city; rainwater management.

Introduction

Need for climate adaptation

Anthropogenic greenhouse gas emissions and the resulting global warming are currently at their highest level in history. This leads to an increase in extreme weather events, especially periods of heat and heavy rainfall (IPCC, 2021). In addition, global warming causes a shift in seasonal precipitation and increases the amount of water vapor in the atmosphere. Because warmer air can absorb more water vapor, the individual components of the water cycle increase. A 1°C increase in air temperature is equivalent to a 7% increase in water vapor absorption (IPCC, 2017). This increases convection, which is predicted to affect the intensity of heavy rainfall events. The associated extreme rainfall can cause disruption and flooding, especially in densely built and heavily

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sealed urban areas (Stadtentwässerungsbetriebe Köln, 2018). This is also reflected in the increasing number of flood disasters, up 134% since 2000. In the same period, the number and duration of droughts increased by up to 29%. According to statistical surveys, floods are the second most frequent cause of damage due to natural disasters, after storms. Around a third of the overall economic damage is due to flooding caused by river floods and wet storms. These river floods affect the sewer system, which is supposed to drain rainwater from urban areas into the rivers (Stadtentwässerungsbetriebe Köln, 2018).

The German Meteorological Service (Deutscher Wetterdienst, DWD) has three warning levels for heavy rain. The levels are differentiated according to one-hour or six-hour thresholds. The first warning level is triggered at 15 to 25 l m^{-2} per hour and referred to as "heavy rain", escalating to "extremely heavy rain" in case of rainfall of more than 100 l m^{-2} per hour (Deutscher Wetterdienst, 2023a). At these rainfall rates, the volume flow in a combined sewer system can be more than 100 times the volume of wastewater in dry weather. Such water volumes exceed the capacity of many sewer systems and wastewater treatment plants. As a result, the wastewater may not be treated properly (Institut für internationale Architektur-Dokumentation GmbH & Co. KG; München, 2007). In case of heavy rainfall, the capacity of the sewer system is far from sufficient. In the future, it will be necessary to develop ecologically and economically efficient adaptation measures to cope with changing levels of precipitation. However, dealing with rare heavy rainfall events cannot be left to public drainage systems alone. Expanding sewer systems to cope with extreme rainfall events would offer neither operational nor economical benefits. While the costs of a sewer system expansion would be prohibitive, it would also be unlikely that the urban drainage infrastructure alone would be enough to cope with rare and exceptionally heavy rainfall events, despite these preventative measures (Maniak, 2016).

Urban areas are particularly susceptible to extreme weather events due to the high density of buildings and infrastructure with sealed surfaces. VanWoert states that a city block has more than five times the runoff volume compared to a similar piece of woodland (VanWoert et al., 2005). Cities must therefore develop integrated, forward-thinking strategies to adapt to climate change. The German Adaptation Strategy and the European Commission's White Paper on the Future of Europe call for studies on the health risks associated with heat exposure and extreme weather events, especially for urban centers. Therefore, today's city planners need to start thinking now about how climate change will affect the coming decades (Deutscher Wetterdienst, 2023b). By mid-2023, approximately 57% of the world's population lived in cities. This is expected to increase to 60% by 2030 and around 70% by 2050 (Statistisches Bundesamt, 2023) (Umweltbundesamt, 2023). In Germany, around 77.7% of the total population lived in urban areas in 2022 (The world bank, 2023). With conventional construction methods, this leads to ever denser urban development and an ever higher degree of surface sealing. Sealed urban surfaces stop water from infiltrating the soil, leading instead to complete runoff. In the event of heavy rainfall, sewer systems and rivers cannot take in the water efficiently, increasing the risk of flooding.

Around 45.1% of settlement and traffic areas are currently sealed, i.e., built up, covered in concrete or asphalt, paved or otherwise hardened. In addition, an area of 56 ha is converted from uncultivated land to settlement and traffic areas each day. Despite a slight decrease in recent years, current land use is much higher than the sustainability target set by the German federal government. The German government aims to reduce land use to below 30 ha per day by 2030 (Umweltbundesamt, 2022). Limiting land use means using existing settlement areas more efficiently or unsealing them. This would allow planners to achieve the competing objectives of creating more living space while reducing land use. The goal for the future is a more sustainable use of land as a resource with no new land use at all by 2050. This applies both to Germany and Europe as a whole (Mann et al., 2020). However, factors such as the high price of land make it difficult to unseal land and create new green spaces (Mentens et al., 2006). The cost of unsealing land is high, and restoration of natural soil structure is not guaranteed (Umweltbundesamt, 2023).

Evaporative cooling in urban areas

Urban rainwater management has traditionally focused on drainage and retention. More recently, evaporation has emerged as a new aspect to consider. The traditional approach is characterized by terms such as rainwater disposal and runoff storm water management. In this context, "runoff losses" is a symptomatic term for non-draining rainwater. Up to now, evapotranspiration has only played a minor role in sewer system models regarding runoff curve numbers (Sieker et al., 2019). Due to the lack of vegetation, urban areas have a low latent heat of vaporization. In a study from 1999, Kondoh and Nishiyama showed that evapotranspiration in Tokyo had decreased by 38% between 1972 and 1995 (Kondoh & Nishiyama, 2000). Urban development reduces convective heat dissipation and transfer through wind. In addition, typical thermal properties of building materials in urban areas such as low air permeability and heat storage capacity also contribute to rising temperatures. It is believed that air pollutants such as aerosols, which are common in polluted urban areas, can absorb and then re-emit long-wave radiation. This prevents radiative cooling of surfaces, creating a sort of pseudo-greenhouse effect (Memon et al., 2008). Increasing urbanization with the associated reduction in vegetation and natural soil leads to a reduction in evaporation at a local, regional and national level. This can trigger a chain reaction of reduced precipitation, which then does not evaporate either. A change in the natural small water cycle can thus lead to a local and regional increase in temperatures (Senatsverwaltung für Stadtentwicklung, 2010). Water evaporation can offer significant cooling potential. Water as a medium transfers more latent energy than any other element: 2,454 kJ kg^{-1} (0.682 kWh kg^{-1}) of energy is required for water evaporation at 20°C (VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen, 2013). From a global point of view, evaporation is the largest energetic component in the conversion of solar radiation. On average, 75% of rainwater evaporates from earth's landmass. From a water management perspective, evaporation of rainfall should therefore be considered an important factor in addition to runoff and infiltration (Senatsverwaltung für Stadtentwicklung, 2010).

Sponge city

City planners are especially discussing the sponge city concept, which can be a solution for water-related and microclimate challenges (see Fig. 1) for urban spaces, consisting of reduced water runoff combined with improved water quality. Further benefits include improved local water storage and reduced greenhouse gas emissions (Nguyen et al., 2019). In addition to maintaining and expanding the separate sewer systems, targeted design of surfaces to make them more resilient against heavy rainfall events are being considered, requiring concerted efforts by city planners, designers of open spaces and traffic planners. Key elements of the sponge city concept include the creation and use of infiltration and buffer areas, which reduce stormwater runoff after heavy rainfall events and increase evaporation and latent cooling during heat waves (Leistner et al., 2018).

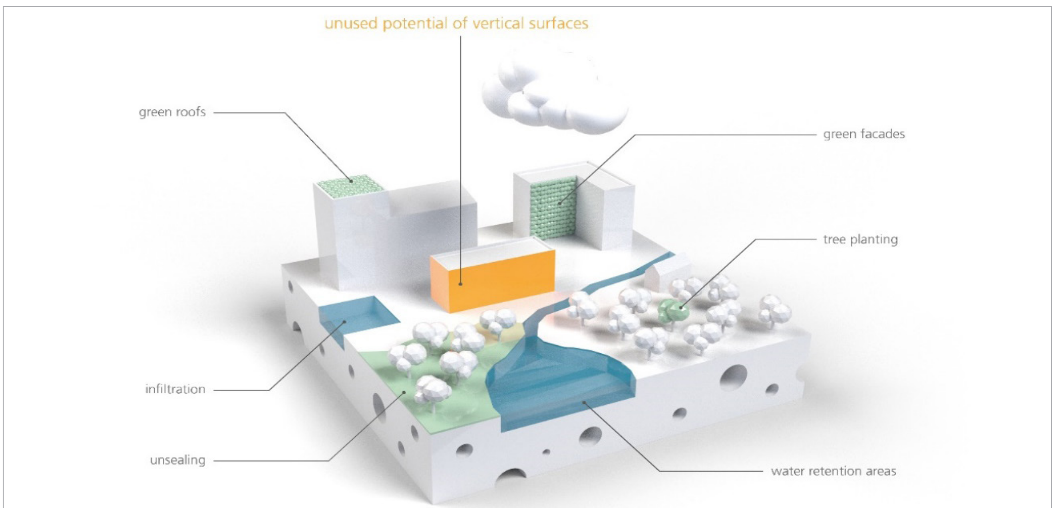

Fig. 1

Elements of the sponge city concept

For example, the current guidelines of Cologne's urban wastewater drainage operation (Stadtentwässerungsbetriebe Köln, StEB Köln) call for the full utilization of the potential of storm water management on the surface. Intermediate storage in retention bodies such as storage swales and runoff drainage via the sewer system or other structures should only be considered as a second step (Stadtentwässerungsbetriebe Köln, 2018). This underlines the necessity of including buildings when looking at rainwater management. Using underground swales, however, means losing out on all evaporative cooling. It is important to identify measures that keep water where it is generated instead of draining it underground. Creating urban green spaces is one measure that can be deployed to utilize ecosystem services. Ecosystem services cover a number of effects, including evaporative cooling, shading and rainwater infiltration as well as reduced heat stress and increased rainwater retention. These green infrastructures support strategies for livable and climate-neutral cities by enhancing the quality of open spaces (Linke et al., 2022).

Water retention in the context of buildings

Retention roofs or green roofs can help to store water on the roof. The depth of the medium used, i.e., the substrate layer, and the roof incline play a key role here. Medium depths of < 10 cm can achieve runoff curve numbers of 0.5 and depths of > 10 cm can achieve runoff curve numbers of 0.3 (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., 2005). While up to 95% of the rainwater can be retained at low rainfall levels (< 10 mm), only 20 to 60% can be retained at higher rainfall levels (> 100 mm) (Kruse et al., 2017). In modern urban areas with tall buildings, the proportion of facade areas is significantly larger than the proportion of roof areas. Roofs of large buildings used as roof gardens or for photovoltaics are often no longer available for water collection. In such cases, building walls can offer an alternative option for rainwater use. In 2017, Van de Wouw et al. found that green facades have a retention potential that is similar to that of green roofs. An experiment was set up to test two living wall systems, one panel system and one plant box system, for a period of two months. Both systems were able to catch and store precipitation, but the plant box system turned out to be superior due to its horizontal surface area and substrate-based water storage capacity. Rainfall of more than around 13 millimeters exceeded the storage capacity (van de Wouw et al., 2017).

The water retention capacity of green facades is an important aspect that is still in need of optimization. This is the only way to reduce the need for irrigation during dry periods and possibly cover it completely with rainwater. In 2017, Huchzermeier et al. examined the runoff curve numbers and runoff delay of green areas. The examination included horizontal and vertical greening system with various substrate layer thicknesses and vegetation types. The results showed that vertical greening systems exhibit a significantly higher runoff delay than horizontal systems. The runoff curve numbers of roofs were compared with DIN 1986-100, which contains average and peak runoff numbers. Currently, no standards contain information for facade greening systems. DIN 1986-100 specifies average runoff curve numbers of 0.3 and peak runoff curve numbers of 0.5 for test specimens with the same incline and substrate thickness (Huchzermeier et al., 2021).

Adaptive facades can increase water retention by using the available space on high-rise building enclosures and thus counteract the urban heat island effect. These facades also influence the heat exchange between the building and the surrounding environment and have to be taken into account for optimal room air-conditioning (Rentz et al., 2022). An important factor in this regard is that these facades must enable decentralized vertical retention of rainwater (Hvejsel & Cruz, 2022).

The concept in this study is to use vertical retention bodies to store the rainwater falling on the roof. The harvested water is then intended to be stored in a vertical retention body instead of tanks for building use. The core of this retention body consists of a mineral-based substrate with a high specific surface area and water retention capacity to maximize water use for runoff minimization and subsequent evaporative cooling. The aim is to collect rainwater on the building in a vertical system in order to relieve the strain on the sewer system, reduce flooding and promote the local water cycle.

Experimental approach

The experimental setup used to test the retention modules is shown in **Fig. 2**. Water (simulating rainfall) is applied from an 80-liter water collection tank filled with municipal drinking water (Oberhausen, Germany) by means of a pump. Water is fed into a regulating and distribution unit through a valve system that sets a defined flow rate. The water is then transferred from this unit to the retention module.

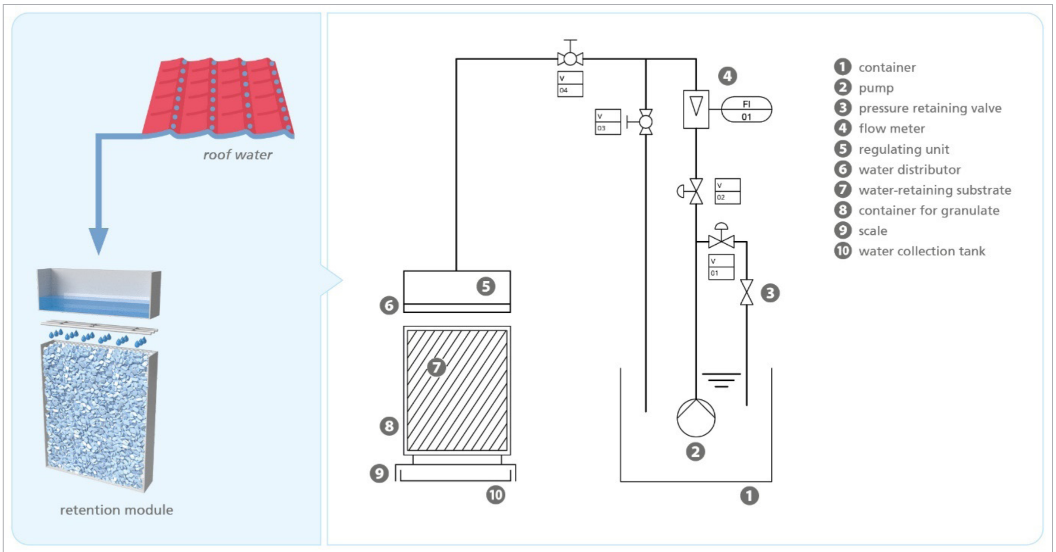

Fig. 2

Structural diagram of the experimental setup to apply water to the retention modules

Three different retention modules (with a volume of 100 liters each) with different geometries were used (see **Table 1**) to examine the water storage characteristics as a function of their spatial dimensions and cross-sectional area. The retention modules consist of an aluminum frame closed off on all sides with watertight panels. The base of the retention modules is connected to the frame and not watertight to allow water, which can no longer be retained in the retention module during the test, to escape downward.

Table 1

Dimensions of the retention modules used

Retention module	Width [m]	Length [m]	Height [m]	Volume [l]	Cross-sectional area [m2]
Cuboid 1	0.30	0.50	0.67	100	0.15
Cuboid 2	0.20	0.50	1.00	100	0.10
Cube	0.46	0.46	0.46	100	0.21

The water-storing substrates used were perlite (Perligran, Knauf Performance Materials GmbH, Dortmund, Germany) with a bulk density of 85 kg m-3 and a grain size of 2 to 6 mm as well as vermiculite (Agrivermiculite, HaGeFe GmbH, Saterland/Ramsloh, Germany) with a bulk density of 86 kg m-3 and a grain size of 2 to 3 mm. These materials had been identified as suitable for water absorption in upstream screening tests. For each test, 100 liters of fresh material were introduced into the retention modules. The retention module was placed on platform scales (Kern & Sohn GmbH, Balingen-Frommern, Germany) to allow gravimetric measurement of the amount of water introduced.

All tests were carried out with a flow rate of 40 l h-1. Referring to one square meter of roof surface, this value represents an exceptionally heavy rainfall event (index 6 to 7) (Schmitt et al., 2018). At the beginning, water was fed into the regulating unit and then cyclically transferred to the retention module to give the water time to distribute within the bulk filling between feeds. Water was distributed until water leaking from the base of the retention module was clearly visible using tissue paper placed under the retention module. The test was then stopped and, after a total of 40 minutes, the amount of water stored in the retention module was determined gravimetrically.

This was used to calculate the relative increase in mass of the filling, defined as:

$$\text{rel. increase in mass} = \frac{m_{\text{Liquid}}}{m_{\text{dry}}} \, [\%] \quad (1)$$

with m_{Liquid}: mass of liquid that was stored by the filling and m_{dry}: dry mass of the filling. Thus, a relative increase of mass of 100% equates to a doubling of the mass of filling.

Findings

Water absorption characteristics of the retention modules

Fig. 3 shows an example of the amount of water introduced into the module (cuboid 1, perlite filling) and the amount of water stored as a function of time. At 0 minutes, the first cycle starts by filling and draining the regulating unit (blue curve), followed by the further cycles. After 9 cycles (24 minutes), water leakage from the retention module was detected and water application was stopped (end of absorption phase).

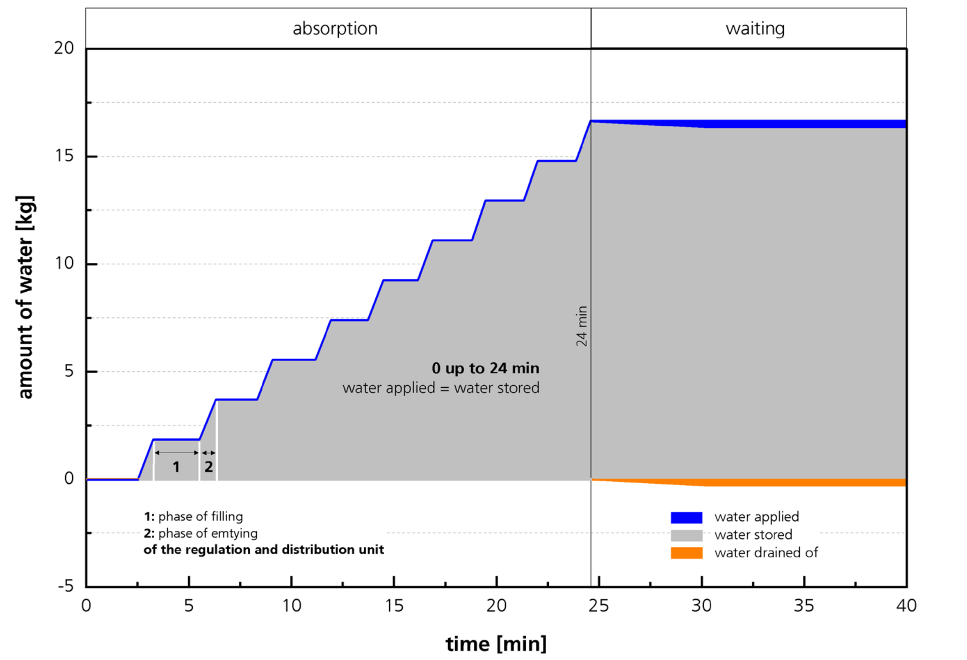

Fig. 3

Amount of water fed to the retention module and stored by the retention module as a function of time for the cuboid 1 retention module with perlite filling

After the water application was stopped, water continued to leak from the module and stopped after a test period of approx. 30 minutes. At the end of the test period, the amount of water absorbed by the retention module was 16.4 kg, corresponding to a relative increase in mass of 193%.

Table 2 summarizes the findings in terms of the relative increases in mass for the perlite and vermiculite fillings for each of the retention modules used.

Table 2

Stored water amounts and relative increases in mass for the retention modules

	stored water amount	rel. increase in mass	stored water amount	rel. increase in mass
Retention module	Perlite [kg]	Perlite [%]	Vermiculite [kg]	Vermiculite [%]
Cuboid 1	16.4	193	21.5	250
Cuboid 2	16.5	194	20.0	233
Cube	13.0	153	15.8	184

In all of the vermiculite tests, the water storage capacity of the filling was greater than that of the perlite test series. The results are consistent with those of Görgen and Rossi-Schwarzenbeck (Görgen & Rossi, 2022), whose laboratory tests yielded similar ranges for different granules (perlite, expanded clay, and pumice). However, water absorption causes the vermiculite filling to compact, which is particularly undesirable in case of multiple drying and wetting cycles.

In terms of the shape of the retention module, the cube-shaped modules yielded the worst results. Retention modules with slimmer geometries, i.e. smaller base area of the retention body, and greater height appear to be advantageous in terms of water distribution throughout the filling. With slimmer modules, the water has the longest vertical distance from the top to the bottom and the substrate therefore has more time to absorb water than with the cube modules. The cube modules could only achieve similar values if the transverse distribution of the water in the horizontal direction could compensate for the reduced vertical length. This does not occur and could be proofed as well by large portions of the filling that remained dry. Further optimization should address the aspect of vertical length taking into account that modules that are too slim could cause wall effects, with a fast water run along the wall.

Sample scenarios for practical application of vertical retention modules

Sample scenarios were studied to assess the application potential of vertical retention bodies in terms of water retention and potential impact on the microclimate. The building shown in Fig. 4 was used as the basis for the scenario, in a detached configuration (see Fig. 4, left) and connected to other buildings (see Fig. 4, right). The detached configuration has no directly neighboring buildings and therefore, in contrast to the building in the connected configuration, there is also space available on the front sides for the retention modules.

The roof area is assumed to be a flat roof with a surface area of 120 m^2 (building width: 8 m, building length: 15 m). Each story is assumed to be 2.4 m high, and the window surface area is assumed to be 25% of the overall surface. The number of stories in the scenario is variable, resulting in the building data listed in Table 3. The orange areas in Fig. 4 represent the free facade area.

Fig. 4

Building scenario used to assess the application potential of vertical retention bodies, in a detached configuration (left) and connected to other buildings (right)

Table 3

Overview of building data depending on story height and type of configuration

No. of stories	Configuration	Facade area [m^2]	Window area [m^2]	Free facade area [m^2]
3	detached	165.6	41.4	124.2
3	connected	108.0	27.0	81.0
6	detached	331.2	27.0	81.0
6	connected	216.0	94.0	162.0

The volume of water to be discharged via the roof was calculated on the basis of a heavy rainfall event with an intensity of 40 l m^{-2} h^{-1} and a duration of 30 minutes, resulting in a total volume of water of 2,400 l accumulating on the roof. The runoff curve number was assumed to be 1.0, i.e., the entire volume of water must be drained from the roof, fed into the vertical retention modules and stored there within 30 minutes.

The configuration of the entire retention system in the scenario is based on the data presented in section 3.1. The entire retention system consists of individual cuboid 1 modules filled with perlite. The perlite filling was chosen because it did not show compaction after irrigation, and the cuboid 1 shape was chosen because it had a larger cross-sectional area than cuboid 2, which offered advantages in terms of water introduction and distribution kinetics. With a total water volume of 2,400 l and a water absorption of 16.4 kg per retention module, a total of 147 modules had to be deployed on the building. The height and width of the cuboid 1 module (see Table 2) results in an area of 0.335 square meters per module and a total installation area required for the 147 modules of 49.3 square meters. Depending on the building configuration and the story height, a utilization rate can be used to assess if the free facade areas listed in Table 3 are sufficient for the retention system configuration to be deployed. The utilization rate is defined as follows:

$$\text{Utilization rate} = \frac{F_{\text{total module area}}}{F_{\text{free facade area}}} \; [\%] \tag{2}$$

with $F_{\text{total module area}}$: area of the total number of modules and $F_{\text{free facade area}}$: free facade area according to Table 3.

Table 4 lists the utilization rates depending on the number of stories and the type of configuration. Utilization rates range from 20 to 61%, i.e., there is sufficient area for all building scenarios.

Table 4

Facade utilization rates depending on story height and type of configuration

No. of stories	Configuration	Utilization rate [%]
3	detached	40
3	connected	61
6	detached	20
6	connected	30

The static load to be considered for a retention system installation can be estimated based on the weight of an empty cuboid 1 module of 20 kg, the weight of the dry substrate (100 liters of perlite filling) of 8.5 kg and the maximum stored water amount of 16.4 kg. This results in a weight of 44.9 kg for each module and a combined weight of 6,600 kg for a total of 147 modules.

The cooling potential through evaporative cooling can be estimated in this scenario based on a maximum water amount of 2,400 liters stored in the retention system. At a temperature of 20°C, energy in the amount of 2,454 kJ1 (0.682 kWh) is required to evaporate 1 kg of water (VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen, 2013). Based on 2,400 liters of water (density at 20°C: 998 kg m-3), the total energy to be removed from the surrounding environment to evaporate the water amount is 5,877 MJ (1,634 kWh).

In this context, however, a number of other factors are relevant that influence the interaction of the retention modules with the environment and the microclimatic effect. With regard to the environment, important factors influencing water evaporation are: wind speed, outside temperature and humidity as well as solar radiation. With regard to the retention modules, important factors are: the spatial orientation of the façade (north, south, etc.), the enthalpy of evaporation for the water stored in the substrate and the exterior material selected for the module, its color and structure. Rentz et al. (Rentz et al., 2022) have developed an initial model for an active façade that is based on the energy and material flows present in the system and can serve as a basis for the retention modules developed in this work. For the influencing factors described above, however, the system-specific material data and interactions must be determined and integrated into the model, which is the aim of further work. For example, the color of the outer material can have an important influence on the energy introduced by solar radiation. In this case, a black color would reflect less heat radiation and thus heat up the module surface more than a white color. The type of surface structure (perforations, baffles, etc.) would, for example, interact with the wind flow and speed.

Furthermore, the operating concept of the retention modules will play an important role with regard to building operation. A key factor here is the load status of the system. It is important to know this in order to decide whether and how much water can be fed into the system or whether an overflow should be activated, for example. The retention modules also create synergies in connection with building operation. For example, the system could be used to cool the building in warm seasons or, in combination with heat pumps, to supply heat in cold seasons.

Discussion

The findings of the proof of concept confirm the application potential of vertical retention modules to store water accumulated on building roofs during rainfall events. The experiments conducted to measure water absorption and storage and the subsequent sample scenarios demonstrate that the available facade areas are sufficient for the deployment of the required retention modules.

So far, water retention measures on buildings have mainly focused on green roofs (retention roofs). The concept present in this study offers the vertical space as an additional water retention space, adding another building block to the sponge city concept. Apart from the potential for water storage to mitigate heavy rainfall events, the concept also addresses the preservation of the local water cycle by preventing the water from draining and instead keeping it on site so that it can be used for evaporation. Evaporation also removes energy from the surrounding environment with the additional benefit of decreasing inner-city warming (urban heat island effect).

There are many unanswered questions about the use of vertical retention modules, depending on where the technology is to be used, whether on old or new buildings, residential or industrial buildings, high-density urban areas or detached buildings. In particular, this applies to the interaction of the retention modules with the building and the building's surroundings, including aspects of available clearances, transfer of weight loads and integration into technical building services.

Conclusions

The escalation of the climate situation mandates a transformation of the urban space. Using sufficiently large retention spaces to hold rainwater makes it possible to provide enough water for evaporation. As an added building block for the sponge city vertical retention modules can act as retention spaces. But at present, the vertical is only rarely considered in the sponge city concept, whereby it offers great potential.

The concept considered in this study is based on vertical retention modules filled with water-storing substrates. The water that accumulates on the roof during heavy rainfall events is to be fed into these and thus contribute to flood prevention. After the end of the rain event, the water evaporation from the modules can contribute to cooling the environment and maintaining the local water cycle.

Based on the findings of this proof of concept, the technology has been scaled up in the meantime to develop and install a prototype with an absorption capacity of 1,000 liters of dry substrate. The prototype has been installed outside at the Fraunhofer UMSICHT site and connected to real roof drainage. The prototype is currently used to examine the following issues arising from the proof of concept:

_ Optimization of water introduction and distribution
_ Interaction of roof drainage and retention body
_ Water evaporation kinetics as a factor of wind, temperature and relative humidity
_ Use of alternative substrates such as residual material from the pit and quarry industry
_ Identification of data for civil engineering and building regulation assessments

The prototype can be visited at the Fraunhofer UMSICHT site. To stimulate stakeholder dialogues and the discussion with the scientific community visualizations and results of the prototype will be given via a project internet page in future.

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