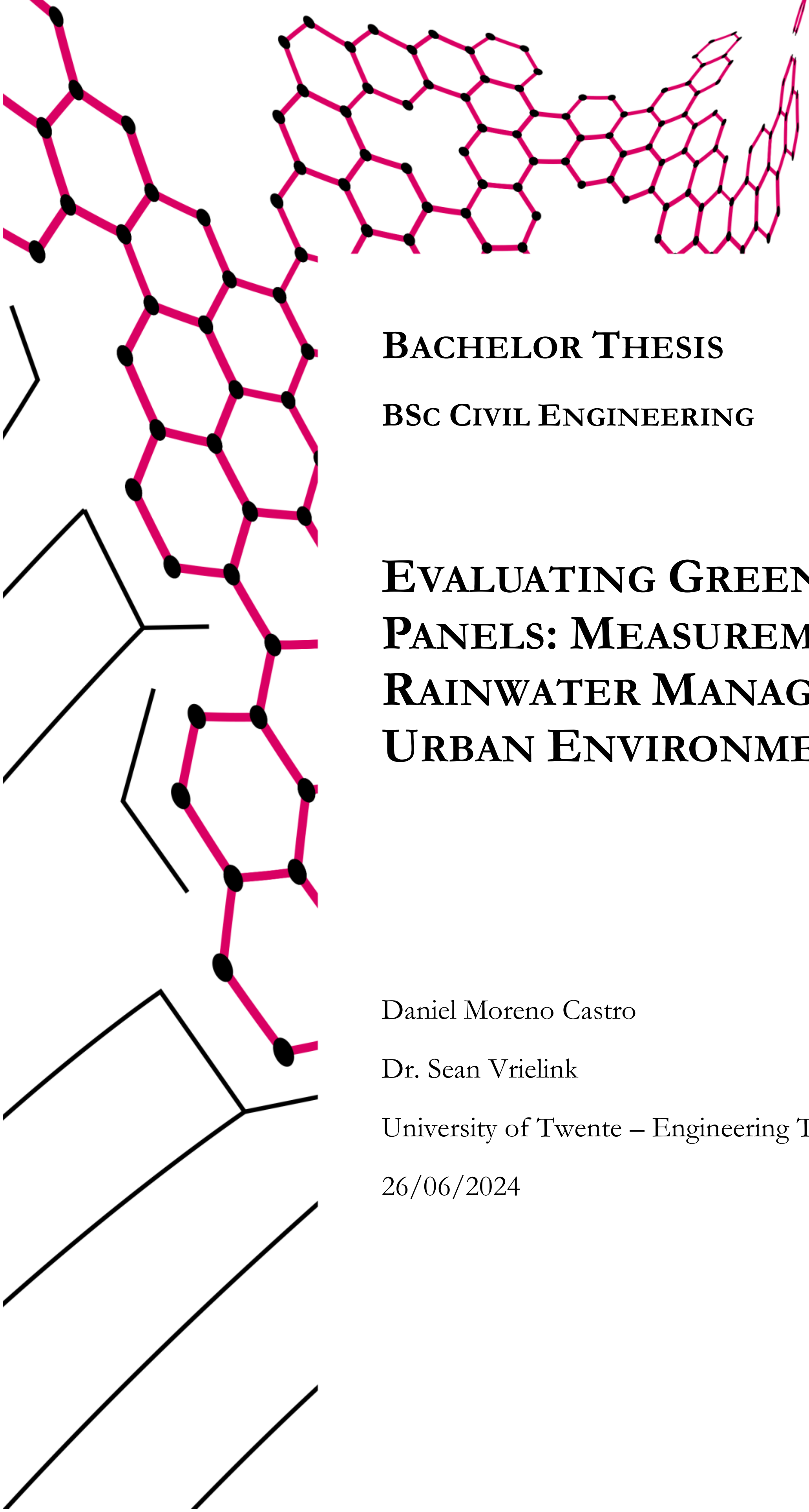

BACHELOR THESIS

BSC CIVIL ENGINEERING

EVALUATING GREEN ROOF PANELS: MEASUREMENTS OF RAINWATER MANAGEMENT IN URBAN ENVIRONMENTS

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Preface

From a young age, I have been fascinated by the composition of nature and science. Now, on my path to becoming a civil engineer, one of my main drivers is to challenge the conventional norms of what a typical 'future' looks like. While the majority envision the future with a 'retro-futuristic' view, with flying cars and advanced technology, I see a future where we return to being closer to nature—not just using it to our advantage, but understanding it and integrating it into our lifestyle, embodying the true essence of biomimicry. This project focused on green panels fulfills that part of me. Incorporating nature back into our urban designs creates a satisfying synergy between my passions for civil engineering and nature.

This culmination of my studies would not have been possible without the guidance and support of my supervisor, Dr. Sean Vink, who helped clarify my doubts and pushed me to achieve my best. I am also immensely grateful to Frank Morssinkhof, lab manager of the Waterlab, for his assistance and advice throughout my experimental work. I would like to thank Aurelio Wijnands, CEO and Co-Founder of Green Panels B.V., who took the time to discuss his initial intentions with his startup during an interview at the beginning of this project.

On a deeper level, I would not be here without the teachings and upbringing my grandfather, "Papito Joel," provided from my childhood. He was the first to instil in me a curiosity about science. I dedicate this thesis to my deceased father and the rest of my family, who have always provided tremendous support throughout this journey.

Daniel Moreno Castro

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Summary

Amidst escalating climate change and urban population growth, urban water infrastructures face unprecedented pressures. Green roof panels, as an innovative solution, have been developed to mitigate these impacts and enhance urban livability. This study aimed to evaluate the performance of extensive green roof panels in managing rainwater, particularly focusing on their capabilities in water retention, evapotranspiration, and water quality enhancement. Utilizing both a literature review and laboratory experiments, the effectiveness of these panels was assessed in controlled conditions. The results demonstrated that the panels absorbed an average of 81% of a simulated heavy rainfall (2.8mm/h), with evapotranspiration rates ranging from 12 to 16.8 ml/h. Moreover, water quality analysis post-filtration revealed a decrease in pH and a notable increase in turbidity, along with a slight rise in nitrite levels following the initial runoff. These findings suggest that green roof panels possess considerable potential for reducing peak rainfall impacts and mitigating urban flooding. However, given the discrepancies between laboratory conditions and real-world settings, there is a pressing need for further field testing and continuous monitoring. This would help substantiate and optimize the use of green roof panels for sustainable urban water management, aligning with broader environmental goals and enhancing urban quality of life.

Keywords: green roofs, rainwater management, sustainable development

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Chapter 1: Introduction

1.1 Research Context

The pressures of climate change, with increased frequency in extreme weather, have presented several challenges for humans and other living beings. Coupled with the rapid urbanization driven by a high influx of population towards urban areas, this has created more hostile environments characterized by increased impermeable surfaces, diminished greenery, heightened pollution levels, and a significant loss in biodiversity. In the Netherlands, where 92% of the population resides in urban areas and which ranks as the sixth most densely populated country in Europe **[19]** Worldometer. (n.d.). Netherlands population. Retrieved from https://www.worldometers.info/world-population/netherlands-population/ , these issues manifest as land scarcity, soaring real estate prices, and challenges in balancing economic growth with environmental sustainability. Both climate change and rapid urbanization contribute to a decreased quality of life, presenting complex challenges that scientists and engineers, among others, have been striving to mitigate in recent decades. One widely regarded strategy is the enhancement of green areas within urban spaces. This thesis specifically focuses on the implementation and effectiveness of green roof panels as a sustainable urban infrastructure solution, aiming to directly address these challenges by exploring their potential in water management.

Urban green areas serve as a common pool resource, as they provide a multitude of advantages to the people and other living beings around it. Some of these advantages include more regulated temperatures, increased air quality, sustainable stormwater management, carbon sequestration and increasing biodiversity. These are some reasons why the Netherlands is pushing on the extension of green-blue infrastructure in urban areas, as mentioned in the National Delta Programme 2024 **[11]** Ministry of Infrastructure and Water Management. (2023). *2024 Delta Programme: Now for Later*. Retrieved from https://english.deltaprogramma.nl.. However, the scarcity of available land makes it increasingly difficult to incorporate green areas within urban environments. One solution to this dilemma lies in the incorporation of modular green panels on roofs.

Green roofs, which mainly incorporate layers of vegetation and substrate **[1]** Archtoolbox. (n.d.). Green roof systems. Retrieved June 5, 2024, from https://www.archtoolbox.com/green-roof-systems/, are increasingly recognized for their critical role in mitigating the environmental impacts of urban expansion. In the densely populated urban centers of the Netherlands, the integration of such green infrastructures is vital not only for enhancing sustainability but also for addressing significant challenges such as water management and the urban heat island effect. With municipalities across the Netherlands striving to align with the Sustainable Development Goals (SDGs), particularly the 6th and 11th SDG which aim to 'ensure availability and sustainable management of water and sanitation for all' and 'make cities and human settlements inclusive, safe, resilient and sustainable', the implementation of green roof panels offers a forward-looking approach that can contribute to a comprehensive solution.

1.2 Scope and limitations

This research focuses on the effectiveness of modular green roof panels in managing rainwater in urban areas, aiming to fill a critical knowledge gap regarding their capacity for water retention and filtration. The green panels used in this study have been developed by Green Panels B.V., a start-up company founded by Aurelio Wijnands, located in Enschede, the Netherlands, in collaboration with the ET faculty of the University of Twente. In a meeting, Aurelio shared his original vision and purpose for the project: to improve living conditions and water management in areas without access to central infrastructure, such as some lower-income regions in Brazil. He suggested that this concept could be adapted to the Netherlands through enhanced, citizen-driven climate adaptation plans. Aurelio confirmed that my research on green panels aligns with these foundational goals. Furthermore, this research aims to address a significant gap in existing studies, as the impacts of green panels on water resources and water quality have not yet been thoroughly investigated. Understanding these impacts in detail is essential for scaling up green panels to an urban scale, providing policymakers and construction companies with the quantified data needed to make informed decisions.

1.3 Problem Statement

Despite the recognized benefits of green roof panels, there remains a significant gap in empirical research regarding their capabilities and performance on rainwater management. Specifically, there is a lack of detailed studies on the water retention capacities, evapotranspiration rates, and the efficiency of water filtration of modular green panels on sloped roofs. This knowledge gap hinders the ability to scale these solutions effectively, limiting their broader implementation across urban landscapes.

Addressing these issues requires a focused investigation into the effectiveness of green roof panels in urban water management. By quantifying their impact on water resources and the quality of runoff, this research seeks to validate the role of green infrastructure in achieving sustainable urban development goals, thereby informing policy and practical applications. This study aims to provide empirical data that could support policymakers and construction companies in making informed decisions about integrating green solutions in densely populated cities, where traditional expansion of green spaces is not feasible.

1.4 Research questions.

The study seeks to empirically assess how green panels can improve water retention and water quality through natural filtration, thus contributing to sustainable urbanization and resilience against climate impacts. By understanding green panels' potential as sustainable water management infrastructure, this research will provide valuable insights into how green roofs can enhance water management, ultimately leading to more sustainable and low impact urban environments.

Thus, the main research questions aimed to answer in this bachelor thesis are the following:

1. How effective are modular green roof panels in retaining water and “peak-shaving” during heavy rainfall events in urban areas?
2. What are the rates of evapotranspiration that a green panel is able to produce after a heavy rainfall?
3. What impact do green panels have on the quality of rainwater runoff?

1.5 Research Motivation

The pressure of climate change as well as an increased rate of the population migrating to the urban areas, a sustainable urbanization design is imperative. While technological advancements enhance our productivity, integrating green infrastructure into urban landscapes is crucial for achieving a harmonious balance in our lifestyles. Nature provides a blueprint for sustainable design, offering solutions to mitigate extreme weather events and promote both physical and mental well-being. This research thesis draws inspiration from biomimicry and modern building technologies to propel advancements in the field of green infrastructure. By harnessing the principles of nature and leveraging innovative approaches, this study seeks to pioneer sustainable solutions that are accessible, cost-effective, and transformative for urban environments.

Chapter 2: Research and Literature Review

The study embodies the principles of water management, focusing specifically on rainwater management. Two primary theoretical frameworks are used to assess the effectiveness of green roof panels: water retention and water filtration. While modular green panels are an innovative concept, extensive research on green roofs can be found online and in peer-reviewed literature. This chapter provides insight into current green roof research, elaborates on the theory and principles of rainwater management, and integrates these frameworks to identify the knowledge gaps that this study seeks to fill. Additionally, it guides the design of physical experiments conducted on these green panels.

For the literature review, the search was conducted using Google Scholar and the University of Twente's database, employing keywords such as 'green roof panels,' 'green infrastructure,' 'rainwater management', 'green-blue network,' and 'nature-based infrastructure.' Additionally, for examples of existing green roof configurations and technical details, websites of private companies such as Groendak and Ecopan were also explored. This study also incorporated climate and water adaptation plans from both the national government of the Netherlands and the municipality of Enschede, which provided a context-specific understanding of the challenges and strategies relevant to urban rainwater management. The primary resources were peer-reviewed papers directly related to green roof panels. Notably, some papers served as gateways to additional publications, which proved to be even more instrumental for this research, providing deeper insights and broader perspectives on the effective implementation of green roof panels for urban rainwater management.

2.1 Rainwater as a resource

Firstly, it's important to recognize the value of rainwater. Historically, rainwater has been an abundant resource in the Netherlands, yet it hasn't always been utilized as such. With climate change leading to drier summers and wetter winters, there is an increased imperative to shift perceptions of rainwater from waste to a valuable resource. Traditionally, urban rainwater infrastructure has been designed primarily to dispose of rainwater from streets quickly. Yet, there's significant potential to repurpose this rainwater for uses such as flushing toilets, watering plants, and other non-potable needs. Green roofs play a crucial role in this transition. They capture, filter, and store rainwater, which can then be used for non-potable purposes. Moreover, water that drains into sewage systems from green roofs is cleaner, reducing the burden on water treatment facilities. However, the extent of this filtration and the effectiveness of different mediums in filtering need further investigation. Fletcher et al. (2015) **[6]** Fletcher, T. D., et al. (2015). SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage. *Urban Water Journal, 12(7), * 525-542. advocates for a decentralized approach to rainwater management to enhance resilience against climate change impacts, such as droughts and flooding. Green roofs exemplify this decentralized strategy by potentially converting the land area of urban buildings into active rainwater management systems.

2.2 Green Panels and Rainwater Management

In urban environments, rainwater typically flows from rooftops and streets into the sewage systems (**Figure 1.** *Rainwater flow diagram in urban areas. Source: City and Country of Honolulu Department of Facility Maintenance.*), which direct them to treatment plants before it returns for use into homes and fields. During heavy rainfall, and especially in areas that are prone to flooding, such as the Netherlands, delaying water runoff into the congested sewage system is a method to mitigate flooding. Green roof panels disrupt this flow by retaining water, reducing peak runoff and relieving the load on urban infrastructure. A study by Hathaway et al. (2008) conducted in North Carolina, USA, demonstrated that extensive green roofs (with less than 100 mm medium depth) could reduce peak flow rates by up to 80% compared to conventional roofs. The climate in North Carolina, which is warmer on average due to its proximity to the equator and experiences heavier rainfall, provides a pertinent example of the effectiveness of green roofs for peak-shaving, offering valuable insights applicable to different climatic contexts like the Netherlands. This ‘peak shaving’ effect significantly reduces the likelihood of urban flooding (Carter and Rasmussen, 2006).

Figure 1. Rainwater flow diagram in urban areas. Source: City and Country of Honolulu Department of Facility Maintenance.

Furthermore, green panels also act as a first membrane of water filtering in the water treatment process. While there are various green roof panel designs with different filtering systems, water retained in the green panels can be filtered from some pollutants and ease stress from water treatment plants. A study by Vijayaraghaven (2016) **[17]** Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations, and trends. *Renewable and Sustainable Energy Reviews, 57,* 740-752. https://doi.org/10.1016/j.rser.2015.12.119 conducted in India, where rainwater typically contains higher concentrations of pollutants compared to the Netherlands, shows that green roofs can effectively reduce heavy metals, nutrients, and suspended solids. While the capacity to filter soluble pollutants varies and depends on the filtration system, this finding underscores the potential for green roofs to serve as robust filtration systems. The success of these systems in a more polluted environment strongly supports the claim that green panels have a demonstrable capacity for filtration, requiring further research to optimize their effectiveness.

2.3 Common green roof types and configurations

This section explores the various configurations and materials used in constructing green roof panels, which is crucial for addressing the core objectives of this research. Understanding the specific characteristics and capabilities of different green roof types, especially extensive systems, directly informs the investigation into their effectiveness in water retention and peak-shaving during heavy rainfall events. Additionally, the choice of vegetation and substrate not only impacts the rates of evapotranspiration but also influences the capacity of these panels to filter pollutants from rainwater. Exploring these configurations provides context for understanding how different green roof setups might influence the outcomes related to the research questions on water retention, evapotranspiration rates, and pollutant filtration.

Green roofs can be categorized into three distinct systems: extensive intensive, and semi-intensive. Intensive green roofs are characterized by their deeper and heavier vegetation, heavier weight, and higher maintenance. On the other hand, extensive green roofs are characterized by their shallower soil depth, smaller vegetation and easier installation. While intensive green roofs are able to simulate nature to a greater extent, this research focuses on extensive green roofs. Extensive green roofs can be installed easier and usually do not require additional structural roof support. These roof types also have the advantage of modularity, where prefabricated panels can be installed extensively with relative simplicity.

Table 1. Green roof system comparison [1] **Archtoolbox. (n.d.). Green roof systems. Retrieved June 5, 2024, from https://www.archtoolbox.com/green-roof-systems/**

	EXTENSIVE	**SEMI-INTENSIVE**	**INTENSIVE**
Plant Options	sedum, moss, grass	sedum, moss, grass, herbs, flowers, shrubs	sedum, moss, grass, large shrubs, trees
Soil Depth	5cm to 10cm deep	10cm to 20cm deep	20 to 80+cm deep
Dry Weight	5 to 15kg dry weight	15 to 20kg dry weight	20 to 50kg+ dry weight
System Types	Tray, built-up	Tray, built-up	Built-up
Maintenance	Minimal	Occasional/Routine	Routine
First Cost	Low	Medium	High

Extensive green panels can have several configurations, although they mainly contain the vegetation, a growing medium, filtration layer, and an impermeable layer, which is usually the modular tray. Each layer can utilize different materials or plants (in the case of the vegetation layer). A list of some of the most common configurations can be seen below.

Vegetation:

Some types of vegetation that are commonly used for extensive green roofs are the following:

- Sedum (Sedum spp.): A popular choice for extensive green roofs, sedum plants are a low-maintenance, drought-tolerant succulent that can thrive in shallow soil.
- Sempervivum (Sempervivum spp.): Also a succulent plant that is well suited for extensive green roofs do to their ability to survive in poor soil conditions and requires low-maintenance.
- Thyme (Thymus spp): A low-growing, fragrant herb that can be used to create a lush, green roof in harsh environments.
- Creeping Thyme (Thymus serpyllum): A low-growing, drought-resistant plant that can be used to create a dense green roof. However, it does not handle high amounts of water well as it may begin to rot.

Growing medium:

There are different possible choices for growing mediums on roof panels. Some of the most popular are the following:

1. Soil-Based Media: Traditional soil-based media are commonly used in both intensive and extensive green roof setups since it can be adapted to any depth and it is the most natural growing medium for plants. These media are usually a blend of soil, compost, and organic matter that provides essential nutrients for plant growth. Soil-based substrates tend to be heavier and may require structural support but excel at retaining moisture and supporting a diverse plant community.

2. Recycled Fabric Materials: Innovative green roofs sometimes utilize recycled fabrics or fibers as a component of the growing medium. These materials, often made from recycled textiles or plastic fibers, help to improve aeration and drainage within the substrate. They are lightweight and can be engineered to retain specific amounts of moisture, making them suitable for both extensive and intensive green roof systems. Furthermore, they make up for a sustainable option and contribute to a circular economy.

3. Expanded Clay Aggregate: This lightweight expanded clay aggregate (LECA) is another popular choice for green roof substrates. It is made by heating clay to very high temperatures, which causes it to expand into lightweight, porous pellets. LECA provides excellent drainage and filtration and helps to reduce the overall weight of the green roof, which is crucial for load-bearing considerations on buildings.

4. Biochar: Biochar is a stable, carbon-rich form of charcoal that is used as a soil amendment in green roof substrates. It enhances soil fertility, helps retain water and nutrients, and increases microbial activity. Biochar is particularly valued for its

sustainability and its ability to sequester carbon, making it an environmentally friendly option for green roofs.

5. Rock wool: Manufactured from basalt rock and steel slag, rock wool is spun into fine fibers, providing a lightweight, fire-resistant substrate ideal for green roofs. It enhances root growth and water retention while ensuring effective drainage and insulation. This makes rock wool an excellent choice for sustainable urban roofing, promoting plant health and building safety.

These materials each bring unique benefits and can be chosen based on the specific requirements of the green roof, such as weight limitations, water retention needs, and types of vegetation planned for the roof. It is also important to consider environmental sustainability and material availability in the area for a sustainable choice.

Filtration:

The filtration layer has two main purposes: to prevent roots from growing and clogging the drainage system, and to filtrate the water. Therefore, a filtration layer is typically composed of a fabric like material such as polypropylene, that is porous and resistant to the penetration of roots. The filtration layer can also incorporate natural materials such as activated charcoal, coconut shell, and even seashells. In order to choose an adequate filtration medium, it is important to know the most prevalent dissolved materials in the rainwater around the area of the house.

2.4 Current research on green roofs

Although this research is mainly focused on water quantity and quality functions of green panels, it is important to have a good overview about the multifaceted benefits and current areas of research of green roofs. This section provides a holistic view of the various advantages associated with green panels. This perspective supports the core research by showcasing the compound value green panels have to offer.

Here are brief descriptions of current research areas on green roofs along with citations of relevant research papers:

a. Thermal Isolation:

Research in this area focuses on the capacity of green roofs to insulate buildings, reducing energy consumption for heating and cooling. Green roofs are studied for their thermal mass and how they can mitigate urban heat island effects **[7]** Fioretti, R., Palla, A., Lanza, L. G., & Principi, P. (2010). Green roof energy and water related performance in the Mediterranean climate. *Building and Environment, 45*(8), 1890-1904. https://doi.org/10.1016/j.buildenv.2010.03.001.

b. Stormwater Management:

This research examines how green roofs can absorb, retain, and delay the discharge of rainwater, thus helping manage stormwater runoff and reduce the burden on urban sewage systems **[3]** Berndtsson, J. C. (2010). Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering, 36(4), 351-360. https://doi.org/10.1016/j.ecoleng.2009.12.014

c. Biodiversity:

Studies in this area explore how green roofs can support urban biodiversity by providing habitats for various species of plants, insects, and birds **[4]** Brenneisen, S. (2006). Space for urban wildlife: Designing green roofs as habitats in Switzerland. *Urban Habitats, 4*(1), 27-36. http://www.urbanhabitats.org/v04n01/wildlife_full.html

d. Psychological and Social:

This research area investigates the psychological and social benefits of green roofs, such as improving mood, reducing stress, and enhancing the aesthetic value of urban environments **[10]** Lee, K. E., Williams, K. J., Sargent, L. D., Williams, N. S., & Johnson, K. A. (2015). 40-second green roof views sustain attention: The role of micro-breaks in attention restoration. *Journal of Environmental Psychology, 42*, 182-189. https://doi.org/10.1016/j.jenvp.2015.04.003

e. Air Quality:

Research focuses on the ability of green roofs to improve air quality by filtering pollutants and particulates from the air **[20]** Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment, 42*(31), 7266-7273. https://doi.org/10.1016/j.atmosenv.2008.07.003

f. Materials and Design:

Studies in this area focus on the engineering aspects, including the development of sustainable materials and innovative designs for more effective green roofs **[17]** Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations, and trends. *Renewable and Sustainable Energy Reviews, 57,* 740-752. https://doi.org/10.1016/j.rser.2015.12.119

g. LCC (Life Cycle Cost) and LCA (Life Cycle Assessment):

Research here involves assessing the environmental impact and cost-effectiveness of green roofs throughout their lifecycle, from construction to disposal **[15]** Saiz, S., Kennedy, C., Bass, B., & Pressnail, K. (2006). Comparative life cycle assessment of standard and green roofs. *Environmental Science & Technology, 40*(13), 4312-4316. https://doi.org/10.1021/es0517522

2.5 Theoretical Frameworks for Water Management

2.5.1 Linear water reservoir model

As highlighted earlier, a key focus of this research is to examine the water storage properties of green panels. To effectively assess these properties, it is essential to establish a structured model for testing. The linear reservoir model is a suitable choice for this task, particularly because the geometry of the green roof panel trays naturally simulates a linear reservoir. This model simplifies complex hydrological equations while comprehensively accounting for all critical aspects of our system—rainfall, storage, evapotranspiration, and runoff. In this model, the inflow of water is represented by rainfall, while the outflow is determined by initial runoff combined with evapotranspiration rates. The diagram below illustrates this model in detail, showcasing how each component interacts within the system.

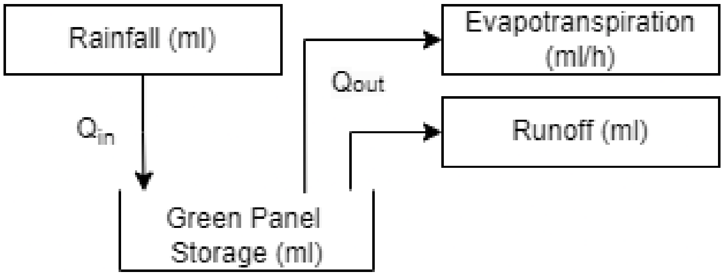

Figure 2. Linear reservoir model diagram.

For this model, rainfall serves as the controlled parameter, while the parameters to be investigated include storage capacity, runoff, and evapotranspiration. The procedure begins by recording the initial conditions of the panels, particularly their weight, since their change in mass is an indicator of the water absorbed. A specified amount of rainwater is then applied to simulate an hour of heavy rainfall, while observing how the panels manage this influx. It is anticipated that the panels will absorb some of the water while allowing the remainder to runoff. Following the simulated rainfall, the panels are weighed again to ascertain the amount of water they have retained; this measurement helps calculate the volume of runoff. The panels are then left undisturbed for at least 24 hours, after which they are weighed once more. The decrease in weight over this period is expected to indicate the amount of water lost through evapotranspiration within 24 hours.

2.5.2 Water Filtration

The theoretical framework for studying the water filtration capabilities of green roofs integrates important principles of water quality management. This involves understanding the mechanisms through which green roofs can modify water chemistry, particularly how they can act as sources or sinks for various minerals and influence water properties like pH and turbidity. Previous research has suggested that the substrates and vegetation typical of green roofs can adsorb or filter out pollutants, affecting the overall quality of runoff water (Vijayaraghavan, Joshi, & Balasubramanian, 2012) **[18]** Vijayaraghavan, K., Joshi, U. M., & Balasubramanian, R. (2012). A field study to evaluate runoff quality from green roofs. *Water Research, 46*(5), 1337-1345. https://doi.org/10.1016/j.watres.2011.12.050.

The role of green roofs in water filtration is grounded in the concept of phytoremediation, where plants and their associated microbial communities degrade, assimilate, or detoxify pollutants through natural biological, chemical, or physical activities **[14]** Reichenauer, T. G., & Germida, J. J. (2008). Phytoremediation of organic contaminants in soil and groundwater. *ChemSusChem*, 1(8–9), 708-717. https://doi.org/10.1002/cssc.200800125. Additionally, the substrate material plays a crucial role in filtering and binding contaminants. This dual function highlights the potential of green roofs not just in managing stormwater volume but also in enhancing water quality.

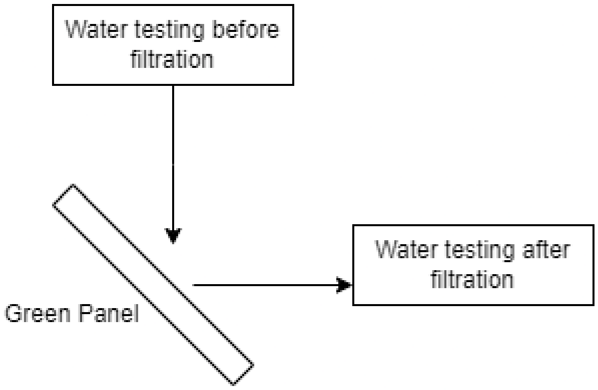

Figure 3. Rainwater filtration testing.

While the current designs of green panels from Green Panels B.V. are not primarily intended for water filtration, understanding these theoretical concepts supports the argument for optimizing design features to enhance filtration capabilities. In the case that empirical evidence from experiments conducted for this research demonstrate significant pollutant removal, it would strengthen the case for recommending design modifications that better facilitate filtration. For this purpose, the Waterlab facilities, at the University of Twente campus are used, with the help of lab manager Frank Morssinkhof.

Chapter 3: Methodology

3.1 Research process

To ensure the production of meaningful outcomes from this research, it is important to define a structured foundation that delineates the problem at hand. Therefore, the flowchart presented below outlines the systematic progression of this study, delineating each phase to demonstrate the structured approach being undertaken. This visual representation serves not only to guide the research methodology but also to enhance the clarity and focus of the investigative process.

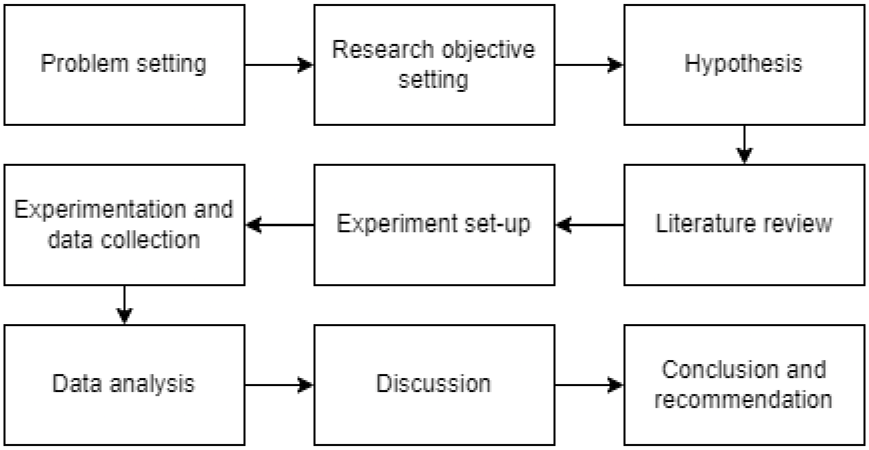

Figure 4. Research process flowchart.

3.2 Experiment design

3.2.1. Objective

The objective of this experiment is to test the water retention and filtration of 1m^2 of green panels. The data collected is used to calculate the initial storage capacity, the rate of evapotranspiration, and the effectiveness of filtration of green panels.

The water retention is divided into two sections: initial water retention, and evaporation. Evapotranspiration is tested over a designated time, while the initial water retention can be tested immediately. Therefore, the experiment will consist in testing three responses of the green panels to stormwater management.

It is important to note that results are heavily dependent on the initial conditions of the panels as well as the environmental conditions around them. Therefore, measuring the initial conditions are of high importance since they will influence the effectiveness of the panels in these three areas of water management.

3.2.2 Hypothesis

Due to the three different tests done, these are the three different hypotheses that will be tested. In order to defend the hypothesis, the Toulmin method of argumentation is implemented. The Toulmin method is a framework for constructing an argument that typically includes six components: claim, grounds, warrant, qualifier, and rebuttal.

1. Water retention:

Claim: The green roof panel will retain 60-75% or more of the applied water, reducing runoff significantly.

Grounds: Studies from Hathaway et al. (2008), conducted in a heavy rainfall climate, demonstrate significant water retention capabilities in extensive green roof panels.

Warrant: Under unsaturated soil conditions, green roof panels should help mitigate a heavy rainfall. Green roof panels, with their absorbent soil and tray design, are engineered to capture and retain rainfall, thereby mitigating runoff during heavy rainfall.

Qualifier: The hypothesis assumes a mitigation in rainwater runoff with an hour of heavy rain conditions (>2.5mm/h) and does not include extreme weather conditions.

Rebuttal: Exceptions might occur with different weather conditions, as well as different panel configurations. A major difference in water retention is expected to happen once the soil is saturated.

2. Water evapotranspiration:

Claim: The water in the panels after 1h of heavy rainfall will evaporate back into the atmosphere within four days or less.

Grounds: Getter and Rowe (2006) **[8]** Getter, K. L., & Rowe, D. B. (2006). The role of extensive green roofs in sustainable development. HortScience, 41(5), 1276-1285. https://journals.ashs.org/hortsci/view/journals/hortsci/41/5/article-p1276.xml found that evapotranspiration rates decrease significantly by the fourth day following heavy rainfall. The study uses sedum plants as well as soil-based growing medium, making it a comparable study.

Warrant: Under similar rainfall and environmental conditions, along with comparable green roof configurations, evapotranspiration rates should be similar. Note: While the experiments from Getter and Rowe have slightly different configurations (filter fabric, and drainage layer), these do not play a major role in evapotranspiration rates, and therefore, are comparable.

Qualifier: Assuming temperate environmental conditions, similar to those in Getter and Rowe’s study, particularly regarding temperature and sunlight exposure.

Rebuttal: Variations in climate conditions can influence evapotranspiration rates. More specifically, the lack of sun exposure or extremely low temperatures can decrease the evapotranspiration capabilities.

3. Water filtration:

Claim: The green roof panels will effectively filter pollutants, including heavy metals, and increase the pH of rainwater, thereby acting more as pollutant sinks rather than source.

Grounds: Berndtsson (2009) observed an improved water quality and pH increase in similar experiments with flat green roofs.

Warrant: The validity of these results depends on the panels having a similar configuration, particularly in terms of filtration layers and growing medium. Although Berndtsson's studies include a filtration layer, they also suggest that a soil-based medium alone can serve as a natural filter, which is the case in our experiment.

Qualifier: Provided that both the filtration layer and vegetation are properly installed and maintained.

Rebuttal: Exceptions to this claim may occur if the filtration layer is absent or poorly maintained. Moreover, Berndtsson notes in the study that "the initial runoff from impermeable surfaces after a dry period is typically more contaminated than subsequent runoff". This could result in the panels acting as a source of contamination instead of mitigating it.

3.2.3. Set up and location

The experiments took place at the Water Lab facilities at the University of Twente. Water Lab coordinator, Frank Morssinkhof, acted as a supervisor for this experiment. Each of the three panels were tested and analyzed individually to have a larger dataset. The complete description of the three experiments can be found in **Appendix C**: Detailed Experimental Protocol.

Initial conditions of the panels and environmental conditions were measured and documented. All data collected from the experiment can be found in section **3.3** Data validation.

3.2.4. Materials used.

A list of materials, along with their designated parameters and specifications, is provided below. For a more detailed description of the materials and associated links, please refer to **Appendix A**: Materials used for experiments..

Table 2. Materials used in experiments.

Materials	Parameters measured	Specifications
Green Panels		Numbered from 1-3
TDS meter	Measures total dissolved solids in water	In ppm
Scale	Weight of panels, change in weight.	<30kg; 0.01kg

16-in-1 water testing strips	Measures 16 parameters: carbonate, hardness, cyanuric acid, total chlorine, free chlorine, free bromine, nitrate, nitrite, iron, chromium, lead, copper, and mercury.	In mg/L, or ppb for lead
pH meter	Measures pH levels of water	pH scale 0-14
Turbidimeter	Measures total turbidity in water	FNU (Formazin Nephelometric Units)/NTU (Nephelometric Turbidity Units)
Laboratory beakers	Water content	mL/L
Soil moisture sensor	Soil moisture	In %

3.2.5. Panel configuration

In section **2.3** Common green roof types and configurations, various configurations of green panels were explored. This section describes the specific green panels designed by Green Panels B.V. that are used in the experiments. Understanding the specific characteristics of these panels helps understand the results of the experiments.

Figure 5. Three numbered modular green panels, labeled 1 through 3, with a total combined surface area of 1 square meter.

Substrates

All 3 panels use the same kind of soil-based substrate. With a small variation on a section of one of the panels, which also contains coarse rocks. However, due to the similarity, they are all treated as the same kind of substrate.

Vegetation

A mixture of sedum plants covers the panels. All three panels had different levels of vegetation: panel 2 had the densest vegetation, followed by panel 1, and panel 3 had the least dense vegetation.

Figure 6. Close-up views of the vegetation on the green panels used in the experiments.

***Table 3. The main kinds of sedum plants found in the green panels*.**

Plant nomenclature	**Image**
Angelina Sedum **[5]** Epic Gardening. (n.d.). *Angelina sedum growing in garden* [Photograph]. Retrieved from https://www.epicgardening.com/sedum-angelina/**.**	

Phedimus spurinus [12] Native Plant Trust. (n.d.). *Image of Phedimus spurius* [Photograph]. Go Botany. Retrieved from https://gobotany.nativeplanttrust.org/species/phedimus/spurius/	
Sedum oreganum **[13]** Rainy Side Gardeners. (n.d.). *Photograph of Sedum oreganum ssp. tenue*. Retrieved from https://www.rainyside.com/plant_gallery/natives/Sedum_oreganum_ssp_tenue.html	

Filter layer

The current configuration of green panels lacks a designated filtration layer. The soil-based substrate acts as the only water filtration layer in this panel configuration.

Water storage layer

The current configuration of green panels does not have a designated storage layer. Instead, the tray itself acts as the water storage layer.

3.3 Data validation

To ensure the accuracy and reliability of our experimental findings, the following data validation methods are employed:

Expert Review: Industry experts were involved, such as Frank Morssinkhof, a water filtration specialist, to review the output data. This ensures that our findings align with established standards and expert knowledge in the field.

Comparative Analysis: By comparing results with those from similar experiments and peer-reviewed research, credibility of the data is enhanced. This comparative approach helps confirm that findings are consistent with existing scientific knowledge.

Reference to Standards: Data from the water filtration experiments are further validated by comparing them with the quality parameters of drinking water. Since drinking water typically contains higher mineral levels to prevent corrosion in distribution systems, we use this benchmark to assess our filtered rainwater. For instance, our tests on tap water using 16-parameter test strips revealed similarities to untreated rainwater, although with slightly elevated levels of nitrates and hardness.

Chapter 4: Results and discussion

4.1 Water storage results

The table below shows the recorded data from the initial water storage experiment. The panels are weighed before and after adding 861ml (or 2.8mm/h) of rainwater.

Table 4. Water absorption after 1h of heavy rainfall.

Water absorbtion				
Panels	Initial weight [kg]	weight +2.8mm of rainfall [kg]	Water absorbed [kg]	% absorbed
1	13.21	13.79	0.58	0.67
2	13.71	14.53	0.82	0.95
3	14.64	15.33	0.69	0.80
Total	41.56	43.65	2.09	0.81

Results in Table 4, show that collectively, all 3 panels (1m2) were able to absorb a total of 2.09L out of the 2.58L of rainwater. This results in a reduction of 81% of a simulated heavy rainfall.

The rainfall of 2.87 mm/h over the area of the green panels, was reduced to:

$$\frac{rainwater\ runoff}{area} = \frac{2.58 - 2.09L}{1m^2} = \frac{0.49L}{m^2} = 0.49\frac{mm}{h * m^2}$$

With the initial conditions of the panels, the experiment demonstrates that they have the capacity of reducing a heavy rainfall of 2.87mm/h into a light to moderate rainfall of 0.49mm/h.

4.1.1 Water Storage Analysis

The green panels show significant influence on peak shaving during heavy rainfall with the given parameters (dry panels, and 1 hour of heavy rainfall). A reduction of 67-95% of water runoff was observed in the experiment, confirming the alternative hypothesis of water retention capacity of 60-75% or more, as found in studies from Hathaway et al. (2008) **[9]** Hathaway, A. M., Hunt, W. F., & Jennings, G. D. (2008). A field study of green roof hydrologic and water quality performance. *Transactions of the ASABE, 51(1), * 37-44..

This outcome seems reasonable and logical since dry panels with soil substrates are known to have notable absorption properties. Furthermore, the panels were not saturated, meaning that there is still further potential for water absorption. Therefore, the panels show to be effective at peak shaving during heavy rainfalls under the given conditions.

A different set of conditions can influence the water storage capacity, mainly, the saturation levels of the substrates.

4.2 Evapotranspiration results

Evapotranspiration is largely determined by three critical factors: vegetation characteristics, substrate properties, and the surrounding environment (Barrio, 2015). It's crucial to understand how these elements impact results. For specifics on vegetation types and substrate properties, please refer to section 3.2.5. As for environmental conditions during the study: temperatures varied from 11 to 18 degrees Celsius, humidity in the laboratory was maintained at 52%, and the initial soil moisture content of the panels was approximately 2%. This setup provides a controlled environment in which the experiment is conducted.

Three tables below show the data collected in the evapotranspiration experiment.

Table 5. Weight and evapotranspiration rate of panel 1 throughout 25h.

Panel 1	
Time [h]	Weight [kg]
0 (dry)	13.21
0	13.79
1	13.74
24	13.57
25	13.49
ET rate [ml/h]	12.00

Table 6. Weight and evapotranspiration rate of panel 2 throughout 25h.

Panel 2	
Time [h]	Weight [kg]
0 (dry)	13.71
Saturated	18.86
0.5	18.83
24	18.59
25	18.48
ET rate [ml/h]	15.20

Table 7. Weight and evapotranspiration rate of panel 3 throughout 25h.

Panel 3	
Time [h]	Weight [kg]
0 (dry)	14.64
0	15.33
1	15.25
24	14.99
25	14.91
ET rate [ml/h]	16.80

Soil moisture data

When relocating the green panels to the laboratory, the soil moisture sensors from SenseBox were temporarily removed and then reinstalled after the experiments. Below is a chart depicting the data recorded by the SenseBox from May 20th to June 11th.

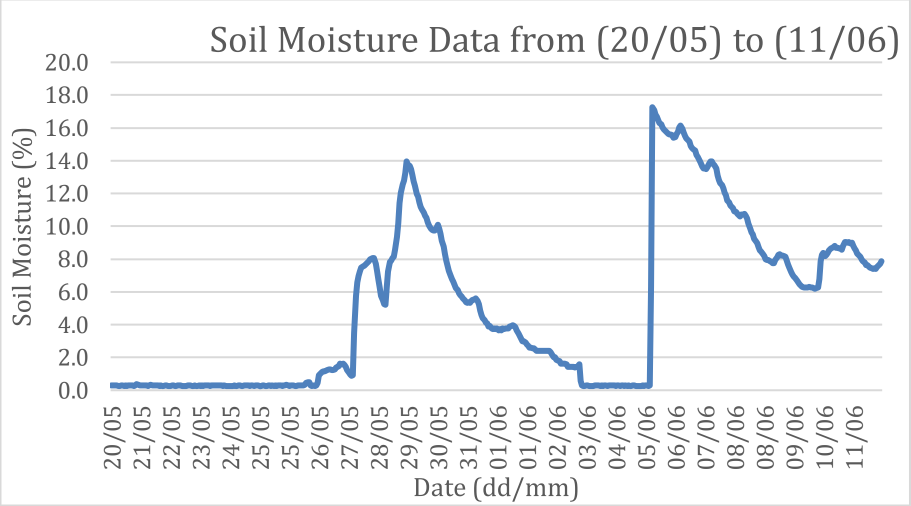

Figure 7. Soil moisture data extracted from opensensemap.org

The chart illustrates fluctuations in soil moisture during this period. Notably, the experiments conducted between June 3rd and June 5th correlate with data indicating a soil moisture level of close to 0%. This drop is due to the removal of the sensors. Once the sensors were reinserted into the panels, the recorded soil moisture levels were initially high but gradually decreased at a steady rate. The following chart provides a more detailed view of this data from June 5th to June 9th.

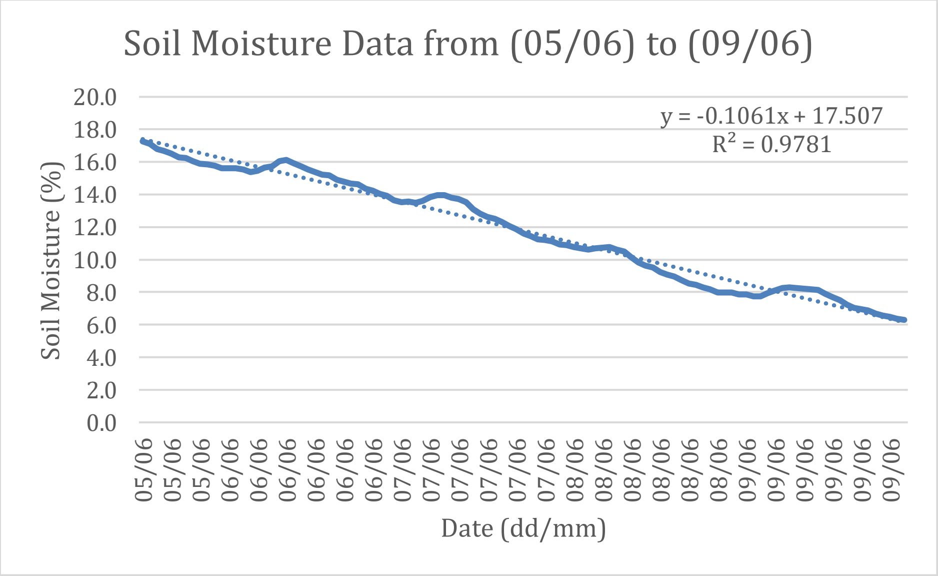

Figure 8. Soil moisture data 4 days after experiments

This portion of the data illustrates a relatively consistent decline in soil moisture. Given the absence of additional rainfall and temperatures fluctuating between 5 to 21 degrees—a typical range for early June in the Netherlands—this dataset provides a viable sample from which to derive evapotranspiration rates. The trend line fitted to the data is linear, and its equation is displayed on the graph. From this equation, a rate of change of -0.106 is derived, which is associated with evapotranspiration rates. Notably, the R-squared value of 0.9781 on the graph underscores the model's accuracy, confirming that nearly 98% of the variability in soil moisture can be explained by the model used.

4.2.1. Evapotranspiration Analysis

Evapotranspiration rates derived from Tables 5, 6 and 7 [section 4.2] show values of 12, 15.2, and 16.8 [ml/h] for panels 1, 2 and 3, respectively. With panels 1 and 3 experiencing only 1 hour of heavy rainfall (2.8mm/h). Assuming constant and linear evapotranspiration rates, as derived from the soil moisture sensor data, this would mean that panels 1 and 3 would take 48.3h and 41h, respectively, to return its original, ‘dry’ weight.

$$Hours\ until\ dry[h] = \frac{Water\ absorbed\ [ml]}{ET\ rate[ml/h]}$$

For panel 1:

$$\frac{580\,ml}{12\,ml/h} = 48.3h$$

For panel 3:

$$\frac{690\,ml}{16.8\,ml/h} = 41h$$

For panel 2 [saturated]:

$$\frac{5150\,ml}{15.2\,ml/h} = 337.8\,h$$

Results indicate that Panels 1 and 2 are expected to revert to their original "dry" weight within four days following a heavy one-hour rain event, thereby supporting the alternative hypothesis and aligning with findings from Getter and Rowe (2006). In contrast, Panel 2 requires approximately 14 days to transition from fully saturated soil back to a dry state. It is important to note that this duration assumes constant evapotranspiration rates and no additional rainfall affecting the panels. Should there be further rainfall, the time needed for the panels to dry could extend significantly.

In the Netherlands, the climate is characterized by frequent rainfall, which can complicate the scenario of a heavy one-hour rainfall followed by a dry period allowing for complete evapotranspiration. This weather challenges the effectiveness of green roofs in consistently reducing flood peaks through evapotranspiration alone, since additional rain is likely to occur before the panels fully dry. Nonetheless, the ability of green roof panels to retain and gradually release rainwater still presents a considerable advantage over traditional roofing materials, which do not offer any water retention. This initial retention and slow release of water by green panels can mitigate the immediate impact of rainfall on urban drainage systems, even if evapotranspiration does not fully proceed between rain events. Further research into optimizing these panels for the specific climatic conditions of the Netherlands is recommended to maximize their effectiveness in urban rainwater management.

4.3 Water filtration results

Pre-Filtration Water Quality Overview:

Before undergoing filtration through the green panels, the rainwater was subjected to a comprehensive quality assessment. Here are the results from the tests:

- **Total Dissolved Solids (TDS)**: The water contained 175 parts per million (ppm) of dissolved substances, indicating a moderate level of minerals and other dissolved materials.
- **16-Parameter strip test:** The analysis of the rainwater, conducted before it passed through the green panel, included testing for 16 different minerals. The results were reassuring, with all mineral levels falling within acceptable ("OK") ranges. Particularly noteworthy was the absence of potentially harmful minerals such as chlorine, bromine, nitrate, iron, chromium, lead, copper, mercury, and fluoride. This indicates that the collected rainwater is initially free from these contaminants. Additionally, while the hardness of the water was found to be on the upper end of the spectrum, it still remained within safe limits. This measure of hardness, important for assessing the water's impact on infrastructure and suitability for use, confirms the water's general quality. More detailed information regarding the 16-parameter strip test can be found in **Table 8.** *Comparison of water quality test results, before and after filtration.*
- **pH Level**: With a pH of 7.7, the water is slightly alkaline, yet still close to neutral, reflecting its balanced state and making it suitable for various uses.
- **Turbidity**: The turbidity measured at 4.75 Formazin Nephelometric Units (FNU), which represents the clarity of the water. While this level of turbidity is relatively low, it suggests a slight presence of suspended particles that could affect transparency.

Post-Filtration Water Quality Overview:

Following the filtration through the green panels, the rainwater was analyzed again to evaluate the impact of the filtration process. Here are the updated results post-filtration:

- **Total Dissolved Solids (TDS)**: The concentration of dissolved substances increased to 259 parts per million (ppm). This elevation suggests additional minerals or other materials were retained during the filtration process.
- **16-Parameter strip test:** After passing through the panels, the water showed a decrease in pH, hardness, and cyanuric acid, suggesting a softening effect by the filtration system. However, there was a detectable increase in nitrate levels, though these remain within acceptable limits. Furthermore, both alkalinity and carbonate levels experienced a sharp decline, nearing zero, which places them outside the typical "OK" range. While the reduction in these parameters might raise concerns, the overall mineral balance continues to maintain its compliance with safety standards, including the still-acceptable levels of nitrates. All measurements from the test can be seen in **Table 8.** *Comparison of water quality test results, before and after filtration.* below.
- **pH Level**: The pH decreased to 6.6, shifting from slightly alkaline to slightly acidic. This change in pH could be attributed to the filtration medium influencing the water's acidity.
- **Turbidity**: There was a significant increase in turbidity to 178 Formazin Nephelometric Units (FNU), indicating a substantial rise in the presence of suspended particles. This suggests that the filtration process may have dislodged particles or introduced new particles into the water, affecting its clarity.

The table below provides a comprehensive comparison of all parameters tested before and after the filtration process. In the table, green indicates an improvement in a parameter, while red signifies a deterioration.

Table 8. Comparison of water quality test results, before and after filtration.

Parameter	Before Filtration	After Filtration
pH	7.7	6.6
Carbonate	40 mg/L	0 mg/L
Hardness	50-100 mg/L	0-25 mg/L
Cyanuric Acid	0-30 mg/L	0 mg/L
Total Chlorine	0 mg/L	0 mg/L
Free Chlorine	0 mg/L	0 mg/L
Free Bromine	0 mg/L	0 mg/L
Nitrate	0 mg/L	10 mg/L
Nitrite	0 mg/L	0 mg/L
Iron	0 mg/L	0 mg/L
Chromium	0 mg/L	0 mg/L
Lead	0 ppb	0 ppb
Copper	0 mg/L	0 mg/L

Mercury	0 mg/L	0 mg/L
Floride	0 mg/L	0 mg/L
Turbidity	4.75 FNU	178 FNU
Total Dissolved Solids (TDS)	175 ppm	257 ppm

4.3.1 Water Filtration Analysis

Testing the water before and after passing through the green panels revealed notable differences in quality. Most notably, a decrease in carbonate from 40 mg/L to 0, hardness from a range of 50-100 mg/L to 0-25 mg/L, and cyanuric acid from 0-30 mg/L to 0. On the other hand, nitrite levels increased from 0 to 10 mg/L, total dissolved solids (TDS) rose from 174 ppm to 259 ppm, pH levels dropped from 7.7 to 6.6, and turbidity significantly escalated from 4.75 FNU to 178 FNU. These changes highlight mixed results in the panel's filtration capabilities: while they effectively reduced some contaminants, they also aggravated others, particularly in terms of turbidity and TDS.

The varied performance of the green panels as a filtration tool suggests their potential to selectively filter specific pollutants, although their overall effectiveness is limited without additional modifications such as a dedicated filter layer. The increase in turbidity and TDS, alongside the drop in pH, indicates that while certain elements are being removed or enhanced, others are either being introduced by the panels. These results highlight the importance of considering specific filtration targets and possibly redesigning the panels to enhance their overall filtration efficacy. This evaluation aligns with findings from Berndtsson (2009), which caution that 'the initial runoff from impermeable surfaces after a dry period is typically more contaminated than subsequent runoff,' suggesting that under certain conditions, the panels could inadvertently contribute to water contamination rather than alleviate it, as seen in the results of this experiment.

4.4 Implications of findings

The experiments on water storage and evapotranspiration using green roof panels demonstrated substantial benefits, achieving up to 81% reduction in peak runoff during heavy rainfall events lasting one hour. These experiments also revealed that a significant portion of the retained water is returned to the atmosphere within four days, showcasing the panels' effectiveness as green rainwater infrastructure—a positive development for sustainable urban planning. Thes outcomes highlight the significant benefits that municipalities, businesses, and citizens in the Netherlands, as well as surrounding countries with similar climates, could gain from adopting green roof panels for enhanced rainwater management. By implementing green roof panels as a first line of defence in rainwater infrastructure, these can also help extend the lifespan of municipal drainage systems by reducing overload and subsequent wear. This could lead to decreased maintenance costs and lower environmental impact. Literature and prior studies corroborate these results, presenting green roof panels as a practical solution to alleviate the challenges posed by intense rainfall in urban environments.

However, the water filtration experiments did not meet expectations as the water quality deteriorated post-filtration. This was likely due to the panels not being originally designed for filtration purposes, coupled with the 'first flush' effect described by Berndtsson (2009). Future enhancements, such as integrating a dedicated filtration layer, could potentially improve these outcomes.

Despite the setbacks in water filtration, green panels have proven to be an effective tool in managing urban rainfall events, aiding in the development of environmental management strategies. On a policy level, these findings could drive reforms and public engagement initiatives aimed at expanding the installation of green roofs. Local governments could foster policies that incentivize green roof adoption, perhaps through subsidies or reduced property taxes for buildings that install such systems. Public engagement efforts could focus on educating the community about the benefits of green roofs, potentially leading to broader support and involvement in sustainable urban development projects.

Overall, the adoption of green roof panels can play a crucial role in transforming urban environments in the Netherlands, aligning with broader environmental goals, and enhancing the quality of urban life and security. However, it's important to note that while the experiments conducted demonstrate their potential under controlled conditions, they offer limited insights compared to real-world applications. This aspect and its implications will be further explored in the following 'limitations and delimitations' section.

4.5 Limitations and Delimitations

This research, while comprehensive in its approach to exploring the capabilities of green roof panels for urban rainwater management, encountered several limitations that impact the applicability of its findings to broader, real-world scenarios. These constraints are important to recognize as they frame the context in which the results should be interpreted and understood. The following points outline key limitations and delimitations that influenced the research outcomes and their potential generalization:

- **Material Constraints**: The experiments were conducted with the materials that were readily available, which limited the scope of testing. While more precise water quality assessments are feasible, they would require engagement with third-party private companies, incurring costs that exceed our current budget.
- **Measurement Precision**: The precision of environmental measurements was compromised by the availability of only basic sensors. This limited our ability to capture highly accurate environmental data.
- **Monitoring Limitations**: Ideally, the weight of the panels would be continuously monitored; however, the lack of necessary equipment meant that we could not supervise the weight changes of the panels constantly.

- **Experimental Setup**: For safety reasons, the panels were stored indoors in the water lab overnight, which may not precisely replicate external environmental conditions. Moreover, the panels were placed flat rather than at an angle, as they typically would be on roofs, potentially affecting the results.
- **Environmental Conditions**: The experiments were limited by the uniformity of the climate during the testing period, which was predominantly sunny. This does not reflect the varied conditions these panels might encounter in real life, such as extended periods of rain leading to saturation, which could influence their filtration, storage, and evapotranspiration capacities differently.
- **Source of Rainwater**: The rainwater used was collected from the roof of the high-tech factory on campus and was stored underground, which might not perfectly simulate rainwater's typical conditions in other settings.
- **Environmental Variation in Testing**: The experiments were designed with limited environmental variation, testing specific conditions such as a rainfall intensity of 2.8mm/h and only the initial runoff for filtration capabilities. To provide a comprehensive understanding, future research should include a broader range of environmental testing to assess the panels' performance under varied and realistic scenarios.

While the findings from the experiments provide valuable insights, it's crucial to approach them with caution before applying them broadly. To ensure our results are robust and widely applicable, future research should expand the variety of materials and equipment used. This would enhance data accuracy and allow for more precise observations. Moreover, by simulating a wider range of environmental conditions, closer to what one might find in typical urban environments, we can ensure our findings are truly reflective of real-world scenarios.

Chapter 5: Conclusion

This research aimed to quantify, under lab conditions, the benefits of green roof panels in stormwater management, specifically focusing on water absorption, evapotranspiration, and filtration. A review of various sources of literature revealed a gap in empirical studies quantifying the potential of green roof panels during the initial hours of heavy rainfall, leading to the execution of three targeted experiments.

The experiments were designed to test three hypotheses:

1. **Water Retention (Storage)**: It was hypothesized that the green roof panel would retain 60-75% or more of the applied water, significantly reducing runoff. This hypothesis was supported by the outcomes, aligning with findings from Hathaway et al. (2008).

2. **Water Evapotranspiration**: The expectation was that water in the panels after 1 hour of heavy rainfall would evaporate back into the atmosphere within four days or less. Results were consistent with Getter and Rowe (2006), confirming the hypothesis.
3. **Water Filtration**: The hypothesis was that the green roof panels would effectively filter suspended solids, heavy metals, and other compounds, and not contaminate the rainwater, while increasing the pH from 5-6 to 7-8. This was the only hypothesis not supported by the results, as the panels did not demonstrate effective water filtration capabilities with the current design and conditions.

These findings, while obtained under controlled laboratory conditions, demonstrate the potential of green roof panels to contribute to peak-shaving and thus to flood prevention under the conditions explored. It is crucial to recognize that these results are preliminary, given the experimental limitations discussed previously. Real-life application and long-term monitoring are required to fully validate these benefits in urban environments.

The integration of such green infrastructure aligns with current environmental policies and challenges, such as the National Delta Programme 2024 and the Sustainable Development Goals (SDGs), particularly the 6th and 11th goals focusing on clean water and sustainable cities. Furthermore, this research advances the field of civil engineering by demonstrating the practical applications of green infrastructure development and highlights the importance of incorporating ecological principles into engineering solutions.

Overall, this study not only fills a crucial knowledge gap regarding the water retention, evapotranspiration, and filtration capabilities of green panels under specific laboratory conditions but also sets the stage for future research to explore modifications that could enhance the multifunctional benefits of green roofs. Further research and testing are imperative to substantiate these findings in real-world settings, which would require extended monitoring and more sophisticated tools than were available for this study. The following section on recommendations will outline specific future studies and modifications needed to advance this field.

Chapter 6: Recommendations

After an extensive dive into the role of green roof panels as sustainable rainwater management infrastructure in urban areas, several opportunities for further investigation arose.

Firstly, while the water filtration capability of green panels needs more exploration, it appears that in the Netherlands, where rainwater is already of low pollution, prioritizing water filtration may not be essential. Instead, focusing on enhancing water storage and evapotranspiration capabilities may offer greater benefits. Some of the most concrete recommendations are the following:

1. **Design improvements for water retention**: Given the substantial water storage and evapotranspiration successes observed, I recommend further design enhancements specifically aimed at maximizing these aspects. This could involve optimizing the substrate depth and composition or experimenting with different types of vegetation that may increase these capabilities without compromising structural integrity.
2. **Policy advocacy**: The benefits observed from the implementation of green panels suggest that urban planning and development policies should actively encourage their adoption, especially with the spatial constraints that the Netherlands is experiencing, in combination with the urge for sustainable water management infrastructure. Such policies could offer incentives for buildings and developments that integrate green roofs, potentially facilitating broader environmental benefits across urban areas.
3. **Community engagement**: I urge local municipalities, businesses, and private citizens to consider the adoption of green panels in their developments and designs. Engaging these stakeholders through educational outreach could increase awareness and adoption rates, furthering the integration of green infrastructure within the community.
4. **Constant monitoring and evaluation**: To truly capitalize on the potential of green roofs, I recommend establishing a comprehensive monitoring framework to track the performance of installed systems over time. This data should be used to continuously refine and enhance design and maintenance practices, ensuring that green roofs remain effective under varying environmental conditions.
5. **Further research and interactions between variables:** Further research towards understanding the relationship between vegetation and stormwater management, as preliminary data suggests a complex interaction that could influence evapotranspiration rates. Extended studies across different climates and with varied panel configurations would provide deeper insights into the optimal setup for maximizing the environmental benefits of green roofs. Lastly, future research should investigate the interplay between various benefits provided by green roofs. For example, exploring how enhancements in rainwater management could impact urban heat island mitigation could provide valuable insights into the multifunctional advantages of green infrastructure.

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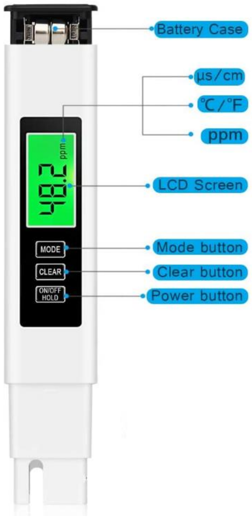
Appendices

Appendix A: Materials used for experiments.

- Scale max 30kg, 0.01kg

- 3 panels from Green Panels B.V. (numbered):

- Total Dissolved Solids measurer (manufacturer: BMUT UG)



- Product description:
  - 3in1 - Reliably measure TDS, EC & Temperature. Three different measurement requirements can be met by one meter.

    - Equipped with a high-quality titanium alloy probe, the TDS water quality tester enables a quick and convenient test. Suitable for drinking water test, swimming pool, laboratory, plants, aquarium, well water, etc.

TDS = The TDS value indicates the sum of the solids dissolved in a solution in the water. Solids are, for example, salts, minerals and metals.

EC = The EC measurement value is used to measure the nutrient concentration in the irrigation water. This ensures that plants have the maximum amount of nutrients available without being damaged due to overdosing.

For further information, access: https://www.bmut.de/en/product/3in1-tds-digitaler-wasserqualitaetstester-und-ec-sowie-temperatur-meter-ppm-ionen/

- Water tester strips (manufacturer: ausyde)

Testing 16 parameters: PH, hardness, cyanuric acid, mercury, fluoride, carbonate root, total alkalinity, chrome, lead, copper, total chlorine, free bromine, nitrite, and iron.

Manufacturer instructions: 1. Dip a drinking water test strip in water for 2 seconds. 2. Take it out and hold for 15 seconds. Do not shake the strip. 3. Compare with the color chart.

For further information, access: https://www.amazon.nl/-/en/AUSYDE-Drinking-Hardness-Measure-Chlorine/dp/B0BHF514VT

- PH meter (manufacturer Hanna Instruments)

Product description:

The HI98107 features a large multi-level LCD which displays both pH and temperature readings simultaneously. The pH readings are displayed with a 0.1 pH resolution and with an accuracy of ±0.1 pH. The pH range of the HI98107 is from 0.0 to 14.0 pH. An exposed temperature sensor allows for rapid automatic temperature compensated pH measurements. Temperature can be set to display in °C or °F. The LCD screen has stability and calibration tag indicators. The battery percent level is displayed at start up alerting the user to the remaining battery power that is available.

For further details, access: https://www.hannainst.com/hi98107-phep-ph-tester.html

- Turbidimeter (manufacturer WTW - Xylem Inc)

Product description:

Turbidity measurement acc. To DIN ISO 27027 for any demand up tp 1100 NTU with lab option

• Measuring range comprises 0.02 -1100 NTU/FNU with automatic measuring range switching

• Adjustable calibration intervals and GLP-compliant documentation

• Stray light behavior according to pharmacopoeia 5.0

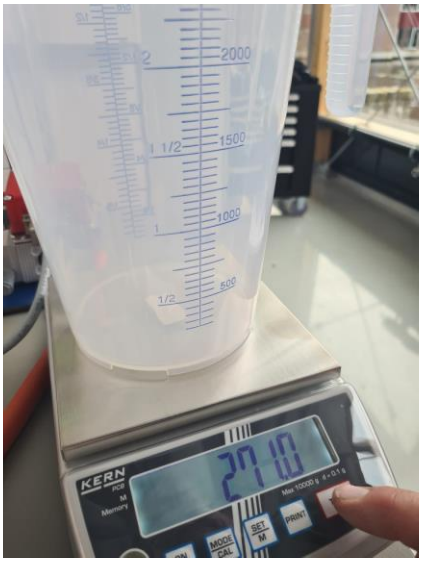
• Higly precise AMCO Clear® Standards

For further details, access: https://www.xylemanalytics.com/en/general-product/id-1393/portable-turbidity-meter-turb%C2%AE-430-ir---wtw

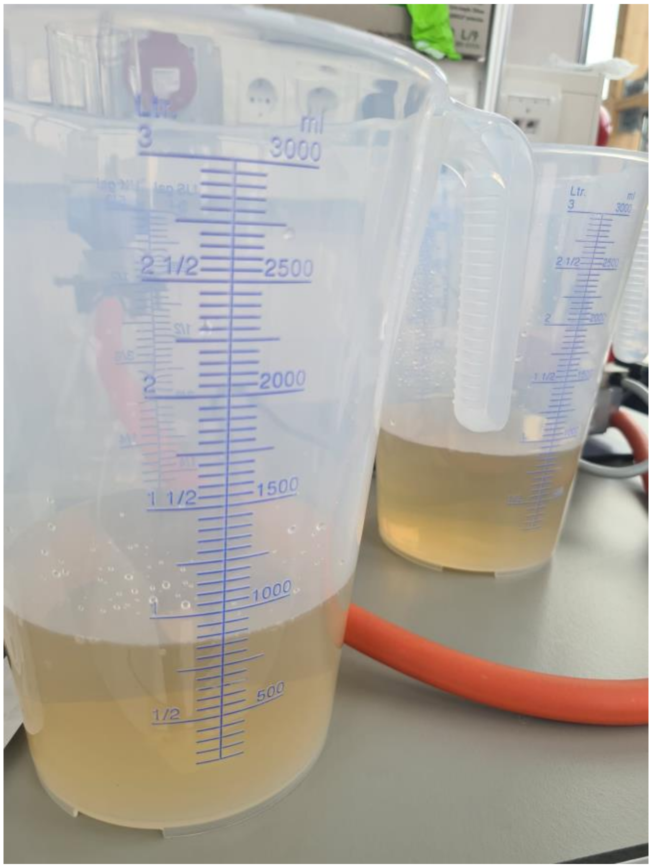
- Soil moisture & Temperature sensors (SMT50)

https://sensebox.shop/product/bodenfeuchte-temperatursensor-smt50
additional specifications: https://www.truebner.de/assets/download/Manual_SMT50.pdf
Operating range: -20 to +85 °C, 0 – 50 % VWC volumetric water content

- Lab plastic beakers



- Rain water samples collected from the roof of High Tech Factory (University of Twente campus)


Ltr
ml
3
3000
2 1/2
2500
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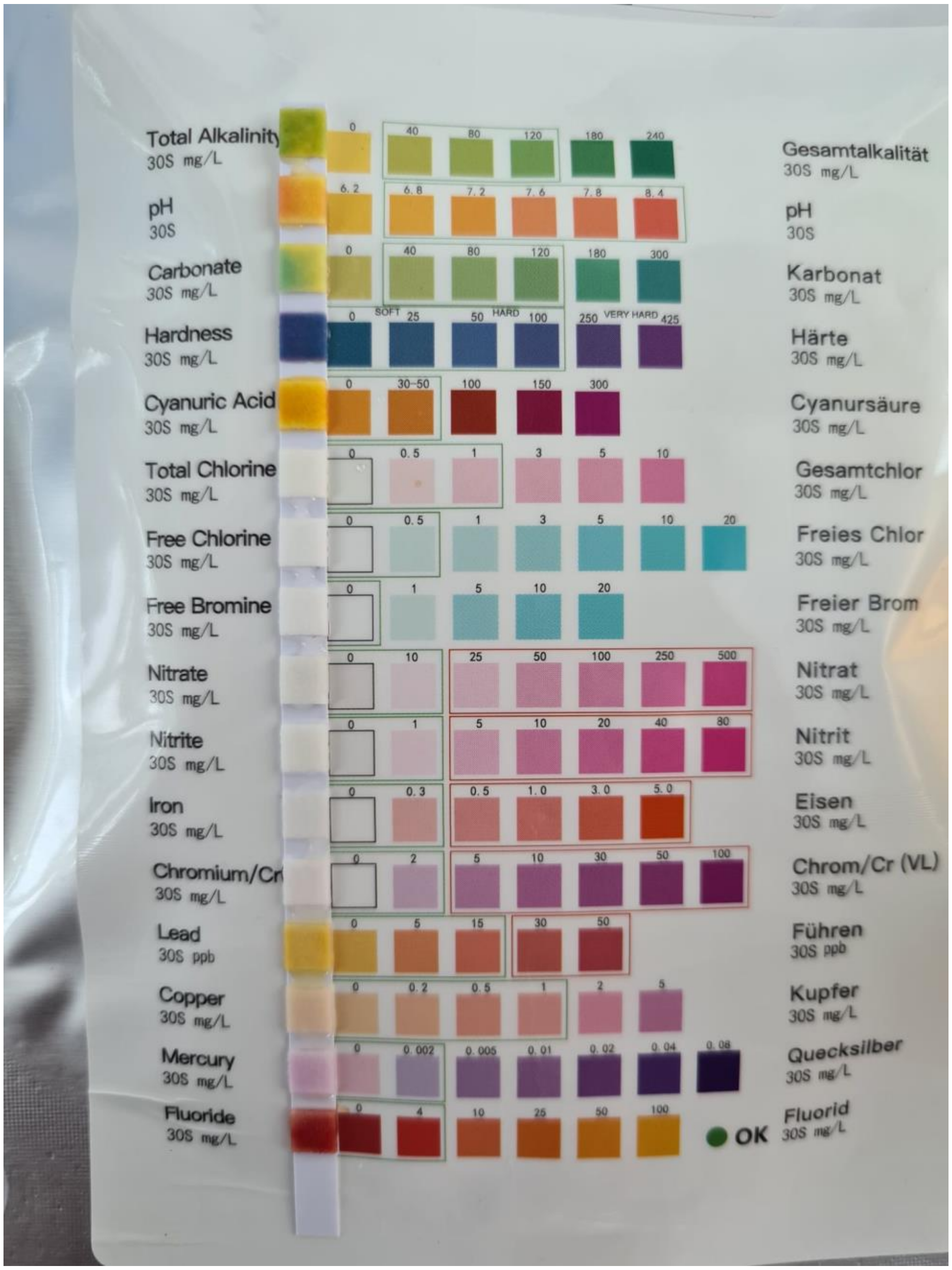
2000
1 1/2
1500
1
1000
1/2
500

Appendix B: 16-parameter test results



Total Alkalinity	30S mg/L	0	40	80	120	180	240		Gesamtalkalität	30S mg/L
pH	30S	6.2	6.8	7.2	7.6	7.8	8.4		pH	30S
Carbonate	30S mg/L	0	40	80	120	180	300		Karbonat	30S mg/L
Hardness	30S mg/L	0	SOFT 25	50 HARD	100	250 VERY HARD	425		Härte	30S mg/L
Cyanuric Acid	30S mg/L	0	30-50	100	150	300			Cyanursäure	30S mg/L
Total Chlorine	30S mg/L	0	0.5	1	3	5	10		Gesamtchlor	30S mg/L
Free Chlorine	30S mg/L	0	0.5	1	3	5	10	20	Freies Chlor	30S mg/L
Free Bromine	30S mg/L	0	1	5	10	20			Freier Brom	30S mg/L
Nitrate	30S mg/L	0	10	25	50	100	250	500	Nitrat	30S mg/L
Nitrite	30S mg/L	0	1	5	10	20	40	80	Nitrit	30S mg/L
Iron	30S mg/L	0	0.3	0.5	1.0	3.0	5.0		Eisen	30S mg/L
Chromium/Cr	30S mg/L	0	2	5	10	30	50	100	Chrom/Cr (VL)	30S mg/L
Lead	30S ppb	0	5	15	30	50			Führen	30S ppb
Copper	30S mg/L	0	0.2	0.5	1	2	5		Kupfer	30S mg/L
Mercury	30S mg/L	0	0.002	0.005	0.01	0.02	0.04	0.08	Quecksilber	30S mg/L
Fluoride	30S mg/L	0	4	10	25	50	100	● OK	Fluorid	30S mg/L

16-Parameter water quality test before filtration.

16-Parameter water quality test after filtration.

Appendix C: Detailed Experimental Protocol

Evaluation of Water Retention, Filtration and Evapotranspiration Efficiency of Green Roof Panels

Summary

This study aims to investigate the water retention and filtration efficiency of a single modular green roof panel. The objectives are to measure the panel's water storage capacity and evaluate its ability to filter contaminants from rainwater. This will be accomplished by conducting experiments on three green roof panels. The experiments involve assessing the initial soil moisture and 'dry' weight of the panel, as well as analyzing the quality of rainwater before and after it passes through the panel. The hypotheses are that the panel will retain 60-75% of the 2.5 mm/h of water applied, simulating a heavy rainfall; and reduce suspended solids and heavy metals by at least 50% after passing through the green panel's substrate.

Introduction

Green roofs are increasingly used in urban areas to manage stormwater, improve air quality, and reduce the urban heat island effect. This study focuses on two key functions of green roofs: water retention and water filtration. Previous research by Hathaway et al. (2008) has shown that green roofs can significantly reduce peak flow rates. On the other hand, a study by Berndtsson (2009) states that the most often found pollutants in stormwater are heavy metals, petroleum hydrocarbons, pesticides, suspended solids, nutrients, and pathogenic microorganisms. Rainwater passing through the green panels will be tested to conclude if there is a reduction of these pollutants. This study aims to replicate and expand upon these findings by conducting controlled experiments on a modular green roof panel.

Experiment 1: Water Storage

Objectives

- To measure the water retention capacity of a single modular green roof panel on a simulated heavy rainfall (2.5 mm/h).

Materials

- 3 modular green roof panel (approx. 0.3 sq meters)
- Locally sourced rainwater samples (min. 2.5L)
- Collection containers

- Weighing scale

Methodology

1. Initial Conditions Measurement:
    - Record initial soil moisture
    - Weighing the three green panels to determine its 'dry' weight, noting that it might not be completely dry.

2. Panel positioning:
    - Position the panels on a 45 degree angle, simulating the placement on a typical sloped Dutch roof.

3. Water Retention testing:
    - Apply a known volume of rainwater (2.5 L) evenly over the panel using the collected rain samples
    - After a specified time (1 hour), measure the weight of the panel again to determine the increase in weight due to water retention.
    - Calculate the percentage of water retained by the panel.

Hypothesis

The green roof panel will retain 60-75% of the applied water, reducing runoff significantly, consistent with findings from Hathaway et al. (2008).

Detailed Steps
1. Weigh the dry panels individually and record their ‘dry’ weight.
2. Position the panels in a 45-degree angle.

3. Calculate the amount of rainwater to be applied (a minimum of 2.5mm/h to be considered a heavy rainfall):

0.861L of water was used in the lab, which corresponds to: 0.861L/0.3m^2 = **2.87mm/h**

3. Apply the rainwater evenly and steadily over the panels (861ml)
4. After 1 hour, weigh the panel again to determine the weight difference, which corresponds to the amount of water retained.
5. Calculate the retention percentage using the formula:

Retention Percentage = ((weight of wet panel – weight of dry panel)/ water applied) × 100

Experiment 2: Water Filtration

Objectives

- To assess the filtration efficiency of the green roof panel by analyzing the quality of rainwater before and after passing through the panel.
- To test for pH, turbidity, suspended solids, nutrients, and heavy metals.

Materials

- 1 modular green roof panel (approx. 0.3 sq meters)
- Locally collected rainwater samples
- Collection containers
- pH meter
- Turbidity meter
- Suspended solids meter (TDS)
- Nutrient and heavy metal analysis kits (for nitrates, phosphates, lead, cadmium, etc.)

Methodology

1. Initial Conditions Measurement:
   - Collect local rainwater samples and place in a beaker
   - Analyze the rainwater samples for pH, turbidity, suspended solids, nutrients, and heavy metals before applying them to the green roof panel.

2. Water Filtration Testing:

   - Apply the analyzed rainwater to the panel.
   - Collect the runoff water after it passes through the panel.
   - Analyze the runoff water for the same parameters: pH, turbidity, suspended solids, nutrients, and heavy metals.
   - Compare the results before and after filtration to determine the filtration efficiency of the panel.

Hypothesis

The green roof panel will reduce suspended solids, heavy metals and other compounds found initially by at least 50%.

Detailed Steps

1. Collect and record the initial pH, turbidity, suspended solids, nutrient, and heavy metal concentrations of the rainwater samples.
2. Apply rainwater evenly over the panel until over-saturated.
3. Collect the runoff water after it passes through the panel.
4. Measure the pH, turbidity, suspended solids, nutrients, and heavy metals in the runoff

water.
5. Calculate the percentage reduction for each parameter using the formula:

Reduction Percentage = ((Initial concentration - Runoff concentration) / Initial concentration) × 100

Experiment 3: Evapotranspiration Rates

Objectives

- To assess the evapotranspiration rates of a single modular green roof panel over a specified period.

Materials

- 3 modular green roof panels (approx. 0.3 sq meters each)
- Rainwater samples
- Weighing scale

Methodology

1. Initial Conditions Measurement:
    - Measure the initial 'wet' weight of the green roof panel immediately after watering to field capacity.
    - Record environmental conditions such as temperature, humidity, and sunlight exposure.
2. Evapotranspiration Testing:
    - Place the panel under controlled or natural environmental conditions.
    - After a predetermined number of hours (24 hours), weigh the panel again to determine the change in weight.
    - Calculate the amount of water lost due to evapotranspiration using the difference in initial and final weights.

Hypothesis

The water in the panels after 1h of heavy rainfall should be evaporated back into the atmosphere within four days or less, in accordance with findings from Getter and Rowe, 2006.

Detailed Steps

1. Ensure the green roof panel is evenly saturated to its field capacity.
2. Weigh the panel and record the initial weight.
3. Place the panel in the test environment for 24 hours under typical weather conditions.

4. Weigh the panel again after the test period.
5. Calculate the evapotranspiration by subtracting the final weight from the initial weight.
6. Analyse the data to understand the rates of evapotranspiration.