UNIVERSITY OF SÃO PAULO
POLYTECHNIC SCHOOL

LUCAS GOBATTI

Nature-based Solutions for rainwater management in São Paulo:
hydrological performance and plant dynamics of vegetated roofs with different substrate depths

São Paulo
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Concentration area: Civil Construction Engineering Innovation

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Dedicated to the moon reflected on the water

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“Deus sive Natura [God, or Nature]”

(SPINOZA, 1677)

Resumo

GOBATTI, L. **Soluções baseadas na Natureza para gestão de águas pluviais em São Paulo**: desempenho hidrológico e dinâmica da plantação em tetos vegetados com diferentes profundidades de substrato. 2022. Dissertação (Mestrado em Ciências) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2022.

Em cidades densamente edificadas como São Paulo, onde a urbanização alterou profundamente o ciclo hidrológico, a gestão de águas pluviais torna-se uma problemática. A impermeabilização do solo diminui a infiltração, aumentando o escoamento superficial, diminuindo a perda por evapotranspiração e aumentando a temperatura das cidades. As Soluções baseadas na Natureza têm o potencial de agir sobre este cenário, gerindo a água de chuva próxima onde precipita. E dentro desta gama de possibilidades em Infraestrutura Verde e Azul, os tetos vegetados extensivos destacam-se para cidades compactas. Onde a competição por uso do solo térreo é alta, gerir as águas pluviais no topo de coberturas é uma possibilidade a ser mais explorada. Porém, pouco se sabe do desempenho hidrológico destes tetos verdes para o clima da cidade de São Paulo. Além disso, poucos experimentos laboratoriais com coleta de dados em tempo real e instrumentação robusta foram executados na cidade, o que demonstra o hiato neste campo científico. Dessa forma, o presente trabalho tem como objetivo quantificar o desempenho hidrológico de tetos vegetados correlacionando às suas condições ambientais e ao mesmo tempo investigar sua dinâmica de vegetação, dada a íntima interdependência entre água, vegetação e calor. Para isto, protótipos edificados de teto vegetado extensivo e telhado cerâmico foram instrumentados e novos modelos com profundidade variada de substrato foram construídos, avaliando o desempenho comparativo destas estruturas. Resultados demonstram que tetos vegetados sem manutenção por mais de 10 anos têm capacidade de reter de 34 a 100% da água de chuva e atrasar de 14 a 37 minutos e diminuir de 30 a 100% a vazão de pico do escoamento resultante. A vegetação espontânea nos modelos laboratoriais também é caracterizada, indicando que substratos com 10 cm podem ter desempenho ótimo para o crescimento de espécies de *Arachis repens* em conjunto a vegetação espontânea, com alguma manutenção recorrente. O trabalho demonstra a correlação entre o desempenho hidrológico do teto, sua estrutura física e também sua condição antecedente aos eventos de chuva analisados. Seu desempenho hídrico aumenta tanto quanto sua profundidade de substrato aumenta e quanto sua umidade prévia diminui. Conclui-se que os tetos vegetados extensivos têm alta capacidade de retenção da chuva incidente e detenção do escoamento resultante, ao mesmo tempo que podem gerar habitat para grande diversidade de espécies sob o clima de São Paulo. Espera-se que o trabalho contribua para a normatização destas estruturas no Brasil e fundamente sua implantação em larga escala através de política pública baseada em evidências científicas.

Palavras-chaves: Teto verde. Profundidade de substrato. Vegetação espontânea. Chuva-vazão. Gestão de águas pluviais.

Abstract

GOBATTI, L. **Nature-based Solutions for rainwater management in São Paulo:** hydrological performance and plant dynamics of vegetated roofs with different substrate depths. 2022. Dissertação (Mestrado em Ciências) – Polytechnic School, University of São Paulo, São Paulo, 2022.

In densely built cities like São Paulo, where urbanisation has profoundly altered the hydrological cycle, rainwater management becomes a concern. Soil waterproofing reduces infiltration, increases surface runoff, decreases evapotranspiration loss and increases the temperature of cities. Nature-based solutions have the potential to act on this scenario, managing rainwater close to where it precipitates. Extensive vegetated roofs stand out for compact cities within this range of Blue-Green Infrastructure possibilities. Where competition for ground land use is high, managing rainwater on top of roofs should be further explored. However, little is known about the hydrological performance of green roofs under the climate of São Paulo. In addition, few laboratory experiments with real-time data collection and robust instrumentation were performed in the city, demonstrating the gap in this scientific field. Thus, the present work aims to quantify the water performance of vegetated roofs correlating with its surrounding environmental conditions and, at the same time, investigate its vegetation dynamics, given the intimate interdependence between water, vegetation and heat. For this, built prototypes of an extensive vegetated roof and a ceramic tiled roof were instrumented, and new models with varying substrate depths were built, evaluating the comparative performance of these structures. Results show that ten years unmanaged vegetated roofs can retain 34 to 100% of rainwater and delay from 14 to 37 minutes and decrease the peak runoff by 30 to 100%. Spontaneous vegetation in laboratory models is also characterised, indicating that substrates with 10 cm may have optimal performance for the growth of *Arachis repens* species along with spontaneous vegetation, with some recurrent maintenance. The work demonstrates the correlation between the hydrological performance of the roof, its physical structure and its antecedent condition to the analysed rain events. Its water performance increases as its substrate depth increases and as its previous moisture decreases. It is concluded that the extensive vegetated roofs have a high capacity to retain incident rain and detain the resulting runoff, and at the same time generate habitat for a great diversity of species under the climate of São Paulo. It is expected that the work will contribute to the standardisation of these structures in Brazil and support their large-scale implementation through public policy based on scientific evidence.

Keywords: Green roof. Substrate depth. Spontaneous vegetation. Rainfall-runoff. Rainwater management.

List of Figures

List of Charts

List of Tables

List of abbreviations and acronyms

ASMC	Antecedent Soil Moisture Content
ADWP	Antecedent Dry Weather Period
A1-A5	Events 1 to 5 in Experiment A
BC	Before Christ
BGI	Blue-Green Infrastructure
B1-B3	Events 1 to 3 in Experiment B
CAM	Crassulacean Acid Metabolism
CAPES	Coordenação de Aperfeiçoamento de Pessoal do Ensino Superior
CFD	Computational Fluid Dynamics
CR	Conventional roof
CT	Ceramic tiled roof prototype
CTH	Centro Tecnológico de Hidráulica
DAEE	Departamento de Águas e Energia Elétrica
DOI	Digital Object Identifier
ES	Ecosystem Services
ESCS	Expanded Shale, Clay and Slate
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FAPESP	Fundação de Amparo à Pesquisa do Estado de São Paulo
FCTH	Fundação Centro Tecnológico de Hidráulica
GIS	Geographic Information System
GRO	Green Roof Organisation
IDF	Intensity-Duration-Frequency
IoT	Internet of Things
IP	Internet Protocol

IUCN	International Union for the Conservation of Nature
LED	Light-emitting diode
LID	Low-Impact Development
MA	Millennium Ecosystem Assessment
M1-M4	Models 1 to 4 (Experiment B and C)
NbS	Nature-based Solutions
NFM	Natural Flood Management
NGO	Non-Governmental Organisation
NWRM	Natural Water Retention Measures
PAW	Plant available water
RES	Regulatory Ecosystem Services
SI	International System of Units
SD	Standard Deviation
SDG	Sustainable Development Goals
ST	Social technology
SuDS	Sustainable Drainage Systems
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environment Programme
USD	United States dollar
USP	Universidade de São Paulo
VR	Vegetated roof prototype
WiFi	Wireless Fidelity

List of symbols

L	Dimension symbol for length
M	Dimension symbol for mass
T	Dimension symbol for time
I	Dimension symbol for current
$\mathsf{\Theta}$	Dimension symbol for temperature
N	Dimension symbol for amount
J	Dimension symbol for light intensity
V	Volume [L^3]
q	Electric charge [TI]
Q	Heat [$\mathsf{L}^2\mathsf{MT}^{-2}$]
P	Momentum [LMT^{-1}]
Φ_V	Volumetric flow rate [$\mathsf{L}^3\mathsf{T}^{-1}$]
I	Electric current [I]
$\dot{Q}$	Heat transfer rate [$\mathsf{L}^2\mathsf{MT}^{-3}$]
v	Velocity [LT^{-1}]
j	Electric current density [$\mathsf{L}^{-2}\mathsf{I}$]
$\dot{Q}''$	Heat flux [MT^{-3}]
σ	Stress [$\mathsf{L}^{-1}\mathsf{MT}^{-2}$]
p	Pressure [$\mathsf{L}^{-1}\mathsf{MT}^{-2}$]
ϕ	Electric potential [$\mathsf{L}^2\mathsf{MT}^{-3}\mathsf{I}^{-1}$]
Θ	Temperature [$\mathsf{\Theta}$]
F	Force [LMT^{-2}]
N	Number of effective records reviewed [1]
C	Coefficient of runoff (rational method) [1]
Q_{VR}	Vegetated roof runoff flow rate [$\mathsf{L}^3\mathsf{T}^{-1}$]

R	Rainfall flow rate [$\mathsf{L}^3\mathsf{T}^{-1}$]
A_{roof}	Roof area [L^2]
t	Time [T]
RR	Retention rate [1]
ΔQ^P	Peak attenuation [$\mathsf{L}^3\mathsf{T}^{-1}$]
Q_{CR}^P	Conventional roof peak runoff [$\mathsf{L}^3\mathsf{T}^{-1}$]
Q_{VR}^P	Vegetated roof peak runoff [$\mathsf{L}^3\mathsf{T}^{-1}$]
$\Delta\mathrm{t}^P$	Peak runoff delay [T]
$t_{Q_{VR}}^P$	Vegetated roof peak runoff time [T]
$t_{Q_{CR}}^P$	Conventional roof peak runoff time [T]
$\Delta\mathrm{t}^S$	Runoff starting time delay [T]
$t_{Q_{VR}}^S$	Vegetated roof runoff starting time [T]
$t_{Q_{CR}}^S$	Conventional roof runoff starting time [T]
N_1	Records published in Group A [1]
N_2	Records published in Group B [1]
n	Number of independent experiments within N [1]
c	Speed of sound propagation in the air [LS^{-1}]
d	Distance [L]
t'	Time duration of US-025 trigger pulse [T]
α	Angle of effect of US-025 sensor [1]
T	Time step data resolution [T]
H	Stone barrier height [L]
L	Water level [L]
P	Height of the weir notch vertex [L]
h_{max}	Maximum designed weir water height capacity [L]
q	Flow rate [$\mathsf{L}^3\mathsf{T}^{-1}$]
β	Weir notch crest design angle [1]

ϵ	Weir notch crest design thickness [L]
h	Water level from the weir notch vertex [L]
C_d	Coefficient of runoff (thin plate weir) [1]
V_t	Theoretical velocity of the fluid [LT^{-1}]
A	Weir tank length [L]
B	Weir tank width [L]
θ	Thin plate triangular weir angle [1]
g	Earth's gravity acceleration [LT^{-2}]
q_{design}	Imposed design flow rate [$\mathsf{L}^3\mathsf{T}^{-1}$]
h_{design}	Imposed design height [L]
d_P	Distance from US-025 sensor to weir vertex [L]
Q	Flow rate [$\mathsf{L}^3\mathsf{T}^{-1}$]
i	Generic time step counter [1]
ϕ	Relative air humidity [1]
c^*	Speed of sound corrected [LT^{-1}]
γ	Correction factor for speed of sound [1]
γ^*	Correction factor derived [1]
h^*	Corrected water level from weir notch vertex [L]
Q_{ET}	Plant evapotranspiration flow rate [$\mathsf{L}^3\mathsf{T}^{-1}$]
Q_{runoff}	Runoff [$\mathsf{L}^3\mathsf{T}^{-1}$]
C_{inf}	Soil infiltration rate capacity [$\mathsf{L}^3\mathsf{T}^{-1}$]
C_{fb}	Freeboard storage capacity [L^3]
$Q_{overflow}$	Overflow flow rate [$\mathsf{L}^3\mathsf{T}^{-1}$]
δR	R error [$\mathsf{L}^3\mathsf{T}^{-1}$]
δQ_{runoff}	Q_{runoff} error [$\mathsf{L}^3\mathsf{T}^{-1}$]
t_1	Duration of Experiment B [T]
t_2	Time substrate field capacity is reached [T]

Contents

1. Introduction

2. Objectives

3. Theoretical background

4. Methods

5. Review of vegetated roofs rainwater management in Brazil

6. Experimental runoff measurement in vegetated roofs

7. Effects of substrate depth in the vegetated roof runoff

8. Unmanaged subtropical green roof vegetation

9. Discussion

10. Conclusions

11. Further work

References

A. Open access data

1 Introduction

> Freedom does not consist in any dreamt-of independence from natural laws, but in the knowledge of these laws, and in the possibility this gives of systematically making them work towards definite ends.
>
> Friedrich Engels in:
> *Anti-Dühring*, 1877

In March 1926, a British scientist known for his contributions to Evolutionary Biology and Mathematics named Haldane wrote an interesting essay titled "On being the right size" (HALDANE, 1926). In this short discourse, he demonstrates that animal bodily equipment is directly related to their size, as other authors corroborate this idea (FLANNERY, 1989). Generalising, the shape and function of animals and their organs are directly related to the natural pressures surrounding them:

> Gravity, a mere nuisance to Christian, was a terror to Pope, Pagan, and Despair. To the mouse and any smaller animal it presents practically no dangers. [...] For the resistance presented to movement by the air is proportional to the surface of the moving object. Divide an animal's length, breadth, and height each by ten; its weight is reduced to a thousandth, but its surface only a hundredth. So the resistance to falling in the case of the small animal is relatively ten times greater than the driving force. (HALDANE, 1926)

Many of Haldane's examples are based on the mathematical principle of the square-cube law, though not directly referenced, whose first written appearance is attributed to Galileo Galilei's "Dialogues concerning two new sciences" (GALILEI, 1638). This simple rule helps us understand many of our day-to-day shapes and structural forms, from animal bone cross-sections to tree trunks and reinforced concrete in contemporary building structural design. Large container ships are getting larger and larger for a reason: the cost of manufacturing increases around a square rate, and added volume increases around a cubic rate (CHOKSHI, 2021; BUDDIES, 2013). Jane Jacobs, known for her significant influence on urban studies and economics, repeatedly refer to Haldane's work when mentioning cities increasing complexity as they expand in size:

> Haldane presents us with an interesting principle about animal size: big animals are not big because they are complicated; rather, they have to be complicated because they are big. This principle, it seems to me, also applies to institutions, governments, companies, organizations of all sorts. (JACOBS, 1980)

Forests and trees are also excellent examples of how scaling is not simple. As one can easily find in urban lanes, a single street tree alone will not be equivalent to a tree from the same species found in the middle of a forest. In the same way, a set of ten individual trees separated will not behave the same way as a forest of ten trees (WOHLLEBEN *et al.*, 2016). That is because the potential generated by a cohesive system of trees called "forest" is not the same as the potential generated by these trees alone. Works such as the Plant Revolution from Mancuso (2017) and other scientific publications the author participated in (BRENNER *et al.*, 2006; GAGLIANO *et al.*, 2012; GAGLIANO; MANCUSO; ROBERT, 2012) show that trees can share resources, can communicate through volatile signalling to warn their peers about a new parasite and also through a mycorrhizal network, a symbiotic and mutual association among a fungus and a plant, as Simard *et al.* (2012) describe.

On the complexity of scaling, in 1978, the economist Thomas Schelling derived a simple model on racial segregation, demonstrated in his book "Micromotives and macrobehavior" (SCHELLING, 1978). Using agent-based simulations, he showed that even a minor intolerance for race or gender mixing could lead to massive urban segregation (SCHELLING, 1971). A variety of authors in the subsequent years used computer simulation software such as NetLogo to expand Schelling's insight into other fields (HAYES, 2013; PEREZ; DRAGICEVIC; GAUDREAU, 2019; TUBADJI; ANGELIS; NIJKAMP, 2017). Thus, transitioning from the scale of individual behaviour to community behaviour may not be trivially solved by a simple scale factor.

In Hegel's Science of Logic (HEGEL, 1816), quantity change in nature (or scaling) is also associated with quality change:

> It is said, *natura non facit saltum* [there are no leaps in nature]; and ordinary thinking when it has to grasp a coming-to-be or a ceasing-to-be, fancies it has

> done so by representing it as a gradual emergence or disappearance. But we have seen that the alterations of being in general are not only the transition of one magnitude into another, but a transition from quality into quantity and vice versa, a becoming-other which is an interruption of gradualness and the production of something qualitatively different from the reality which preceded it. Water, in cooling, does not gradually harden as if it thickened like porridge [...]; it suddenly solidifies, all at once. It can remain quite fluid even at freezing point if it is standing undisturbed, and then a slight shock will bring it into the solid state. (HEGEL, 1816)

These authors mentioned above shed light on a relevant matter — the central topic of the present introduction: interdependence in nature. Changes in quantity can be a complex matter which may lead to changes in quality. Eventually, a German philosopher was capable of summarising this idea brilliantly. Friedrich Engels, in his "Dialectics of Nature" (ENGELS, 1883) consolidated the scientific *zeitgeist* of perceiving nature as a dynamic, interconnected flow instead of a static set of separated pieces. A dialectical and materialist way of perceiving nature is interdependence *and* particular dependence on one's immediate material context. This perspective brought about the basis for Marx and Engels Das Kapital (MARX; ENGELS, 1867), applying these thoughts to human economic and political relations. Despite the distance humans developed from nature, indigenous leaders such as Krenak (2020) and Kopenawa (2013) recall that humanity is also a manifestation of nature. That means humanity is subject to natural laws and interdependent on Earth, and humans are primarily dependent on their immediate material contexts, such as family, one's neighbourhoods, economic background, culture and so on.

The idea of dialectics is not new. It is present in Plato's Parmenides (KANGAL, 2019); in originary and indigenous peoples' cultural heritage across the globe (ANDRAE-MAROBELA *et al.*, 2012), and since before the beginning of India's Buddhist history (BAIHUI, 1986). Nevertheless, even though not a new idea, Engels captured the spirit of the time. Humanity had a tremendous historical understanding of interdependence in nature, but following Ancient Philosophy, the main interests involved breaking down natural phenomena into smaller, understandable static parts. However, between the XVIII and XIX centuries, dialectics began to be restored by philosophers such as Leibnitz, Hegel, Spinoza, Marx and Engels. Modern and contemporary scholars applied the ideas of these philosophers brilliantly to Sciences such as Kuhn (1970) and Harvey (2001).

Isaac Newton's famous maxim "Physics, beware of Metaphysics", meaning "Science, beware of thought", shows the relevance of the present introduction. Scientists working in the exact sciences field lack understanding of the history of human thought and are thus seldom able to "think about their thoughts" (HEGEL, 1892). The philosophy of Engineering or the philosophy of technology underlies the technological practice, be the practitioner or scientist conscious of that or not.

Hence, how can artificial and human-made Blue-Green Infrastructure (BGI) properly dialogue with the set of natural laws that these engineering structures mutually and symbiotically interdepend upon? Moreover, how does the immediate environmental context influence its performance?

1.1 Problem statement and research gap addressed

Fundamentally, Blue-Green Infrastructure or Nature-based Solutions (NbS) should pursue a dialectical approach (GOBATTI, 2021). After efforts to break down these structures' performance into aspects related to different natural phenomena such as water, heat, vegetation or fauna, and into different Ecosystem Services (ES), scientific work is moving towards a holistic and systemic viewpoint. Seeking a long-term service of Nature-based Solutions is seeking to understand the laws of nature that underlie these structures implementation and interact with them. For that, investigating how these structures perform under local conditions is essential.

In this sense, the present work brings a holistic analysis of a vegetated roof (or green roof) performance towards rainwater management. Vegetated roofs are a type of Nature-based Solution that can generate a wide range of Ecosystem Services but are still underused in places where their performance can generate significant impacts across different scales. Quantifying these roofs' performance for relevant parameters that describe their impact in rainwater retention and detention is yet a scarcely addressed topic for tropical and subtropical climates and consequently a research gap.

Previous studies demonstrate that the water performance of vegetated roofs is highly dependent on its structure and place of insertion (LIU *et al.*, 2019). There is very scarce reliable data to quantify this performance for the climate of São Paulo using physical models varying structural factors. Among these structural factors, vegetated roofs are dependent on parameters such as type of substrate, substrate depth, species utilised and slope. In addition to that, as pointed out by Theodosiou (2003), the environmental conditions are also relevant and, as pointed out by LIU *et al.* (2019), so are previous soil moisture content before the rainfall events analysed.

The gap increases when considering the meagre interconnections between different fields of study that can bring different optics for vegetated roofs practice. The present work addresses these gaps, bringing three experimental analyses focusing on water and vegetation dynamics and interconnecting the phenomena involved with heat dynamics. Hence, bringing a concise discussion towards the interconnection of the natural phenomena observed.

1.2 Relevance

Large cities such as São Paulo, Brazil, from lacking urban planning aligned to nature, disorderly grew and expressively modified their microclimates and hydrological cycles (KIM *et al.*, 2021). Urban systems generate climate disturbances and adapting to this new reality require immediate actions. For that, environmental and social services provided by NbS can help better managing its associated climate risks (NEDER *et al.*, 2021; CARMIN; DODMAN; CHU, 2013; BULKELEY, 2010). Among these impacts, the augment of impervious surfaces influences the natural drainage systems dynamics (PENG *et al.*, 2019), a direct product of urban planning at the service of cars and individual transportation means instead of walking distances (GEHL, 2010). As an outcome of this influence, the rainfall regime is altered, surface runoff is increased, soil infiltration is reduced, and peak discharge rates are increased (VALIPOUR; SINGH, 2016).

As a solution for such a conjuncture, a systemic and articulated set of measures must be undertaken, represented by the international agendas for sustainable development. In a semantic analysis of the term “development”, some authors point out that sustainable development is fallacious and what is needed is human degrowth and post-extractivism (ACOSTA, 2017; KOTHARI; DEMARIA; ACOSTA, 2015). Nevertheless, Gadda *et al.* (2019) recall that Brazil has compromised to engage towards reaching the Sustainable Development Goals (SDGs) under the United Nations (UN) 2030 Agenda (UN, 2015).

Raymond *et al.*, (2017) show that Nature-based Solutions can support reaching a variety of SDGs. Bulkeley (2017) brings a concise definition of what NbS are from the "H2020 Smart and Sustainable Cities Programme":

> Living solutions inspired and supported by nature that simultaneously provide environmental, social and economic benefits and help to build resilience. Solutions that bring more nature and natural features and processes into cities, landscapes and seascapes, though locally adapted, resource efficient and systemic interventions. (EUROPEAN COMISSION, 2015)

Bulkeley (2010) also recalls that NbS "has emerged as an umbrella term for the family of related ideas that capture the distinct contributions that natural systems provide, including for example Ecosystem Services". As defined by the Millenium Ecosystem Assessment (MA), ES are "the benefits people obtain from ecosystems" (MA, 2005), which is a subset from the set of total functions an ecosystem can express.

Though NbS involve a range of possible urban BGI structures, Stovin (2009) points out the difficulty of installing many of the leading Sustainable Drainage Systems (SuDS), also known as Low-Impact Development (LID) in densely built cities. It becomes a problem because of huge land-use competition, but the author also states that for some cities with a high proportion of built footprints, rooftop areas represent about 40 to 50% of the sum of its impervious areas. Hence, urban rainfall runoff from roofs represents a significant portion of the discharged water volume to the rainwater collection system.

Therefore, the use of vegetated roofs, a type of NbS, may be able to generate significant impacts for urban water management from making use of these rooftop areas, in addition to providing other ES. The potential exists, but performance must be systematically quantified locally.

1.3 Research proposition

The central proposition of the present work is that vegetated roofs can play a significant role in supporting the management of rainwater runoff in the subtropical climate of São Paulo municipality and the creation of habitat for species.

As a secondary proposition, shallower substrate depths are expected to promote proportionally less water retention and detention. However, showing that a vegetated roof can promote a satisfactory delay in the peak of discharge even with shallow substrate depths can support the use of thin vegetated roofs in São Paulo, avoiding costly structural retrofitting and promoting urban greenery in a broader range of building rooftops.

As a tertiary proposition, it is expected that planted species of *Arachis repens* (popularly known as peanut grass, or *grama-amendoim* in Brazil) in irrigated unmanaged green roofs can spread satisfactorily even in shallow substrate depths, also demonstrating the variety and biodiversity promoted from avoiding to remove voluntary species.

1.4 Dissertation outline

In this way, the present master's dissertation will break down relevant performance aspects from a vegetated roof in independent experiments. It will demonstrate experimentation towards different aims and correlate as much as possible these with one another, always having the vegetated roof as the main character. The present work is structured as a sequence of chapters which are further summarised:

- → Chapter 1: the introductory chapter. Brings a contextualization and motivation derived from a Philosophical background, Philosophy of Engineering and Philosophy of Technology fields; brings the main problems here addressed; justifies the relevance of these problems.
- → Chapter 2: the objectives chapter. Brings the general and specific objectives of the present dissertation.
- → Chapter 3: the theoretical background chapter. It brings a general review of relevant aspects of vegetated roofs concerning their structure, primary Ecosystem Services, history, social aspects, heat dynamics, water dynamics, flora, fauna, maintenance and monitoring and low-cost construction.
- → Chapter 4: the methods chapter. Summarizes the methods involved in the reviewing process and the experimental research.
- → Chapter 5: brings a specific review on runoff water quantity effects that vegetated roofs can perform, focusing on the Brazilian climate.
- → Chapter 6: brings the specific methods applied for obtaining the results towards the experiments described in Chapter 5, experiments A and B. The chapter shows concisely how the primary sensors were fabricated, installed, calibrated, and data

was collected and processed to obtain results on retained and detained rainfall water quantity within vegetated roofs.

→ Chapter 7: brings the main results for the hydrological performance of vegetated roofs with different substrate depths compared to ceramic tiled roofs, showing two different experiments that complement each other. These are experiments A and B.

→ Chapter 8: shows the methods and results for a third experiment, experiment C, that describes the vegetation dynamics of unmanaged green roofs, focusing on spontaneous vegetation and how these dynamics change depending on the substrate depths.

→ Chapter 9: the discussion chapter. Brings a concise final dialogue involving results across all experiments above described and the background literature review.

→ Chapter 10: the conclusion chapter. Brings the final words regarding the present work and wraps up its achievements, applications, and impact.

→ Chapter 11: the further work chapter, closes this dissertation stating which pathways can be taken by those who want to further develop the investigations described.

2 Objectives

> The Earth is alive, it cannot
> have an owner.
> Can you see at last?
>
> Davi Kopenawa, Yanomami, at: *ISA*, 2020, our translation

2.1 General objectives

As general objectives, the present research aims to quantify the performance of vegetated roofs regarding the rainwater runoff retention and detention, when installed in buildings in São Paulo city, which has a humid subtropical climate according to the Köppen Geiger classification (ALVARES *et al.*, 2013). In addition, it aims to describe the vegetation dynamics for the first months of operation of physical models with different substrate depths.

2.2 Specific objectives

In order for that to be achieved, the following specific objectives must be observed:

- → Experiment A: quantify the runoff retention and detention capabilities of a vegetated roof prototype under the humid subtropical climate of São Paulo in representative natural rainfall events.
- → Experiment B: correlate the runoff retention and detention capabilities of four vegetated roof models with different substrate depths to their previous soil moisture content using artificial rainfall events.
- → Experiment C: characterise vegetation growth in the initial three months of life in unmanaged vegetation cover models, with different substrate depths, identifying the spontaneous species that appear and some of the mechanisms that allow these species to thrive.

3 Theoretical background

> What we observe is not nature itself but nature exposed to our method of questioning.
>
> ---
>
> Werner Heisenberg in: *Physics and Philosophy: the revolution in modern Science*, 1958

This chapter is divided into sections, covering a general review of vegetated roofs. In Section 3.1, the structural aspects of a vegetated roof are defined, and Section 3.2 presents its primary Ecosystem Services. As it is not a new structure but used for centuries in different cultures; Section 3.3 shows a brief historical contextualization. Section 3.4 brings relevant social aspects related to the construction of vegetated roofs and means for low-cost construction. Section 3.5 shows relevant aspects related to substrate composition.

In the present work, we refer as “vegetated” instead of “green” because, as described in Section 3.6, these systems can still provide relevant functions even when their vegetation is not green coloured. In temperate climates, vegetated roofs may become brownish during winter, which is part of its seasonal dynamics, an aspect that should be embraced and not avoided. Section 3.7 also characterises life beyond vegetation that can use vegetated roofs as habitat or support.

Section 3.8 brings relevant aspects related to maintenance and monitoring, which strongly connect to the final experiment herein described, Experiment C, regarding unmanaged vegetation. Section 3.9 and Section 3.10 describe in general manner aspects related to water and heat that vegetated roofs can help regulate, which has a close relation to Experiments A and B in the present work.

3.1 Structure

Vegetated roofs (VR) are a type of Nature-based Solution that can provide a variety of Ecosystem Services (OBERNDORFER *et al.*, 2007). An example of a VR can be seen in Figure 1. Bibliometric studies show that vegetated roof research is a fairly novel and trans-disciplinary area of investigation, publication rates increased in the last twenty years and represent mostly temperate ecosystems (BLANK *et al.*, 2013).

Figure 1 – A cottage with a vegetated roof.
Source: Arild Vågen, 2013.

Vegetated roofs are defined by Osmundson (1999) as a planted open space, separated from the ground by a building. Gobatti *et al.* (2022) bring a diagram illustrating the main layers of a vegetated roof, which is redesigned in Figure 2.

From the bottom-up, the waterproofing layer is immediately installed over the existing roofing system (NAKAMURA, 2011). Vegetated roofs are more conventionally planted over flat roofs, having a slight slope for water drainage. However, installing these systems over other roof formats, such as gable or shed, is viable. Depending on the slope, the addition of brackets can be necessary to prevent the substrate from slipping off in high pitched roofs (ZINCO, 2017). Waterproofing can be done for long-term performance or low-cost construction. Asphalt blankets are typically indicated for the first option, lasting for five to ten years (AMORIM; SOARES, 2021), but are costly and need a skilled workforce. For the second option, commercially available geomembranes are cheaper and can be easily installed by gardeners, but may require more recurrent maintenance and usually cannot be exposed to direct severe weather (KELSEY, 2020). The waterproofing

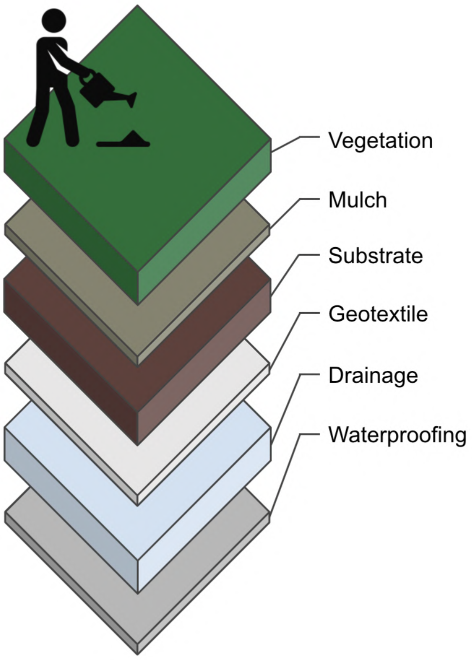


Figure 2 – Generic layers of vegetated roofs commonly used in Brazil.
Source: adapted by the author from Gobatti *et al.* (2022).

layer controls fluid migration from the substrate to the slab or existent roof via a low permeability barrier.

The drainage layer has a considerable impact on vegetation well-being. Soil saturation is a different phenomenon compared to water pooling. Under saturated conditions, the empty spaces of soil are filled with water, but under soil pooling conditions, there is overwatering (FAO, 1985) that can suffocate and rotten plant roots. The drainage layer, thus, impedes overwatering and stores part of the rainfall depending on the materials and types of commercial layers adopted (BÄR, 2019).

On the other hand, the geotextile is a porous layer that can let water flow through but can hold back most grains of soil. Though not a complete barrier for solids, letting small grains still traverse, the layer can hold the substrate until the plant's rooting system stabilises it. It is a material easily found in the construction industry (AECWEB, 2015).

The vegetated roof's substrate layer has an awe-important role in providing the means for vegetation to grow and being the foundation of many regulatory services. The substrate is a mixture of different grain sizes and materials, increasing the roof thermal inertia and retaining and detaining water (AMPIM *et al.*, 2010).

Mulching is a technique not typically displayed in vegetated roofs generic layering. It tends to create itself spontaneously; however, adding it during the first moment of planting can positively impact vegetation growth since its first development days. Mulch is a layer of organic matter such as dry leaves that can prevent nutrient leaching from the mechanical impact of rainfall and can improve water storage by reducing evaporation (CIANCIARUSO *et al.*, 2006). Thus, extremely important for creating a healthy microclimate for fauna and flora.

The vegetation, the top-most layer of a vegetated roof, is deeply interconnected to the mulch and substrate layer. Roots will generally go down to the geotextile layer but can penetrate all the way to the waterproofing layer. Plants must be selected to harmonise with the local ecosystem and its water shortage conditions and shallow substrate depths. Regarding the understanding of local conditions, Oliveira, Rodrigues and Oliveira (2021) undertook an interesting and comprehensive research on the use of native species for vegetated roofs in Brazil. The vegetation changes the surface albedo and can influence heat and water dynamics through evapotranspiration.

3.2 Ecosystem Services

Nature-based Solutions as defined by the International Union for Conservation of Nature (IUCN) are "actions to protect, sustainably use, manage and restore natural or modified ecosystems, which address societal challenges, effectively and adaptively, providing human well-being and biodiversity benefits" (COHEN-SHACHAM *et al.*, 2016). According to Almassy *et al.* (2018), these solutions can encompass under the urban setting: *(i)* parks and urban green areas; *(ii)* grey infrastructure with green features; *(iii)* blue areas; *(iv)* allotments and community gardens; *(v)* external building greens; *(vi)* green areas for water management; *(vii)* derelict areas and *(viii)* green indoor areas. Vegetated roofs, vegetated walls or façades and balcony greens are part of the external building greens, which encompass green structures in relation to the built environment.

As also described by Almassy *et al.* (2018), NbS can have different forms and scale of organisation for its implementation. The types of stakeholders vary from the private sector, NGO and Civil Society Organisations, citizens or community groups, public sector institutions and to coalitions between multiple stakeholders.

As shown in Figure 3, vegetated roofs can provide a variety of Ecosystem Services. Recalling Chapter 1, ES are "the benefits people obtain from ecosystems" (MA, 2005).

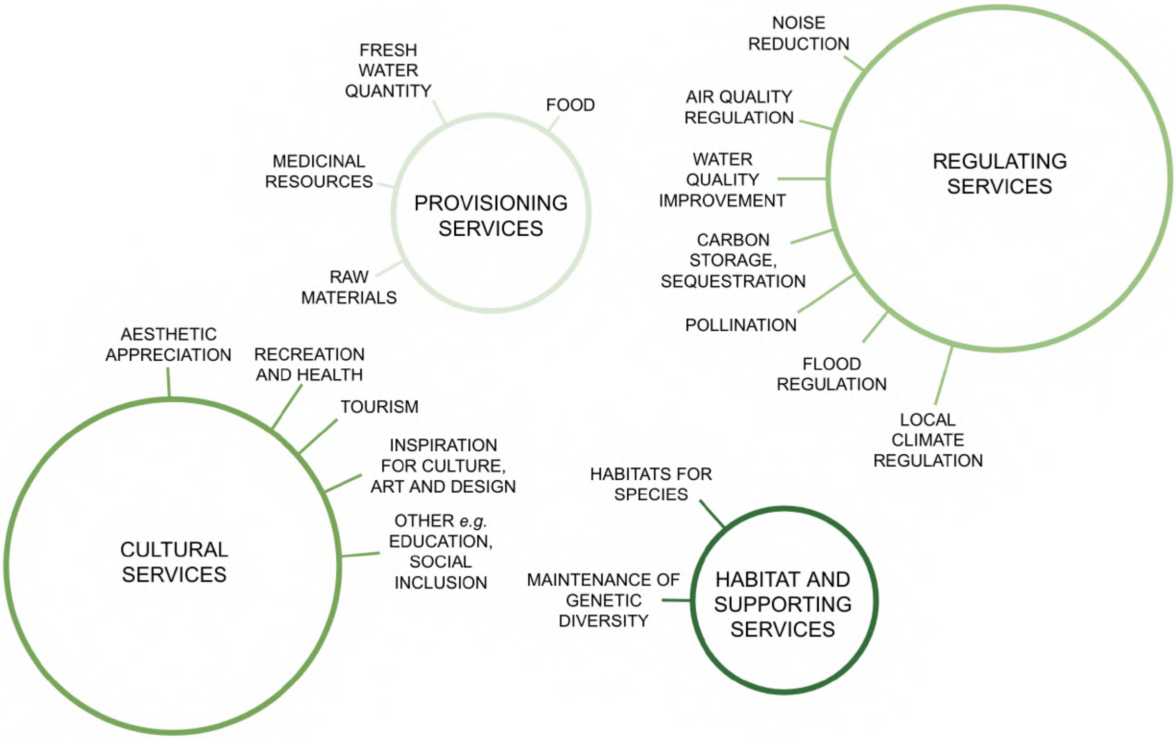


Figure 3 – Ecosystem Services provided by vegetated roofs.
Source: adapted by the author from Almassy *et al.* (2018).

These are cultural services, provisioning services, habitat and supporting services and regulating services. In the present dissertation, greater focus will be given to the regulating services and the habitat and supporting services, to which water and vegetation are respectively directly associated.

Ecosystem Services are quantifiable and support the dialogue between different areas of knowledge providing a common parameter: capital. Though it has its many perks from attributing a human value to nature, as Schlaepfer, Lehmann and Fall (2017) highlight, — how can one tell how much the workforce of a predator bird to prevent prey caterpillars from eating a crop costs? What happens if there's a new substance that kills much easier these same caterpillars? Will it depreciate the value of that bird's workforce? Is human monetary system, thus, part of nature? — it is being a widely used tool.

3.3 History

Vegetated roofs have been part of human architecture, be it vernacular or standardized, for a long time in history (FERRAZ, 2012). Mendes (2014), in his master's dissertation, brings a brief yet comprehensive review on the history of these structures.

Figure 4 – Illustration of the Hanging Gardens of Babylon. Vegetated roofs and stone arches are visible to the right-hand side at a distance.

Source: Heemskerck [1498-1574].

First appearance registered is in the Hanging Gardens of Babylon, one of the Seven Wonders of the Ancient World (Fig. 4). The gardens were built around 500 BC in the allegedly Babylon, which is believed to be within the borders of today's Iraq, by the Neo-Babylonian king Nebuchadnezzar II (RAGAZAS, 2013). In order to solve the structural stress generated by the garden roofs added weight and moisture content, stone arches were used for reinforcement and reed (*Juncus sp.*) and tar were used for waterproofing (HOOF; DIJKEN, 2008 apud MENDES, 2014).

Scandinavian countries also used such technique towards thermal insulation using peat roofs. Peat, or turf, is a compact material deriving from accumulation of organic matter and decayed vegetation (STRACHER; PRAKASH; REIN, 2015) and provides a diversity of ES (NATIONAL TRUST, 2013). Mendes (2014) points that vegetated roofs at this moment in history may have been a feasible and cost-effective option for dwellers to protect from severe weather. Historically, the growth of plants in roofs can be a mere consequence of the building materials used and the costly maintenance, generating the environment for spontaneous colonisation.

Hence, depending on the section of history analysed, vegetated roofs can represent rather opulence or poverty. In the Brazilian modern architecture, vegetated roofs were adopted by famous exponents such as Le Corbusier's Terrace Gardens and Roberto Burle Marx (ALMEIDA; BRITO; SANTOS, 2018). In contemporary times, vegetated roofs are widely researched across the globe aiming at quantifying its ES and providing means for a cost-effective mainstreaming, having in Germany the beginning of such novel movement. A detailed view of vegetated roofs history can be found in Jim (2017).

3.4 Social aspects

Aforesaid historical background shows that technology can communicate different social and economic conditions: rather wealth from opulent architecture or management difficulty from impoverished dwellers. Aiming for a technology that can spread and mainstream in Brazil, it is relevant to understand what a technology is and how it generates certain outcomes given prior design decisions.

Technology can be defined as "scientific knowledge used in practical ways in industry, for example in designing new machines" (OXFORD DICTIONARY, 2022). Dagnino (2014) demonstrates, nevertheless, that technology is never neutral: it is created by specific actors in society and inherently part of its historical, cultural and social context, becoming therefore a social phenomenon (CORRÊA, 2021).

Under capitalist and specially neoliberal conditions, conventional technology nowadays aims at generating profit. Social technology (ST), on the contrary, aims at addressing social issues. Gobatti *et al.* (2022) demonstrate this difference by exemplifying two different vegetated roof approaches: a modular system developed by a private industry with a specific shape and function that is made with costly machines and sold in the market for profit; and an open-sourced and low-cost system that uses materials available at construction depots and has technical manuals to support technicians to easily install and indicate long-term maintenance needs. Both options result in the same technology: a vegetated roof that will accomplish the same Ecosystem Services. But the social aspect of the services provided is excellently addressed by the social technology option, as it generates emancipation and has the primary goal of aiming for solving social demands instead of generating profit.

In this sense, it is necessary to highlight what exactly a social technology is. The Institute for Social Technology (ITS BRASIL, 2019) summarises the main aspects of a social technology into four groups:

- → Knowledge, Science and Technology: ST has as starting point in the social problems consciousness; is carried out with organisation and systematisation; introduce or generate innovation in communities.
- → Participation, citizenship and democracy: ST emphasises citizenship and democratic participation; adopts participatory methodology in work processes; drives its dissemination and reapplication.
- → Education: ST carries out a whole pedagogical process; develops dialogue between popular and scientific knowledge; is appropriated by communities, which gain autonomy.
- → Social relevance: ST is effective in solving social problems; has environmental sustainability; brings about social transformation.

In conclusion, for mainstreaming vegetated roofs and generating technologies aware of their contexts, a social optics is helpful. For that, open-sourced and low-cost technologies that generate emancipation are needed. A low-cost construction manual can be found in Gobatti *et al.* (2022) and for participatory approaches Freire (1972) is a touchstone reference.

3.5 Substrate

Types of vegetated roofs are normally recognized by their substrate depths. The substrate has great influence in most of the Ecosystem Services provided by vegetated roofs, and also in the botanic selection. Main types of vegetated roofs are extensive and intensive. Extensive vegetated roofs have shallower substrate depths and utilise drought tolerant plants; intensive vegetated roofs need greater maintenance and have deeper substrate depths, being able to accept wooden plants and arboreal individuals. Some references bring an intermediate type, the semi-intensive vegetated roof, and also bring substrate depth boundaries for each type, but literature is fuzzy in standardising these boundaries.

In terms of materials used in the substrate mixture, Ampim *et al.* (2010) has done a complete compendium and therefore is a relevant reference. Charts 1, 2, 3 and 4 are, thus, adapted and pertinent aspects for water quantity and vegetation dynamics summarised from the tables presented by Ampim. The content inside the table is referenced where the author consulted third-party work.

Chart 1 shows substrates derived from natural and mineral components. From those, sand and clay are particularly widely used in Brazil. Chart 2 shows substrates derived from artificial or modified mineral components. From those, perlite and vermiculite can be found used in substrate mixtures for vegetated roofs in Brazil, though they tend to be expensive. Expanded clay is normally nationally adopted in VR drainage layers. Chart 3 shows substrates derived from recycled or waste and plastic foam materials. Crushed bricks are difficult to find in Brazil, and tend to be expensive, being used particularly by bonsaists and sold in specialised markets in small quantities. Chart 4 shows substrates derived from organic materials. From those, composts are widely used as substrate mixture in Brazil, including rice hull, a type of organic substrate which is not included in the tables.

The vegetated roof substrate also plays a primary role in improving the acoustic performance of buildings. Research shows that these structures can provide significant sound reduction for diffracted sound waves in comparison to non-vegetated roofs (VAN RENTERGHEM; BOTTELDOOREN, 2011). The substrate water content also affects the acoustic insulation performance of a vegetated roof, as Liu and Hornikx (2018) shows, indicating that as the substrate moisture content increases, noise attenuation tends to decrease in most cases.

3.6 Flora

The correct botanic selection for a vegetated roof is a critical aspect so that it can generate Ecosystem Services in an optimal manner (OLIVEIRA; RODRIGUES; OLIVEIRA, 2021). Morphological and physiological characteristics need to be taken into account and, as Oliveira, Rodrigues and Oliveira (2021) complete, favourable aspects are: resistance to drought and water stress; resistance to variable luminous conditions; resistance to wind; resistance to excessive pollution; low maintenance requirements; capability to attract pollinators; capability to prosper in a shallow substrate and having adequate

Material	Characteristics
Sand	Provides anchorage for plants and facilitates wetting, but has saturation concerns and is not a good source of nutrients (Bunt (1988); Dunnett and Kingsbury (2014); Handreck and Black (2002))
Clay	Provides moisture and nutrients retention, but can clog drainage layers and geotextile (Bunt (1988); Miller (2003))
Lava (scoria)	Is a lightweight and porous media, but may need added dolomite for pH regulation (Dunnett and Kingsbury (2014); Handreck and Black (2002))
Pumice	Is a lightweight and porous media, but is costly (Dunnett and Kingsbury, (2014); Handreck and Black (2002))
Gravel	Is a stable anchorage and can improve drainage, but is heavy and poor in nutrients and water retention (Dunnett and Kingsbury (2014); Miller (2003); Köhler (1990))

Chart 1 – Vegetated roof growing substrates from natural and mineral components.

Source: adapted by the author from Ampim *et al.* (2010).

Material	Characteristics
Perlite	Is a porous, stable, draining and sterile material, but parts are crushable during transportation; is poor in nutrients and in water retention (Bunt (1988); Handreck and Black (2002))
Vermiculite	Is a lightweight and porous material, able to retain water and supply Mg and K, but deteriorates quickly and does not hold water well (Dunnett and Kingsbury (2014); ESCSI (1994))
Expanded shale, clay and slate (ESCS)	Is a porous and lightweight material, with good nutrient supply, does not break or decay and is inert, but may be too light to provide anchorage (Bunt (1988); Dunnett and Kingsbury (2014); Handreck and Black (2002))
Rockwool	Is a lightweight material, porous and is able to regulate air and water supply, but does not supply nutrients (Bunt (1988); Dunnett and Kingsbury (2014); Handreck and Black (2002))

Chart 2 – Vegetated roof growing substrates from artificial or modified mineral components.

Source: adapted by the author from Ampim *et al.* (2010).

Material	Characteristics
Crushed clay bricks, tiles or brick rubble	Is a stable and strong material able to hold moisture, but can have a high pH (Dunnett and Kingsbury (2014))
Crushed concrete	Is a low-cost material available in demolition sites, but is alkaline and does not hold moisture well (Dunnett and Kingsbury (2014))
Aerated concrete	Has good capacity for water retention when mixed with organic matter, but require periodic maintenance (Cresswell and Sims (2007))
Subsoil	Available in construction sites as by-product, but is excessively compact and poor in nutrients (Dunnett and Kingsbury (2014))
Styrofoam	Strong for compression stress, improves drainage and aeration, but holds no nutrients and may be too light (Bunt (1988); Handreck and Black (2002))
Urea-formaldehyde resin foam	Holds and absorbs water well, but degrades over time (Bunt (1988))

Chart 3 – Vegetated roof growing substrates from recycled or waste and plastic foam materials.

Source: adapted by the author from Ampim *et al.* (2010).

Material	Characteristics
Peat	Has great water holding capacity and low bulk density, but its decomposition shrinks the medium and wetness can be a concern (Handreck and Black (2002))
Coir fiber dust	Has better water retention than most peats and high K content, but holds high amounts of chloride; is low in calcium and sulfur (Handreck and Black (2002))
Composts (bark, poultry litter and yard waste)	Provide nutrients in abundance, improves water retention and has a high microbial counts, but can present variable salinity, potential toxicity and weeds may occur if composting isn't done properly (Handreck and Black (2002); Friedrich (2005))
Worm castings	Has abundance of trace minerals, provides P and K, and is structurally steadier, but can generate Zn toxicity (Handreck and Black (2002))

Chart 4 – Vegetated roof growing substrates from organic materials.

Source: adapted by the author from Ampim *et al.* (2010).

roots to this substrate conditions. A well selected group of species to colonise a vegetated roof can diminish the necessity of irrigation, improve air quality via carbon sequestration (SHAFIQUE; XUE; LUO, 2020), individuals can support each other through stratification and microclimate generation, among other interrelations.

Native species, thus, are able to meet these requirements at the same time as living in harmony to their immediate context. This way, Köhler, Schmidt and Laar (2003) summarised plant species with indicated use for vegetated roofs, further modifying the work of Agarez (2001). Chart 5 suggests species with high use potential in extensive VR and Chart 6 suggests species with high use potential in intensive VR.

Though a list of possible plants can help identify common families, morphology or structures, it is not all that simple. The charts presented bring species of exotic plants and invasive plants for Brazilian ecosystems, such as the *Tradescantia zebrina*. Both exotic and invasive are non-native plants, but exotic ones are simply organisms found in ecosystems where they didn't evolve and invasive are organisms that exceed control and can cause harm to the ecosystem (NAVEEN, 2011). "An exotic species becomes invasive when the population starts to increase through reproduction that happens because there are no natural enemies in the new habitat" (NAVEEN, 2011) causing the ecosystem to eventually lose its balance. For a better understanding of species and botanic characteristics, Oliveira, Rodrigues and Oliveira (2021) is a recommended source, bringing taxonomic groups native to the Brazilian ecosystems.

The subject of flora in vegetated roofs will be further discussed and expanded in chapter 8.

3.7 Fauna

Due to systematically extinguishing vegetated areas, the mainstream urban planning also creates a concern regarding habitat for species. Pollinators and invertebrates, such as bees, butterflies, beetles, wasps and dragonflies, are among the small species of fauna that can benefit from the new green areas created by vegetated roofs. Pollination, in addition, is responsible for much of the flora reproduction and genetic diversification and also for increasing the nutritional value of food (ROSE *et al.*, 2016).

Species (Family)	
Amaranthus deflexus (Amaranthaceae)	*A. hybridus, A. spinosus* (—)
Cleome affinis (Capardiaceae)	*Chenopodium ambrosoides* (Chenopod.)
Silene gallica (Caryophyllaceae)	*Commelina benghalensis* (Commelin.)
Acanthospermum australe (Compositae)	*Ageratum conyzoides* (Comp.)
Ambrosia elatior (Comp.)	*Artemisia verlotorum* (Comp.)
Bidens pilosa (Comp.)	*Eclipta alba* (Comp.)
Emilia sonchifolia (Comp.)	*Erigeron bonariensis* (Comp.)
Eupatorium pauciflorum (Comp.)	*Gamaochaeta spicata* (Comp.)
Jaegeri hirta (Comp.)	*Parthenium hysterophorus* (Comp.)
Porophyllum ruderale (Comp.)	*Senecio brasiliensis* (Comp.)
Siegesbecjia orientalis (Comp.)	*Sonchus oleraceus* (Comp.)
Tagetes minuta (Comp.)	*Xantium cavanillesi* (Comp.)
Ipomoea acuminata (Conv.), *I. purpurea*	*Lepidium pseudodidymum* (Brassicacea)
L. virginicum (—)	*Sinapsis arvensis* (Bras.)
Mormodica charantia (Curcubitaceae)	*Cyperus esculentus* (Cyperaceae)
C. ferax, C. rotundus (—)	*Croton glandulosus* (Euphorbiaceae)
C. lobatus (—)	*Euphorbia brasiliensis* (Euph.)
Phyllanthus corcovadensis (Euph.)	*Brachiaria decumbens* (Poaceae)
B. plantaginea, B. purpuracens (—)	*Cenchrus echinatus* (Poac.)
Cynodon dactylon (Poac.)	*Digitaria horizontalis* (Poac.)
D. insularis (Poac.)	*Eleusine indica* (Poac.)
Panicum maximum (Poac.)	*Paspalum maritimum* (Poac.)
Pannisetum clandestinum (Poac.)	*P. setosum* (Poac.)
Rhynchelitrum roseum (Poac.)	*Setaria geniculat* (Poac.)
Sorghum halepense (Poac.)	*Hyptis suaveolens* (Labitae)
Leonitis nepetaefolia (Lab.)	*Leonurus sibirica* (Lab.)
Stachys arvensis (Lab.)	*Aeschynomene rudis* (Leguminosae)
Cassia ocidentalis (Leg.)	*C. tora* (Leg.)
Sida cordifolia (Malvaceae)	*S. rhombifolia, S. spinosa* (—)
Mollugo verticillata (Molluginaceae)	*Oxalis oxyptera* (Oxalidaceae)
Polygonum persicaria (Polygonaceae)	*Portulaca olearacea* (Portulaceae)
Borreria alata (Rubiaceae)	*Richardia brasiliensis* (Rub.)
Solanum americanum (Solanaceae)	*S. nigrum* (Sol.)
Waltheria indica (Sterculiaceae)	(...)

Chart 5 – Species with high use potential for extensive VR.

Source: Köhler, Schmidt and Laar (2003) modified from Agarez (2001).

Species (Family)	
Acalypha reptans (Euphorbiaceae)	*Ageratum houstonianum* (Compositae)
Anomatheca laxa (Iridaceae)	*Aptenia cordifolia* (Aizoaceae)
Arachis repens (Leguminosae)	*Axonopus compressus* (Poaceae)
Barieria repens (Acanthaceae)	*Begonia ulmifolia* (Begoniaceae)
Calathea insignis (Marantaceae)	*B. leopadina, C. stromata* (—)
Callisia repens (Commelinaceae)	*C. rotundifolia* (—)
Callisia warszewiciana (Commelinaceae)	*Cuphea gracilis* (Lythraceae)
C. ignea (—)	*Episcia cupreata* (Gesneriaceae)
Envolvulus glomeratus (Convolvulaceae)	*E. pusillus* (Convolv.)
Fittonia verschaffeltii (Acanthaceae)	*Hemigraphis repanda* (Acanth.)
Kalanchoe blossfeldiana (Crassulaceae)	*Lampranthus productus* (Aizoaceae)
Maranta bicolor (Marantaceae)	*M. leuconeura* var. *Erythroneura* (—)
M. leuconeura var. *Kerchoveana* (—)	*Oxalis vulcanicola* (Oxalidaceae)
Paspalum notatum (Poaceae)	*Portulaca grandiflora* (Portulacaceae)
Sanseviera trifasciata (Liliaceae)	*Sanvitalia procumbens* (Compositae)
Schizocentron elegans (Melasomataceae)	*Sedum dendroideum* (Crassulaceae)
Siderasis fuscata (Commelinaceae)	*Spilanthes repens* (Compositae)
Stenotaphrum secundatum (Poaceae)	*Tagetes patula* (Compositae)
Tigridia pavonia (Iridiaceae)	*Torenia fournieri* (Scrophulaceae)
Tradescantia pallida var. *purpurea* (Com.)	*T. spathacea, T. zebrina*
Turnera ulmifolia (Turneraceae)	*Unxia kubitzkii* (Compositae)
Verbena hybrida (Verbenaceae)	*V. tenera, V. rigida*
Wedelia paludosa (Compositae)	*Echiveria elegans* (Crassulaceae)
Kalanchoe blossfeldiana	*K. gastonis-bonnierri, K. waldheimii*
Polygonum capitatum (Polygonaceae)	(...)

Chart 6 – Species with high use potential for intensive VR.

Source: Köhler, Schmidt and Laar (2003) modified from Agarez (2001).

As seen in figure 5, MacIvor and Ksiazek-Mikenas (2015) demonstrate that invertebrate colonisation of vegetated roofs has its many mechanisms of occurrence. During the roof installation, invertebrates can be among the substrate or vegetation used; after its installation, colonisation from invertebrates can happen via air (flying or blown by the wind), via surface (climbing) or via human interventions.

Vegetated roofs can work as a migration hotspot in urban areas, providing shelter to travelling insects and functioning as a green corridor (GRO, 2021). Small wooden structures known as insect hotels or bug hotels can be installed to mimic dead wood, which plays an important role in supporting nidification. These small man-made structures provide nesting facilities specially to solitary insects, and there are specially adequate designs for different insects (GEORGIA WILDLIFE, 2013). Spaces of water can also generate an heterogeneity of habitat for species in vegetated roofs, supporting birds and

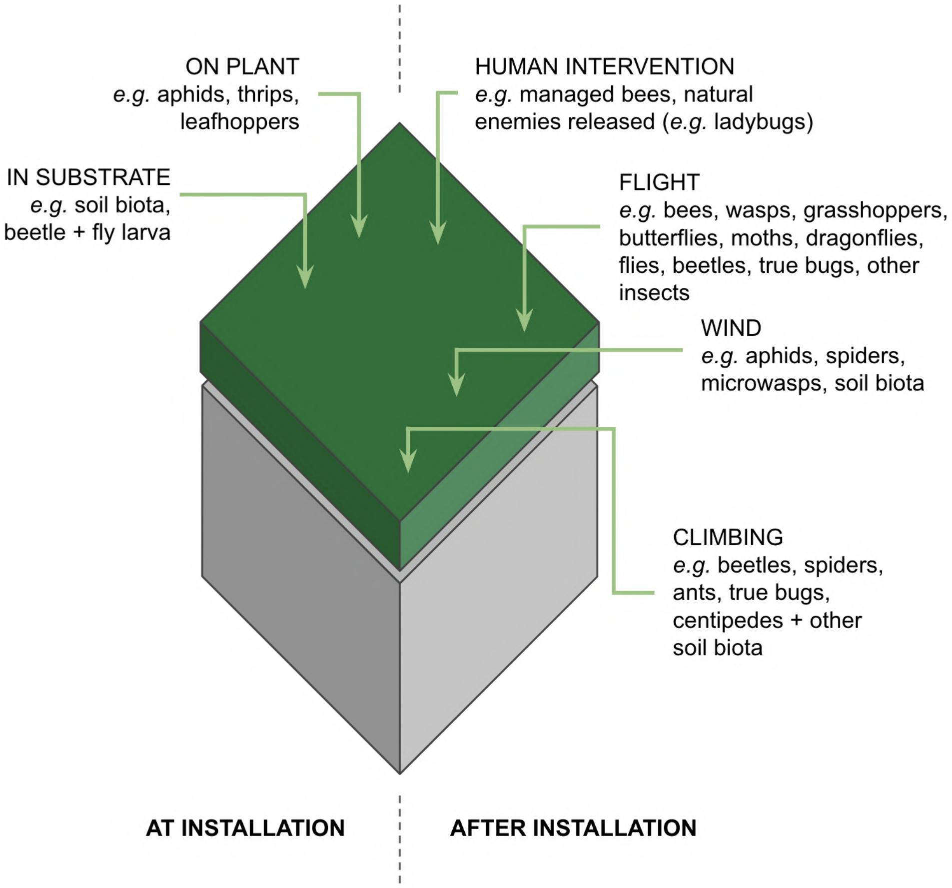


Figure 5 – Mechanisms of invertebrate colonisation in vegetated roofs.
Source: adapted by the author from MacIvor and Ksiazek-Mikenas (2015).

other insects (APPL, 2017). The local characteristics of vegetated roofs, as pointed out by Kyrö *et al.* (2018) that researched beetle communities, have greater influence than the surrounding conditions in insect communities. This is an indication that, even in degraded urban areas, some communities may find in vegetated roofs a place to thrive.

3.8 Maintenance and monitoring

As any other artifact humans create, such as objects, Civil Engineering structures or furniture, maintenance is needed. And to better understand maintenance needs, evaluate the provision of Ecosystem Services and future improvements, monitoring is essential. Though necessary to every roofing system, maintenance in vegetated roofs still has limited research (NAGASE; DUNNETT; CHOI, 2013). For that, Pereira (2022) brings interesting discussions regarding these aspects for vegetated roofs. Two main maintenance needs for vegetated roofs are gardening related and waterproofing membrane related.

As for gardening, periodic weeding is necessary (USEPA, 2008), even if the vegetated roof prioritises a naturalist landscaping as will be further discussed in the present work. Extensive vegetated roofs normally demand less pruning and weeding maintenance, but there may be necessary regular irrigation and fertilising, especially in the first months after planting (CORREA; GONZALEZ, 2002). Intensive vegetated roofs normally need greater maintenance, as the aesthetic disposition of species may be relevant (USEPA, 2008).

As for the waterproofing membrane, its durability may vary depending on the material used. Asphalt blankets can become less flexible and more crumbly, slowly losing its impervious properties (AMORIM; SOARES, 2021).

There is also general maintenance related to fertilising and irrigation. Those are aspects that should be taken into account when selecting species and scheduling a gardening routine. Ideally vegetated roofs would only use natural rainfall for watering, but initial conditions may need added artificial irrigation.

As defined by the Cambridge Dictionary (2022), monitoring means “to watch and check a situation carefully for a period of time in order to discover something about it”. For vegetated roofs, it is possible to monitor different aspects in many different ways. Monitoring the vegetation dynamics, water quantity, water quality, heat dynamics, evapotranspiration, are some of the aspects widely researched in the state-of-the-art of related literature. As Pereira (2022) points out, results obtained can be used in applications such as mathematical modeling for computational simulation, being evidence of how a structure behaves.

Almassy *et al.* (2018) demonstrates the main forms of monitoring NbS by urban setting, across a variety of different cases studied in Europe. Table 1 shows the percentage of NbS studied that presents each monitoring system implemented.

3.9 Heat regulation

In urban conditions, by decreasing the surface albedo and increasing thermal inertia from adding concrete buildings, cities became heat islands (KRÜGER, 2016). Concrete traps heat along the day and release it at night, increasing the overall temperature of the environment and diminishing thermal amplitudes. But this process can become exaggerated and compromise the tenuous equilibrium of life, deeply modifying the urban fauna and

NbS \ Monitoring approach	Formal monitoring system	Indicators used in reporting	Monitor. and evaluation reports	Web-based monitoring tool	GIS mapping	Citizens involved in monitoring
External building greens	21-30	21-30	21-30	1-10	1-10	21-30
Grey infrastructure with green features	21-30	11-20	11-20	1-10	1-10	21-30
Parks and semi-natural green areas	21-30	11-20	21-30	1-10	1-10	21-30
Allotments and community gardens	11-20	11-20	11-20	1-10	1-10	+40
Green indoor areas	31-40	11-20	0	11-20	0	31-40
Blue areas	21-30	11-20	21-30	1-10	1-10	11-20
Green areas for water management	21-30	11-20	21-30	1-10	1-10	21-30
Derelict areas	21-30	11-20	11-20	1-10	1-10	31-40

Table 1 – Proportion of Nature-based Solutions using each monitoring approach, from the total of case studies analysed in Almassy *et al.* (2018), expressed in %.

Source: adapted by the author from Almassy *et al.* (2018).

flora composition if compared to the previous natural state of that same urban area. These changes in environmental conditions are drivers of evolutionary conditions change for living beings, as further described in the book *When Darwin comes to town* (SCHILTHUIZEN, 2018) and research such from KIM *et al.* (2021).

In terms of city scale, vegetated roofs can contribute to mitigate the heat island phenomena. Alexandri and Jones (2008) demonstrate this effect of vegetated roofs and walls in different cities of the world, analysing urban street canyons. Street canyons are a built environment condition that repeatedly appears in big cities: both sides of a street with tall buildings create an aspect of canyon. This condition can generate specific phenomena such as the concern of using trees with high leaf bulk density that may trap not only longwave solar radiation, absorbing shortwave solar radiation, but also trap vehicle pollution under its canopy and inside the canyon: a condition where a tree can, as strange as may it sound, worsen air quality conditions for a pedestrian at street level (ABHIJITH *et al.*, 2017). This phenomenon can be observed in figure 6.

Research can use Computational Fluid Dynamics simulation to better understand the services of heat regulation provided by vegetated surfaces. Heat island effects are a relevant environmental concern widely researched and green surfaces may provide positive increments in surface properties towards generating better comfort conditions for urban

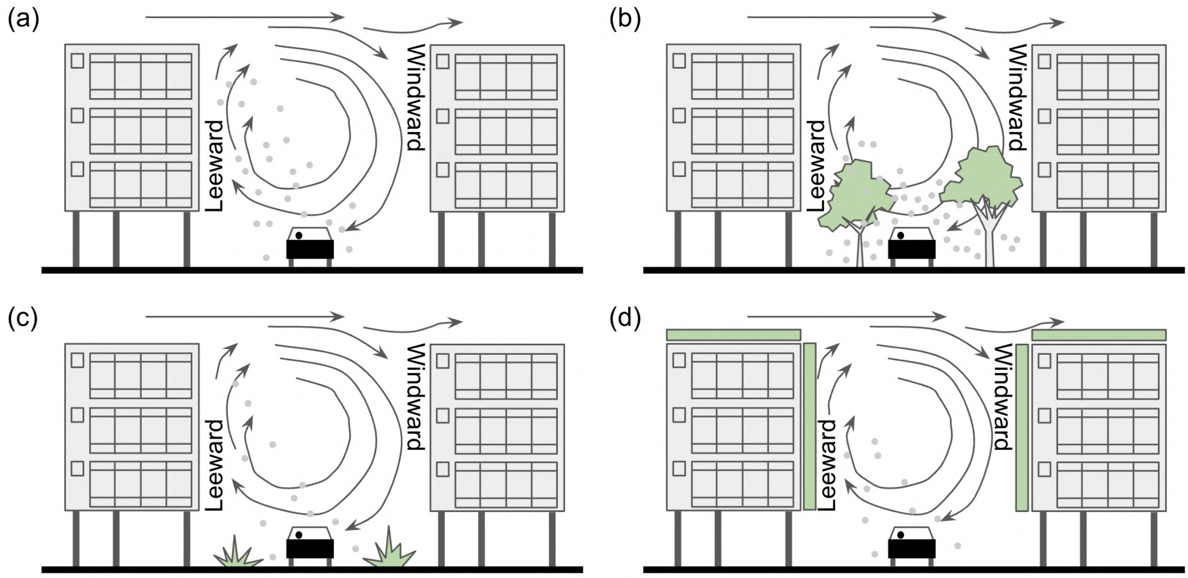
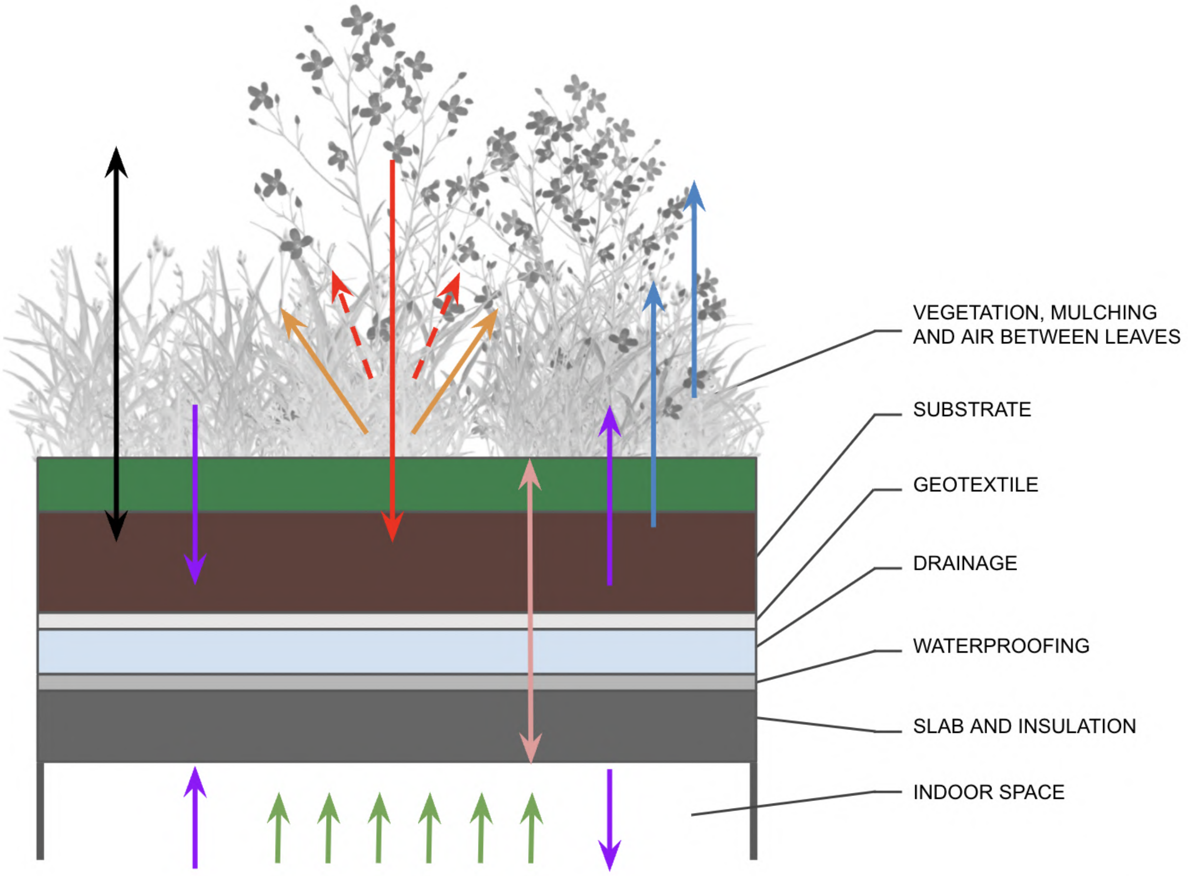


Figure 6 – Air pollution dynamics in street canyons: (a) vegetation free street canyon, (b) street canyon with trees, (c) street canyon with hedges, and (d) street canyon with green roof and green wall.
Source: Adapted by the author from Abhijith *et al.* (2017).

citizens (GOUVÊA, 2007; ALEXANDRI; JONES, 2008). Software such as ENVI-met can provide interesting analysis, as seen in Werneck (2018), though its high demand for computational processing capacity may need oversimplification so an environmental consultant can operate it (BROADBENT *et al.*, 2019).

In terms of vegetated roofs' heat dynamics influence for the building internal conditions, Ferraz (2012) conducted a research comparing prototypes with and without VR. In her research, it was clear that vegetated roofs generated greater thermal inertia, both impeding excessive heat to enter the building in warm external conditions and also trapping heat inside the prototype during colder external conditions. The vegetated roof would also attenuate temperature peaks and valleys, decreasing the thermal amplitude. A summarised graphic view of the main heat fluxes can be seen in figure 7.

Furthermore, heat, water and vegetation dynamics are interconnected through evapotranspiration. The ET mechanism removes heat from the vegetated roof and increases the cooling effect provided by this Nature-based Solution (CASCONE *et al.*, 2019). A comprehensive review of energy related aspects can be found in Saadatian *et al.* (2013).



↓ ↗	Shortwave heat reflection and absorption from vegetation and substrate	↕	Heat flux from conductivity through layers
↗	Longwave heat exchange between layers, vegetation and substrate to atmosphere	↑ ↓	Heat storage in materials' mass
↕	Longwave heat exchange between layers, vegetation and substrate to atmosphere	↑	Heat from people and installations
↑	Heat loss through evaporation of water in the substrate and through plant evapotranspiration		Heat from plant photosynthesis is not depicted

Figure 7 – Structural factors of vegetated roofs and its main heat fluxes.

Source: adapted by the author from Ravesloot (2015); based on Feng, Meng and Zhang (2010), Ouldboukhitine *et al.* (2011), Tabares-Velasco and Srebric (2012) and Djedjig *et al.* (2012).

3.10 Water regulation

Water regulation in vegetated roofs is a phenomenon that happens at the building level and has impacts throughout the urban rainwater collection system. As next chapters will bring an in-depth review of water regulation at a roof scale, focus here will be given to its macro and city-wise consequences.

But first, there is a brilliant connection regarding water, heat, electricity and mechanics that may enlighten the understanding of how much of these dynamics derive from similar basis. Lofrano (2018) in his doctorate thesis reviews the history and concepts related to fluid mechanics, hydraulics and correlated areas that endeavoured modelling porous media water flow. He mentions that, in 1899, Charles S. Slichter (1864—1946), published the *Theoretical investigation of the motion of ground waters* (SLICHTER, 1899), where he deduces hydraulic conductivity in a media comprised of uniform spheres. In his work, Slichter (1899) managed to mathematically approach the hydraulic problem by considering it similar to heat and electricity, using Darcy's Law for such task:

> In Chapter II of the paper I investigate the general problem of the movements of water in soils and rock. I find that the problem is capable of mathematical treatment, and I show that the question is analogous to a problem in the conduction of heat or electricity, or to any other problem involving a transfer of energy. I show that there exists in the case of ground-water movements what is known as a potential function, from which we may derive, in any determinate problem, the velocity and direction of flow, and the pressure at every point of the soil or rock. The existence of the potential function is made the basis of much of the work that follows. (SLICHTER, 1899).

In this sense, a soil, or a porous media that has water flowing through, is a resistance in a hydraulic system; the same way as an electric resistor that has electrons travelling through is a resistance in an electric circuit; and the same applies to a physical material that changes heat conduction, it is a resistor for calories flow. Visualising these dynamics helps understanding how computer simulation can be a very good model for water in Computational Fluid Dynamics (CFD), for example. Soil can be seen, in terms of water quantity, as a resistor in a hydraulic circuit, see figure 8.

Though an analogy with many limits, a brief comparison of analogous equations is brought in chart 7. Dimensions are comprised of foundation units from the International System of Units (SI), as suggested by Hayes *et al.* (1994), in which the dimension of a generic quantity X is given in equation 1:

$$dim X = \mathsf{L}^a \mathsf{M}^b \mathsf{T}^c \mathsf{I}^d \Theta^e \mathsf{N}^f \mathsf{J}^g \tag{1}$$

Where the dimensions: L to *LENGTH*; M to *MASS*; T correspond to *TIME*; I to *CURRENT*; Θ to *TEMPERATURE*; N to *AMOUNT*; J to *LIGHT INTENSITY* and a, b, c, d, e, f and g are dimensional exponents.

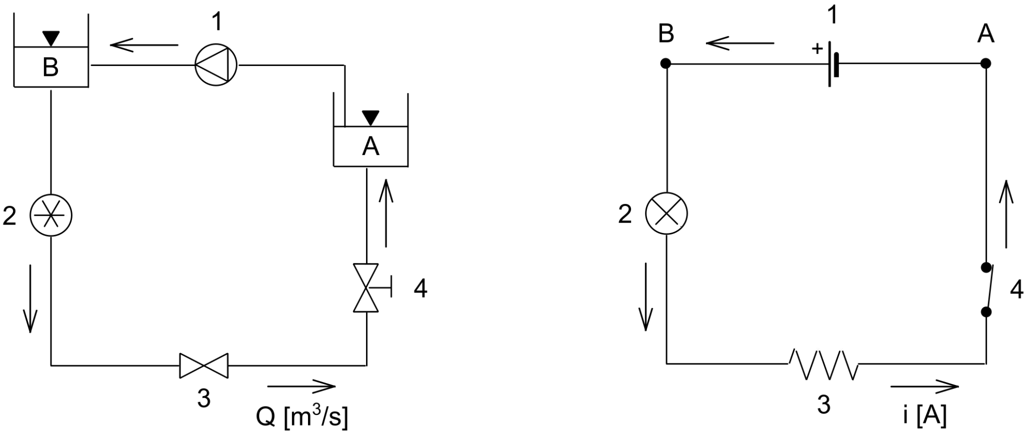


Figure 8 – Analogy between a hydraulic circuit (left) and an electronic circuit (right): *1* Hydraulic pump / voltage source; *2* Turbine / bulb; *3* Throttling valve or porous media / resistor; *4* shut-off valve / switch.

Source: Pugliesi (2012).

Type	Hydraulic	Electric	Thermal	Mechanical
Quantity	Volume V $[\mathrm{L}^3]$	Charge q $[\mathrm{TI}]$	Heat Q $[\mathrm{L}^2\mathrm{MT}^{-2}]$	Momentum P $[\mathrm{LMT}^{-1}]$
Quantity flux	Vol. flow rate Φ_V $[\mathrm{L}^3\mathrm{T}^{-1}]$	Current I $[\mathrm{I}]$	Heat tran. rate $\dot{Q}$ $[\mathrm{L}^2\mathrm{MT}^{-3}]$	Velocity v $[\mathrm{LT}^{-1}]$
Flux density	Velocity v $[\mathrm{LT}^{-1}]$	Current density j $[\mathrm{L}^{-2}\mathrm{I}]$	Heat flux $\dot{Q}''$ $[\mathrm{MT}^{-3}]$	Stress σ $[\mathrm{L}^{-1}\mathrm{MT}^{-2}]$
Potential	Pressure p $[\mathrm{L}^{-1}\mathrm{MT}^{-2}]$	Potential ϕ $[\mathrm{L}^2\mathrm{MT}^{-3}\mathrm{I}^{-1}]$	Temperature Θ $[\Theta]$	Force F $[\mathrm{LMT}^{-2}]$

Chart 7 – Analogous equations by type of energy transfer.

Source: adapted by the author from Kovács and Majáar (2018).

Deriving from similar foundations, many aspects of nature in different physical scales are interconnected. In this sense, interventions at a micro building level may influence macro urban scales. Which is great news, considering that Sustainable Drainage Systems can face difficulties when spreading only throughout public spaces: there can be a lot of competition for occupying areas of land in densely built cities, as recalling from Stovin (2009).

If roofs have such a representative proportion of city coverage and if managing rainfall within the roof area is a possibility, it should be further explored. In this sense, vegetated roofs can provide two main services for better managing rainfall in densely built cities, as described by Berndtsson (2010) and illustrated in figure 9:

i. Retention, or the partial storage of total rainfall within the substrate volume, plants volume or drainage layer volume. This water saturation of the VR, specially filling

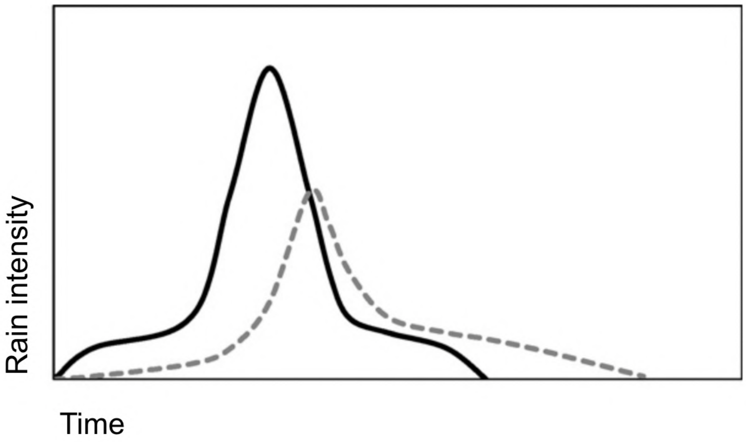


Figure 9 – Estimated illustration of a vegetated roof runoff (dashed line) generated by a given rainfall event (black line).

Source: Berndtsson (2010).

empty substrate pores, contributes to the urban drainage by avoiding a portion of total rainfall quantity to ever reach the rainwater system, running off the VR by evapotranspiration. As in an electric resistor part of the electric current is dissipated in heat, part of the water in a VR porous media flow is dissipated in evapotranspiration.

ii. Detention, or the delaying and attenuation of peak runoff from the totality of the rainfall event. This delay and attenuation are functions of the VR structural factors and are provided mainly by the substrate porous media resistance abilities, similarly to electric resistors. In contrast to retention, whose runoff is captured and will never reach the urban rainwater system, detention works towards better distributing runoff through time. Hence, contributing to reducing the rainwater collection system demand.

The subject of water regulation in vegetated roofs will be further discussed and expanded in chapter 5, chapter 6 and chapter 7.

4 Methods

> A scientist in his laboratory is not a mere technician; he is also a child watching a spectacle of natural phenomena which move him as deeply as a fairy tale. Nor do I believe there is any danger of the spirit of adventure dying out: the most vital force I see when I look around me is that very spirit of adventure, that indestructible urge akin to curiosity.
>
> Marie Curie by Marguerite Perey in: *The Woman We Called 'La Patronne'*, 1967

For the exploratory and descriptive objectives described in chapter 2 to be accomplished, quantitative and qualitative research will be conducted in an outdoor laboratory environment, installed at the Polytechnic School of the University of São Paulo.

As the present work involves a literature review and the combination of three complementary experiments, some chapters are independently written. These are chapter 5, chapter 6, chapter 7 and chapter 8, which involve a specific introduction, specific methods, specific results and specific discussions and conclusions. Thus, each of these chapters will present its methods independently, however an outline of the methodology involved is here described.

For the reviewing process, an exhaustive summary of indexed and grey literature is presented in chapter 5. National and international literature is consulted and specific boolean operators and keywords are used to find the most relevant records. The results are organised in relation to a relevant Brazilian climate classification in order to demonstrate the correlation of vegetated roofs' performance with its surroundings.

For Experiments A and B, materials used and methods involved are described in depth in chapter 6. Masonry prototypes and physical models of vegetated roofs with different substrate depths were monitored using sensors for quantifying rainfall, runoff, solar radiation and soil moisture content, besides weather variables. Results are demonstrated in chapter chapter 7.

For Experiment C, the materials used and the methods involved are described in chapter 8. Physical models of vegetated roofs with different substrate depths were monitored using the Point-Intercept method to quantify their vegetation dynamics and identify qualitatively the species and characteristics that may assist their spontaneous colonisation.

5 Review of vegetated roofs rainwater management in Brazil

When birds talk to stones and
frogs to waters — it is poetry
they are talking about.

Manoel de Barros in:
Poesia Completa, 2011,
our translation.

5.1 *Introduction*

Contemporary cities undergo a range of environmental issues caused by mainstream urban planning and land use and occupation practices SANTOS *et al.* (2021). The decrease in soil permeability by added concrete and asphalt turn basins into less pervious areas (SANTOS *et al.*, 2021; JACOBSON, 2011; SHUSTER *et al.*, 2005), increasing surface runoff and decreasing runoff travel time for reaching urban water bodies (HELLIES; DEIDDA; VIOLA, 2018). As a consequence, peak runoff rates are increased and flood risk becomes a concern (CRISTIANO *et al.*, 2021). As pointed out by McClymont *et al.* (2020), marginal human settlements built in high risk regions such as floodplains and unstable slopes can be affected by extreme events that can trigger floods, having "inadequate drainage infrastructure and unenforced building codes" (MCCLYMONT *et al.*, 2020; UN-HABITAT, 2020; UN-UNISDR, 2015). Although risk is often not a choice, occupying marginal areas is a common practice in developing countries such as Brazil, according to Rasch (2015). Flooding events that can damage allotments and households are a common drawback to the current type of urban planning, and therefore solutions for attenuating these problems must be sought.

Nature-based Solutions (NbS), a novel approach involving the previously known Sustainable Drainage Systems (SuDS), is a pathway to be followed for flood risk management (HARTMANN; SLAVÍKOVÁ; MCCARTHY, 2019). NbS according to the European Commission (EC, 2015) are "Solutions that are inspired and supported by nature [...]". As pointed out by Hartmann *et al.* (2019) and Holstead *et al.* (2014), Natural Flood Management (NFM) and natural water retention measures (NWRM) are types of NbS that can support flood risk management via landscape features. Brought by the recent “State of finance for nature” report from the United Nations Environment Programme (UNEP, 2014), it is expected a tripling in these structures investments by 2050. NbS encompass SuDS such as bioretentions and vegetated roofs that have been widely demonstrated to have positive impacts on rainwater quantity and quality management for urban catchment areas (MCCLYMONT *et al.*, 2020; BERNDTSSON, 2010). In turn, these structures assist cities into becoming more pervious and capable of attenuating and delaying runoff, thus creating time for rainwater to stay for longer, which is the scope of the Sponge Cities (HAMIDI; RAMAVANDI; SORIAL, 2021).

Among these solutions, vegetated roofs (VR) can generate a wide set of Ecosystem Services (ES), which the International Union for Conservation of Nature (IUCN) defines as the “benefits people obtain from ecosystems” (MA, 2005). As mentioned by Vesuviano and Stovin (2013) the VR are an interesting solution for densely occupied cities, which have large competition for ground land use. Being installed in normally underused building rooftops that can represent up to 50% of cities impervious areas (VESUVIANO; STOVIN, 2013; DUNNETT and KINGSBURY, 2014), VR can retain, delay and attenuate rainwater (BERNDTSSON, 2010). In this sense, these NbS can provide urgent and awe-important regulatory ES to contemporary cities flood risk management (KRAUZE; WAGNER, 2019).

However, for the mainstreaming of vegetated roofs as drainage systems, robust public policy incentives are necessary (CLAR; STEURER, 2021). Public policies can better regulate and plan the wide application of VR (LIBERALESSO *et al.*, 2020), a process just as common drainage systems undergo. Via public policy incentive, citizens and stakeholders can better adopt these structures (CLAR; STEURER, 2021). This is a necessary step for the wide application of VR, given that these green envelopes will be mainly installed on top of private buildings. On top of that, for a widely effective public policy, standardisation, norms and quality control are necessary (KOROL; SHUSHUNOVA, 2017; CATALANO *et al.*, 2018). In order to give practitioners and technicians security for designing and building VR as well as the public sector the reference for evaluating these structures, standards are needed.

For planning and designing vegetated roofs in order to improve its rainwater management performance, experimental work can support the characterisation of indexes and relevant parameters. Alone an experimental research cannot satisfy these requirements, but the review and summarisation of a robust bulk of research may do. In this sense, a blind spot is reached, given that Brazil does not have a recent review of literature in the field available for the national and international communities. Previous nationally published research managed to achieve robust reviewing processes (BÄR; TAVARES, 2017), but is not accessible to the international community as it is written in Portuguese and is currently outdated. Previous worldwide review articles also demonstrate taking into account less of the available research made in Brazil, as most of it is not indexed in internationally recognised databases.

The present work, therefore, addresses this gap by reviewing the state-of-the-art of the literature on green roof water quantity performance in Brazil. As literature indexed in international bases is scarce, this review encompasses also nationally published and grey literature. Also, as widely demonstrated by the field review literature, environmental factors strongly affect green roof performance (HELLIES; DEIDDA; VIOLA, 2018; ZHENG *et al.*, 2021; HANUMESH, CLAVERIE; SÉRÉ, 2021). The main objectives of this article are, thus, to (*i*) produce average outcomes of green roof water retention performance for each Brazilian climate with experimental data available under standardised indicators and (*ii*) review and synthesise the Brazilian literature relevant discussions, results and recommendations in VR water quantity management and present it to the international scientific community.

With the efforts of this review, it is expected to generate foremost scientific contributions nationally and internationally. The present work contributes to shedding light to future innovative and needed research trends in Brazil on VR, so that scientists and researchers can better direct their efforts. It also contributes to the international community, increasing the data availability resolution on VR water quantity performance in Brazil and referencing national findings in relation to the international literature.

Through the standardisation and better characterisation of vegetated roofs performance towards rainwater quantity management, both water and energy budget investigations on Blue-Green Infrastructure (BGI) are supported and advanced. Water budget is correlated to plant evapotranspiration dynamics, which is the main mechanism of heat extraction from Green Infrastructures (BROADBENT *et al.*, 2019; VEIGA; GÜTHS; SILVA, 2020). Thus, for quantifying energy dynamics in BGI, quantifying the water dynamics is necessary, which is a relevant application of this article. Besides that, the implementation of VR in cities can also change land coverage, hence promoting positive impacts on the energy balance of cities (MACHADO *et al.*, 2020). In this sense, the present review supports the advance of the UN's Sustainable Development Goals (UN, 2015), especially the SDG 13 of Climate Action and SDG 11 of Sustainable Cities and Communities.

5.2 Background

In order to quantify the vegetated roof's water performance, it is useful to visualise it in terms of fluid mechanics. The VR is enveloped by a control volume with water inflows and outflows. And these inlets and outlets are in turn influenced by a range of different factors.

5.2.1 Structure and water balance

A generic vegetated roof structure can be seen in figure 10. From bottom upwards, a VR is placed on top of a waterproof slab or an inclined roof starting with a drainage layer. This bottom-most layer has the function of letting water drain off the VR avoiding substrate oversaturation, see Vesuviano and Stovin (2013). A pervious webbing of geotextile is normally used to separate the drainage layer from the substrate layer (LOUZADA, 2016). Right after, the substrate layer is commonly a mixture of different materials involving normally earth and soil and other aggregates for improving water retention, nutrition and drainage capacity (AMPIM *et al.*, 2010). A mulching layer, consisting normally of dry organic matter such as decaying leaves or tree bark is indicated to help decrease substrate evaporation and nutrient washing, see Nagase, Dunnett and Choi (2013). Finally, the vegetation layer is the external skin of the VR. This layer involves the use of a selection of botanic species that can ideally perform well under the constraining conditions of shallow substrate and high temperature and water availability variation amplitudes (NAGASE; DUNNETT, 2010).

Entering and leaving the VR control volume via its control surfaces, there are inflows and outflows, as seen in figure 10. As main water inflows there are natural rainfall events and artificial watering events if an irrigation system is implemented. As main outflows there is runoff from the bottom, the draining of the VR gravitational excess water, and evaporation from soil and evapotranspiration from plants, both from the top. The sum of inflows and outflows will indicate the remaining water inside the roof's control volume, or the water retained, which is saturating the roof's pores. The accounting of this

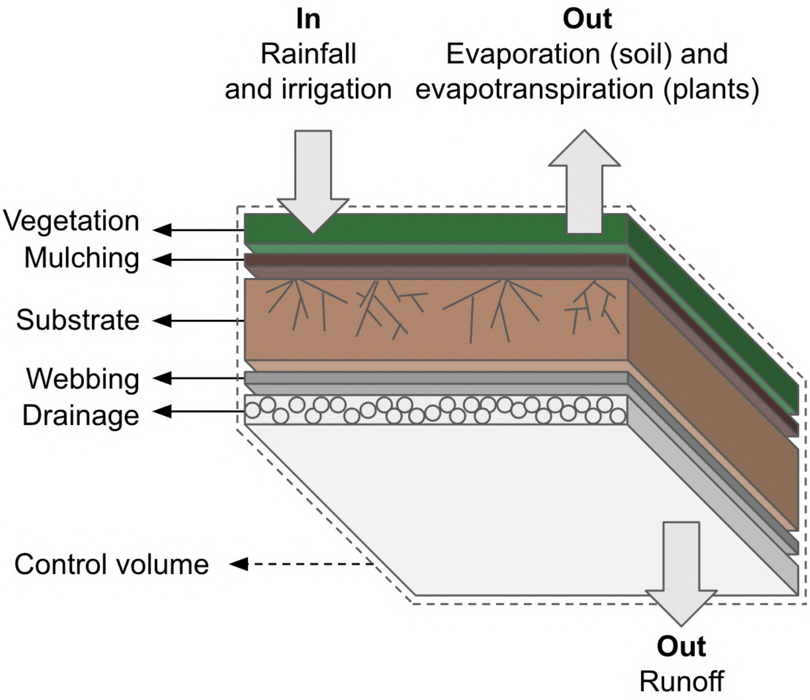


Figure 10 – A generic vegetated roof structure and its main control volume water in and outflows, expanded from Berndtsson (2010).

stored water can also be estimated by the VR soil moisture content, and the final sum of inflows and outflows is the water balance or water budget.

5.2.2 Water quantity affecting factors

Water quantity performance on vegetated roofs is widely affected by a number of factors that are in this work divided into classes.

The first class are structural influencing factors, which comprehend design premises that do not change through time. Substrate characteristics are within this group, such as substrate depth and mixing materials, which are demonstrated by Liu *et al.* (2019) and VanWoert *et al.* (2005) to modify the VR hydrological performance. Drainage layer characteristics are also within this group, demonstrated by Baryła *et al.* (2018) as also influencing water performance. Besides these, the VR slope also influences the runoff rates as well as the roof area (BERNDTSSON, 2010).

The second class is named the dynamic influencing factors, which are deeply affected by the initial design premises but may change through time. These involve the vegetation influence, as the VR flora can grow, expand and develop its aerial parts and root system through the VR lifespan and represent a profound change in the roof's hydrological performance (SOULIS *et al.*, 2017; GONG *et al.*, 2021). Vegetation can change height and VR plant coverage as well as increase or decrease its diversity, depending on how it is managed (DUNNETT; NAGASE; HALAM, 2008). As direct consequences of vegetation, evapotranspiration (ET) and antecedent soil moisture content (ASMC) are considered as affecting dynamic factors, which has been observed to influence the hydrological performance of VR (STOVIN *et al.*, 2015).

The third class comprehends environmental influencing factors, which are not related to the design of the roof, but much more to the geographical location where the roof is installed. These climate-related factors, as pointed out by Zheng *et al.* (2021), can be the climate's rainfall intensities, the seasons effect and the antecedent dry weather periods (ADWP) (TUCCI, 2005; VOYDE; FASSMAN; SIMCOCK, 2010). As also pointed out by Zheng *et al.* (2021), Viola *et al.* (2017) demonstrated that the hydrological performance of VR increases when ET and rainfall have the same seasonality and decreases when their phases are opposite.

5.3 Review methods

For achieving the objective of characterising the retention and detention outcomes of vegetated roof experiments across Brazil, two complementary methodological phases are conducted. First, the identification of relevant works and, second, the processing of their results using the same metrics, hence generating a possibility of statistically summarising the results.

5.3.1 Reviewing process

An exhaustive review for specific keywords was conducted in online databases in order to identify relevant research. The Scopus and Compendex (Engineering Village) databases and the Coordination for the Improvement of Higher Education Personnel (CAPES, in Portuguese) Brazilian scientific database were consulted. Grey literature from university theses or other minor databases were also included, as well as work originally published only in Portuguese language.

The terms and boolean operators OR and AND were used with relevant keywords as a first search mechanism in all databases. In order to find research published in Portuguese, these terms were translated for different synonyms. The step-by-step for narrowing down the final works here reviewed is demonstrated in figure 11, where keywords are searched in any part of a given work, not only in its title and abstract. The N value is the number of effective records selected for the in-depth reviewing process.

5.3.2 Retention and detention indicators

A vegetated roof hydrological performance can be summarised by a set of indicators. As seen before, these indicators dynamics are affected by the aforementioned set of influencing factors. These indicators are the quantitative measures of the roof's retention and detention performance. The phenomena involved in this quantification are conceptually illustrated in figure 12.

The retention performance of a VR is how much of the rainfall this roof can store after a rainfall event, which is given as a volumetric quantity (BERNDTSSON, 2010). Retention is an awe-important phenomenon that can decrease the volume of rainfall running off an allotment and reaching the rainwater drainage public system, hence decreasing the public system demand. Hence, the runoff coefficient (C) represents the proportion of discharged volume in comparison to the rainfall volume, as seen in equation 2. C is a variable lying between 0, where there is no runoff (a possible real situation), and 1, where all rainfall becomes runoff (an ideal and theoretical situation).

$$C = \frac{\int_0^t \ Q_{VR} \ dt}{\int_0^t \ R \times A_{roof} \ dt} \qquad C \in [0, 1[\tag{2}$$

Where Q_{VR} is the VR runoff flow rate, R is the rainfall flow rate, A_{roof} is the VR area (which is the catchment area), and t is the total event time.

The VR retention performance is, thus, quantified by the retention rate (RR), the complimentary coefficient of C. In equation 3, the retention rate is the proportion between the retained volume and the incident rainfall volume on a VR, where the retained volume is the difference between the accumulated runoff and the accumulated incident rainfall. RR varies from 0, where there is no retention (an ideal and theoretical situation), and 1, where all rainfall has been retained (a possible real situation).

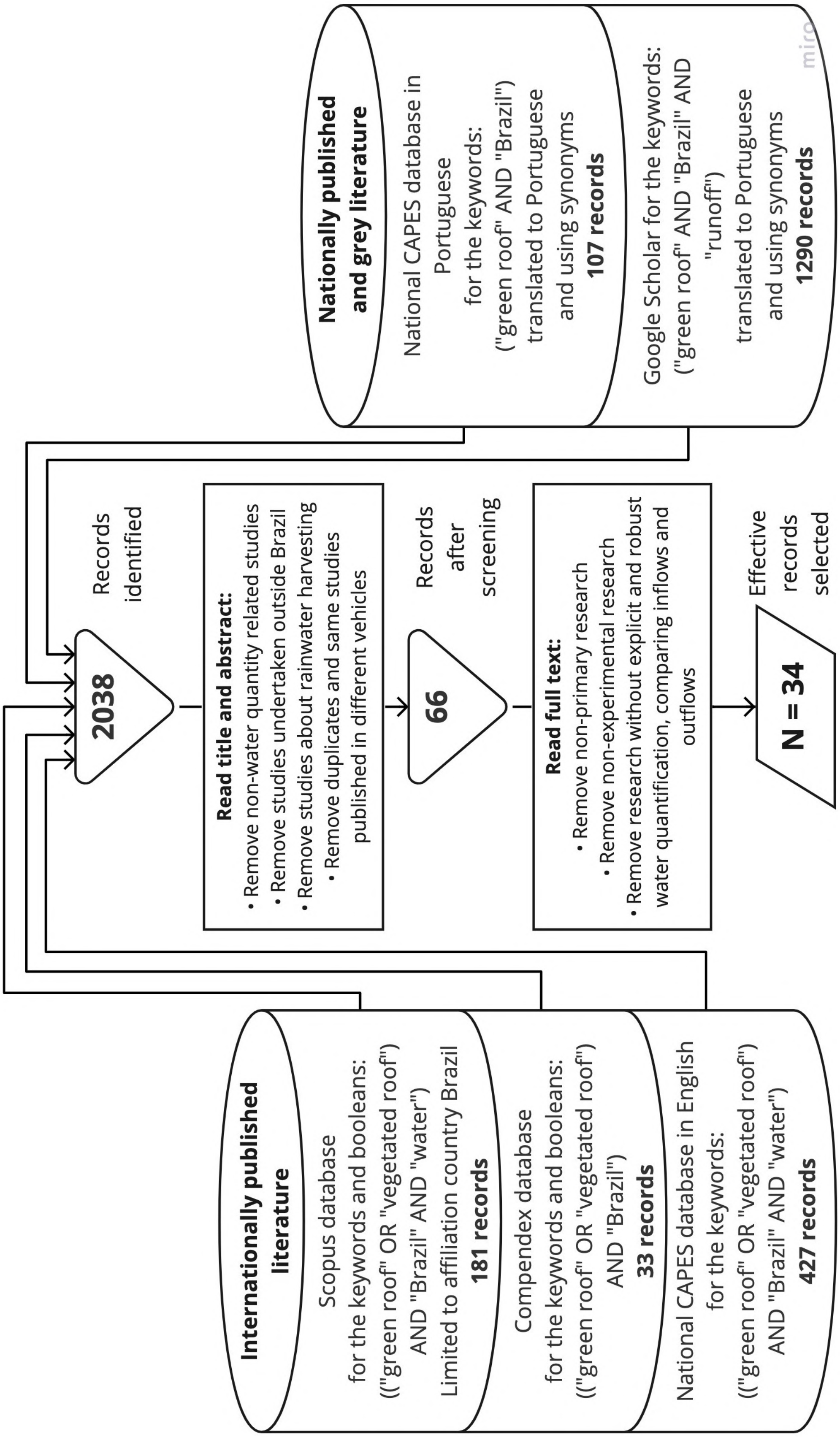


Figure 11 – Flowchart for selecting the N works here reviewed.

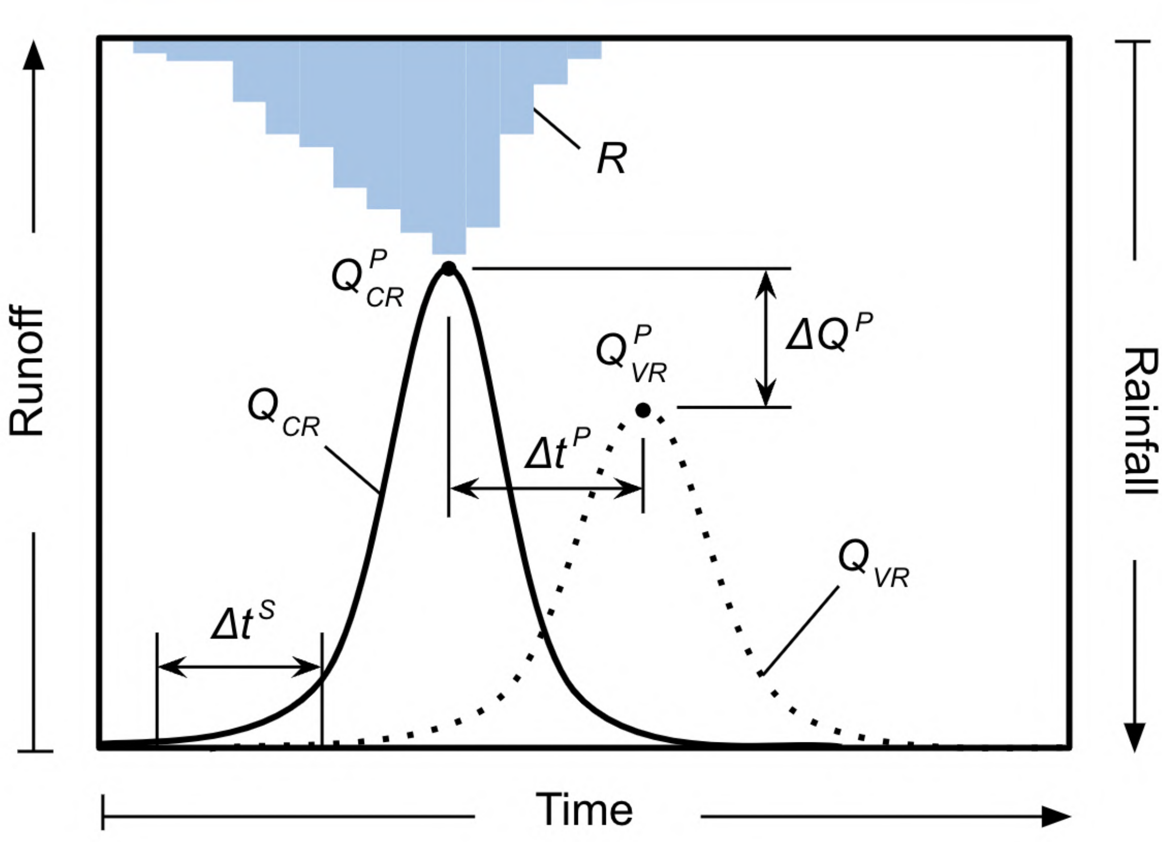


Figure 12 – Hydrograph comparing a vegetated roof (VR) runoff and a conventional roof (CR) runoff, with indications of peak discharge delay and attenuation.

$$RR = \frac{\int_0^t R \times A_{roof}\ dt - \int_0^t Q_{VR} dt}{\int_0^t R \times A_{roof}\ dt} = 1 - C, \qquad RR \in \,]0,1] \tag{3}$$

The detention performance is how much the VR contributes in attenuating or delaying the discharged drained rainwater (BERNDTSSON, 2010). This is a performance always in comparison to a conventional impervious roof, for example. Detention performance is also relevant, as having the runoff attenuated and delayed can also be a contributing factor if analysing the scale of a neighbourhood. When some of the allotments have a lower peak runoff and a delayed discharge, these allotments' drainage is less overlapping the discharge from their neighbours. Thus, it is not contributing to demanding an increase in the public rainwater collection system capacity, it is spreading out the demand over time.

As indicators of the detention performance there is peak attenuation (ΔQ^P) in litres per second, peak runoff delay ($\Delta \mathrm{t}^P$) in seconds and runoff starting time delay ($\Delta \mathrm{t}^S$) in seconds, as seen in figure 12 and equations 4-6:

$$\Delta Q^P = \left|Q^P_{CR} - Q^P_{VR}\right| \qquad [L/s] \tag{4}$$

$$\Delta \mathrm{t}^P = \left|t^P_{Q_{VR}} - t^P_{Q_{CR}}\right| \qquad [s] \tag{5}$$

$$\Delta \mathrm{t}^S = \left| t^S_{Q_{VR}} - t^S_{Q_{CR}} \right| \qquad [s] \tag{6}$$

Where Q^P_{CR} is the conventional roof peak runoff, Q^P_{VR} is the VR peak runoff, $t^P_{Q_{VR}}$ is the VR peak runoff time, $t^P_{Q_{CR}}$ is the conventional roof peak runoff time, $t^S_{Q_{VR}}$ is the VR starting runoff time, $t^S_{Q_{CR}}$ is the conventional roof starting runoff time.

5.3.3 Data extraction using the rational method

In order to extract the data from each record, it was necessary to standardise the indicators generated by each experiment. Not all works demonstrated the hydrological performance of VR in the same way, thus a widely used and simple way of generating reliable outcomes was chosen.

In this sense, the Rational Method was used. As Loiola *et al.* (2019) indicate, this method is classically used for micro-drainage applications and was originally built for estimating peak runoff in small urban catchment areas. This is the case for VR, as the catchment area is the roof surface area itself, as seen in equation 7 (LOIOLA *et al.*, 2019).

$$Q = C \times i \times A_{roof} \tag{7}$$

Where Q is the peak hydrograph, i is a chosen design rainfall intensity that is associated with a return period and critical duration and A_{roof} the roof area. The variable C is exactly the dimensionless runoff coefficient from equation 2, thus a parameter that correlates rainfall and runoff. The runoff coefficient is dependent on the surface material and soil occupation, being high for low infiltration surfaces (*e.g.* asphalt and concrete parking lots) and low for permeable surfaces (*e.g.* parks and forests). Instead of the results being demonstrated as C, they are demonstrated using the RR coefficient, which is more intuitive, as it varies positively the more retention a VR can hold.

Finally, in order to georeference the data, the Köppen Geiger climate classification was used, as described in Alvares *et al.* (2013). The classification system of Köppen was first published in 1884 (KÖPPEN, 1884) and since then remains the most widely used system in the world for its simplicity and accuracy. The classification uses simple rules and simple climate symbols and is based on monthly temperature and rainfall. Alvares *et al.* (2013) produced a map for Brazil under this system's rules using 2,950 weather stations and is the base for the present work's classification. In the present review, an associated average RR is generated for each climate zone in Brazil where there has been experimental research on VR hydrological performance.

Some of the works hereby reviewed did not present data in table format, only in plot format. In this sense, it was necessary to extract quantitative data from graphical data. For that, WebPlotDigitizer turned out to be a handy alternative and was used when necessary.

5.4 Results review

Results are presented in complementary sections that can better expand and illustrate the outcomes and patterns found in the selected records. First, a metadata analysis is presented. Second, an analysis of the methods used for measuring runoff. Third, a sequence of sections to expand qualitatively on the structural, dynamic and environmental water quantity influencing factors. And finally a quantitative summary of retention outcomes is given, georeferencing the results found.

5.4.1 Metadata

By analysing the records metadata, relevant patterns are noticeable. The increasing quantity of works published per year can be seen in figure 13. This growth that went from no work published in 2005 to six in 2019 and four in 2021 indicates that the subject is a field being more and more explored.

Among the selected $N = 34$ records, there were two main groups of works as seen in figure 14. Group A, holding 8 of the 34 records, or 23.5%, is characterised by internationally published records in English. These are research articles indexed in Compendex or Scopus bases, reaching a worldwide audience. Group B, on the other hand, holding 26 out of 34 records, or 76.5%, is characterised by nationally published literature in Portuguese. These are research articles published in Brazilian journals or thesis with a robust methodological approach. When the same research generated a thesis and an article, only the article was chosen.

From the total set of records, relevant patterns regarding the methodological approaches used by each author or group of authors are highlighted in figure 15. All works

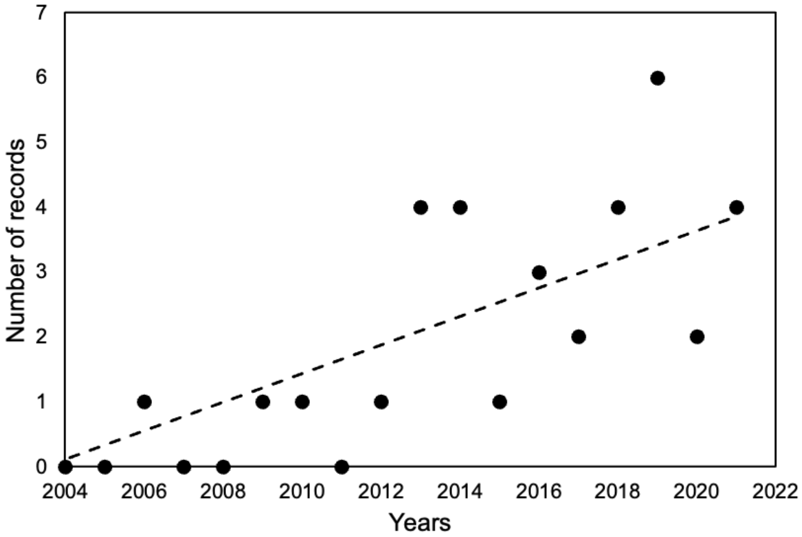


Figure 13 – Number of records by year among the N selected.

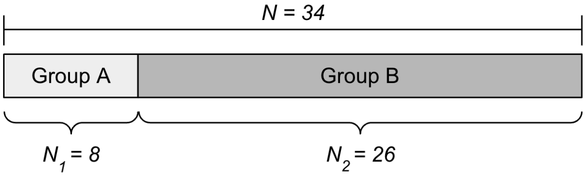


Figure 14 – Graphical proportion of records published by group.

characterised retention, as this was the simpler and more important indicator, thus a compulsory outcome for a record to be selected. Most of the works characterised rainfall dynamics such as duration, intensity or depth, but not all of them. Almost half included other relevant environmental data, such as temperature, radiation or wind speed, which influence the hydrological VR performance. Very few managed to characterise the detention indicators of peak delay and peak attenuation. Also few works used simulated rain, most of the experiments used natural rainfall events. These numbers demonstrate that most of the experiments had great difficulty in measuring a systemic interrelation of data.

Figure 16 brings, on the other hand, relevant patterns regarding the influencing factors analysed. It is possible to notice that antecedent dry weather period and soil moisture content were the most investigated factors, and roof area, substrate material and evapotranspiration the least investigated. These metadata can help demonstrate the gaps and blind spots this set of selected works expresses. As it is an exhaustive review, the absence of studies or quality investigation in the spots presented can give opportunity for further innovative work to rise.

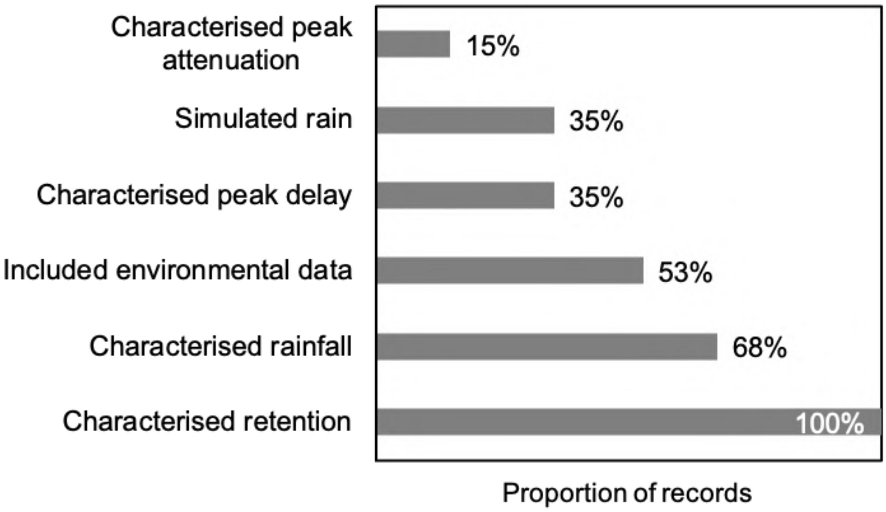


Figure 15 – Methodological approaches for water balance in the selected records.

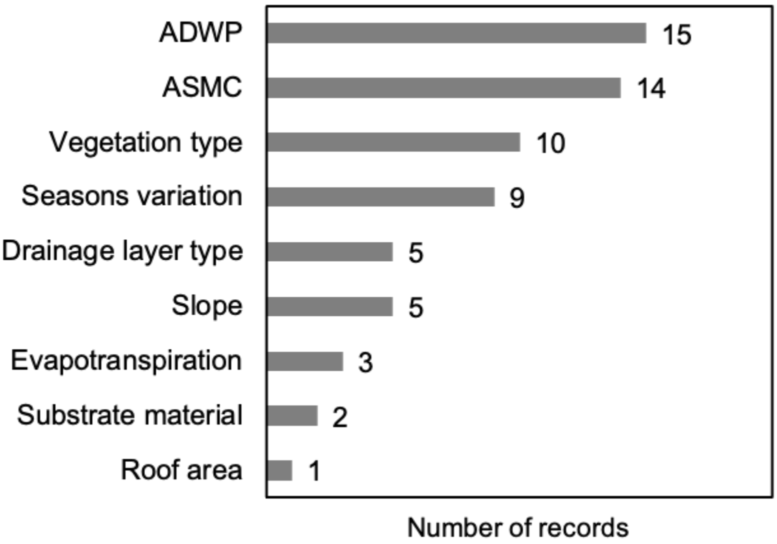


Figure 16 – Influencing factors analysed. An only record can have analysed more than one influencing factor.

5.4.2 Runoff measurement

Measuring the relevant inflow and outflows from the VR models and prototypes, or the rainfall and runoff, are essentially a flow rate measurement. As seen in the metadata analysis, not all works were capable of undertaking detention measurements. This is because it needs sensing of flow rate, which can be a difficult and expensive measurement. In this sense, the different methods each research was able to implement are here divided into sections and expressed in table 2.

Method	Quantity measured	Runoff indicators and rainfall conditions			
		Retention		Detention	
		Simulated	Natural	Simulated	Natural
Section 1: volumetric measures	Volume	Yes	Yes	No	No
Section 2: manual flow rate measures	Flow rate	Yes	Yes	Yes	No
Section 3: sensor flow rate measures	Flow rate	Yes	Yes	Yes	Yes

Table 2 – Runoff indicators (retention or detention) and rainfall conditions (simulated or natural) each method is able to measure.

Section 1: 68% of the N records here described were only capable of measuring total inflow and outflow volumes, which is easier to be done, *e.g.* collecting runoff on a tank. As an experimentalist may need to be accompanying the event in order to measure runoff delays or peak attenuations, these studies managed to characterise only simulated events. To characterise natural events, only runoff volumes could be generated, which constrains important work outcomes of detention.

Section 2: 12% of the N records here described were capable of making manual flow rate measurements. This second section of studies could only get full retention and detention data from simulated rainfall events, as the experimentalists needed to be there collecting the data at all times. However, this type of instrumentation can also generate retention data for natural events.

Some of the methods in the works reviewed can exemplify this section. Silva *et al.* (2019) use a tank coupled with a graduated cylinder and a floater. As the water level of the tank increases, so does the floater level raises and thus water flow is discretly measured by an observer. This method enables measuring flow rate, but is not a real-time sensing technique. A similar technique was used by Souza (2018), where graduated tanks were used to collect the runoff volume from a VR prototype and a CR prototype. An observer with a watch took note of the time for each graduation step reached. Louzada (2016) directioned the VR modules' runoff to tanks on top of weighing scales. The runoff flow rate was indirectly inferred by the weight added at each timestep, recorded by an observer.

Section 3: 20% of the N records here described were capable of measuring flow rate using real-time sensing. These studies managed to create real-time sensing methods, which enabled the experimentalists to collect runoff flow rate data from natural events regarding retention, runoff start delay, peak runoff delay, and peak attenuation.

Despite the real-time sensing difficulty, some works attained interesting solutions for flow rate measurement that should be highlighted. Watrin *et al.* (2020) directioned the outflow of VR modules to translucent graduated plastic containers and pointed cameras recording real-time. In this way, an experimentalist can easily assess the volume through time and find experiment boundaries. The same was made by Costa (2016), but using simulated rain events, recording a graduated cylinder with a cellphone camera. Persch *et al.* (2021) used a tank coupled with an ultrasonic sensor to measure water level, enabling real-time flow rate sensing. Castro *et al.* (2020) also used a tank and a water level sensor, but did not specify which sensor was used, and Tassi *et al.* (2014) used the same setup. Laar and Grimme (2006) used tipping buckets to measure runoff, a technique also used by Hill *et al.* (2015) at *gritlab*. Ilha *et al.* (2012) measured the runoff by comparing the rainfall volume with the retained rainwater as a function of substrate moisture. To measure soil moisture content the authors used real-time sensing with a soil moisture probe sensor. Silva (2014) used a tank to collect runoff and a pressure transducer sensor with data logger to capture water level, thus capturing real-time runoff flow rate.

5.4.3 Structural factors investigation

To start the influencing factors investigation, the first outcomes analysed will be related to the VR structure. Structural factors should comprise the VR substrate depth, substrate materials, slope, roof area and the drainage layer. However, no research involving different substrate depths with clear characterisation of rainfall-runoff has been recorded yet in Brazil under the present reviewing process described.

5.4.3.1 Substrate material

The substrate materials for vegetated roofs are summarised by Ampim *et al.* (2010). They have a great influence in the hydrological performance of VR, as previously pointed out by Stovin *et al.* (2015).

Liberalesso *et al.* (2021) evaluate the addition of rice husk in the vegetated roofs' substrate hydrological properties. The carbonised rice husk has a high holding capacity and increasing its proportion in a substrate demonstrates also an increase in the VR retention. The behaviour, as Liberalesso *et al.* (2021) indicate, should be probably caused by incomplete combustion processes that the carbonised rice husk undergoes, transforming it from hydrophobic to a material with a high density of micropores, increasing its water holding capacity (MILLA *et al.*, 2013).

It is interesting to note that Liberalesso *et al.* (2021) decided to investigate the rice husk as it is a widely available material in the region of study. This should be an incentive for researchers to try and verify the hydrological properties of added materials that are discarded from industrial processes and incorporate it on green roofs. This practice can have a great potential of positively influencing the life cycle of materials and thus saving production energy and reducing costs. The same way, though not generating rainfall-runoff data, Oliveira (2012) analysed different types of substrates for use in green roofs with materials available within Brazil. The substrates analysed are mixtures with different proportions of soil, crushed coconut husk fibre and peat. The substrates demonstrating better retention capacities were those with a higher percentage of soil and lower percentage of coconut husk. This may be explained by the increased difficulty for water to find preferential pathways in between soil particulate material in comparison to the more porous coconut husk.

In terms of vegetation development, Silva (2014) found that regular vegetable substrate commonly used for gardening did not guarantee a good botanical growth. The author discusses that it may have happened because this substrate lacks organic matter.

5.4.3.2 Slope and roof area

As demonstrated in the present work's background section, slope and roof area can influence rainfall-runoff performance. Castro *et al.* (2020) investigated two green roof setups having different slopes: one with a flat zero degree slope and another with a 15-degree slope. The authors observed that runoff rates were always higher in the sloping roof, and for many events the flat roof will not even release runoff. This was an indication that the slope is strongly positively correlated with runoff rates. These finds are in harmony with other works reviewed such as Bonsere (2019) and Moruzzi *et al.* (2014).

Bonsere (2019) also indicates that there can be a correlation between the roof slope and its antecedent soil moisture content (ASMC). This finding is relevant for better plant selection in different green roof slopes.

Under a theme with only one available study, Persch *et al.* (2021) demonstrated a correlation between the roof's catchment area and their water retention performance. Evaluating three different roofs with 1, 3 and 12 m^2, the best relative retention outcomes always came from the largest roof.

5.4.3.3 Drainage layer

The drainage layer choice is also a factor that can influence the hydrological potential of a VR, as researched by Vesuviano and Stovin (2013). Klein (2017) used VR testbeds with different drainage layer geometries and depths. In her experimental outcomes, it was found that deeper drainage layers with geometries that can also retain some water had greatly reduced the VR modules runoff. Mendonça and Melo (2020) investigate the use of precast modular cementitious supports, which are observed to generate a positive retention outcome in comparison to other conventional roofing systems. The authors Mendonça and Melo (2020) indicate that this performance may be associated to EVA aggregates presence used in the modules composition, which are residual material from the shoe industry.

Santos (2019) undertook an interesting experiment, comparing the retention of a VR module with an expanded clay drainage layer to the retention of only the expanded clay layer. The results demonstrate that the regular VR module could retain an average of about 71% (RR = 0.71) and the module with only expanded clay retained about 30% on average (RR = 0.30). This indicates that there is a relevant contribution from the drainage layer to the total retention of the vegetated roof.

Louzada (2016) evaluated different geosynthetic materials for the drainage layer: geotextile membranes (non-woven permeable fabric), geonet membranes (a polyethylene net with thickness of around 1cm to allow for drainage and no retention) and geocompost membranes (a combination of the two). The authors found that the module with only geotextile provided better retention rates, but other factors should be considered. When not being provided with a drainage layer to remove excess water, plants may be negatively affected. That means though there may be an initial increase in the VG hydrological performance, the loss of planted species may also decrease ET rates after some time, diminishing the VG capacity to recover its retention performance after a rainfall event.

5.4.4 Dynamic factors investigation

Dynamic factors are also considered to be a consequence of the vegetated roof design, but which has variable influence on the VR performance. These comprise aspects that may change through time, such as the VR vegetation, thus the VR evapotranspiration, and also the soil moisture content.

5.4.4.1 Vegetation

The plant layer on a vegetated roof can have great influence on its rainfall-runoff management properties as indicated by the international literature (SOULIS *et al.*, 2017; SZOTA *et al.*, 2017). Previous studies analyse this influence and point out that interception can be a great cause of these contributions (STOVIN; VESUVIANO; KASMIN, 2012) and also the evapotranspiration rates that will be further discussed.

Savi and Tavares (2018) characterised the retention rates for different species, classifying from higher to lower: *Bulbine frutescens, Sedum mexicanum, Zoysia tenuifolia, Callisia repens, Tradescantia zebrina var. Purpusii.* A relevant point to notice is that Arachis repens species were tested but did not tolerate frosting, as the experiment was undertaken in the southern regions of Brazil. The authors noticed that succulent species had the best outcomes, but discuss that this can be because of substrate coverage: these plants grew more vertically and left gaps of bare soil exposed to radiation, increasing substrate evaporation rates.

On the other hand, Loiola *et al.* (2019) analysed modular tray lightweight green roof systems comparing vegetated modules with succulent species, bare soil modules and a fibre-cement roofing system. The composition of vegetation used was 70% *Callisia repens*, 15% *Portulaca oleracea* and 15% *Aptenia cordifolia*. The authors found unexpected results when wet bare soil units better retained rainwater than wet vegetated units. This can be because of plant selection, as succulents have a Crassulacean Acid Metabolism (CAM) which assists in losing less water during hot summer days. This may indicate that bare soil lost more water to evaporation than the vegetated units lost to ET, showing that the succulent plants' presence may make it difficult for the soil to recharge its rainwater retention capacities (LOIOLA *et al.*, 2019). Castro *et al.* (2020) used green roof modules with vegetation and roof modules with bare soil, but found that vegetated modules had a better response to retention performance, however they did not clearly identify the species used.

Silva *et al.* (2019) analysed VR models with different vegetation types, one of them a bromeliad roof. The authors indicate that green roofs with bromeliads were able to retain more water, possibly because part of the rainwater was retained within the bromeliad tanks as a consequence of their geometry. Liberalesso *et al.* (2021) use *Sedum rupestre* in his VR modules. By using a phone camera and the software ImageJ® the authors were able to find out the vegetation cover ratio in each given experiment timestep (LIU *et al.*, 2019; NOYA *et al.*, 2017). Documenting its growth, the authors noticed that in drought conditions the main limiting factor for vegetation development in vegetated roofs is mainly water availability, which resonates with (VIJAYARAGHAVAN, 2016).

Barros (2013) undertook his investigations using two different types of local plants from the Brazilian semiarid. Comparing the retention capacity of modules with *Aloe vera* and *Melocactus zehntneri*, the author found that the latter species had a better contribution for the VR hydrological performance. Thus, as a general rule, plants that evapotranspirate more can help regenerate the substrate capacity of water retention and plants that evapotranspirate less may also reduce soil evaporation rates, hence diminishing the VR retention performance. There also enters into the account the proportion of substrate coverage that can affect the substrate evaporation rates.

5.4.4.2 Evapotranspiration

Only one work attempted measuring ET rates (ARBOIT *et al.*, 2021). The authors used VR modules and bare soil modules in order to capture not only ET but also substrate evaporation. For an average runoff coefficient of $C = 0.47$, 32% of the amount of rainfall was estimated to return to the atmosphere by ET and 21% remained stored in the substrate layer of the VR modules. In bare soil modules, for a runoff coefficient of 0.43, 34% became ET and 23% remained stored. This indicates that both bare soil and vegetated modules behaved closely on an equivalent basis, which may be explained by the vegetation type used, succulent. This possibility is reinforced by the fact that VR roofs in this experiment had worse performance than bare soil for retention, which may be due to vegetation not letting the retention capacity be recovered.

Evapotranspiration rates in Arboit *et al.* (2021) were found to be higher after rainfall events and lower in dry periods, indicating the used *Sedum rupestre* species ability to modify its behaviour depending on environmental conditions. ET rates were also higher in summer and lower in winter, as the experimental data collection lasted for half a year.

Laar and Grimme (2006) managed to quantify the cooling effect of evapotranspiration in the roofs. The authors indicate that the ET and evaporation of the nine-month period studied under a 335 mm accumulated rain generated a 228 kWh cooling per square metre in the VR modules, a relevant outcome for connecting rainwater management and heat balance for energy saving.

5.4.4.3 Antecedent soil moisture content (ASMC)

Many authors indirectly infer the antecedent soil moisture content by correlating with the antecedent dry weather period, but few actually measure this property physically. Previous established studies also use this association between ASMC and ADWP. Tucci (2005), as indicated by Klein (2017), classifies ASMC in three strata, evaluating accumulated rainfall depth from five days prior to an event: ASMC I, where accumulated depth is lower than 13mm; ASMC II, where accumulated rainfall is between 13-28mm and ASMC III, where accumulated rainfall is higher than 28mm. Tassi *et al.* (2014) quantified these classes of ASMC, demonstrating that the average RR for ASMC I was 0.79, for ASMC II 0.7 and for ASMC III 0.5, indicating that retention rates decrease as soil moisture content increases. This is also seen by Liberalesso *et al.* (2021), which show a strong negative correlation between ASMC and RR, and also the case of Klein (2017), Silva (2014), Mendonça and Melo (2020) and Moruzzi *et al.* (2014).

Opposite results have also been reached, as Persch *et al.* (2021) capture no significant influence from the previous soil moisture conditions in the VR prototypes retention capacity.

5.4.5 Environmental factors investigation

Environmental factors are considered to be the factors which are not a consequence of the vegetated roof design, but natural phenomena in the VR surroundings. These aspects are also dynamic and may change through time, such as the incident rainfall characteristics (*e.g.* depth, duration, intensity), the antecedent dry weather period and the weather seasons.

5.4.5.1 Rainfall characteristics

It is relevant to characterise the rainfall events that precipitate in the vegetated roofs, as different depths, intensities and durations can affect the roof's hydrological performance differently. To illustrate this difference, as many researches quantified runoff start delay as somewhere from around ten minutes to two hours, Castro *et al.* (2020) captured long duration and short depth rainfalls, achieving runoff delays 25 hours.

Silva *et al.* (2019) put VR trays under different simulated rainfall events using a rain simulator. In these authors' investigation it was found that both relative retention and relative peak flow attenuation was higher as more intense was the rainfall event. Persch *et al.* (2021) also correlate the VR water quantity results to rainfall depth and duration. The authors, on the other hand, show that as rainfall depth increases, retention decreases. These findings are in line with Liberalesso *et al.* (2021).

5.4.5.2 Antecedent dry weather period (ADWP)

Antecedent dry weather periods are relevant factors, with its importance internationally highlighted within the field's literature (STOVIN; VESUVIANO; KASMIN, 2012; LEE; LEE; HAN, 2015).

Watrin *et al.* (2020) assessed three modules in which two of them were vegetated roofs and the other a control fibre-cement roof. These modules were compared in three different situations: one with dry soil, when antecedent dry weather period was large; in a second situation when soil was wet from a short ADWP and in a third and average situation. The situation of longer ADWP demonstrated higher retention rates, which is in line with Liberalesso *et al.* (2021) findings. Watrin *et al.* (2020) point out differences from analysing only the event isolated and its previous rain period. Within an event, runoff is highly influenced by rainfall depth, however the ADWP had a greater impact on retention capacity when taking into account how it changes the antecedent moisture content.

Persch *et al.* (2021) show no significant correlation of increasing antecedent dry weather periods with rainfall retention improvements. The authors point out that this lack of correlation has been previously observed by other authors, such as Nawaz *et al.* (2015). They assign this phenomenon to the climate where the experiment is positioned and the vegetation used: a humid subtropical climate and using succulent plants.

5.4.5.3 Season

Analysing VR under different seasons can be a way of accounting at the same time for a whole set of environmental variations in rainfall, radiation, plant evapotranspiration, wind regimes, air temperature and other conditions. Few works managed to do that, as it implies a sometimes year-long data collection period.

Despite the challenge, Tassi *et al.* (2014) quantified this seasonal variation. In their work, it was shown that retention rates were higher in the autumn ($RR = 0.72$) and lower in the winter ($RR = 0.50$), with intermediate values in summer ($RR = 0.71$) and spring ($RR = 0.70$). Pessoa (2016) closely observed a related phenomena: summer $RR = 0.67$, autumn $RR = 0.60$, spring $RR = 0.51$ and winter $RR = 0.53$. The very close values of RR in autumn, winter and spring may indicate that more long-term studies need to be undertaken, but it may be clear that in winter the green roofs will perform worse, which must be correlated to environmental dynamics and especially ET rates.

Persch *et al.* (2021) also present a year-long analysis during four seasons under a subtropical climate. In these authors' work, it is shown that VR prototypes assessed had their worst retention performance in winter and best average performance in spring. The authors discuss that this outcome can be related to the intensification of biomass growth in the latter season, thus increasing plant rainfall interception and evapotranspiration rates.

5.4.6 Summary of retention outcomes

To summarise the data found, the retention outcomes were used. This decision is based on the amount of researches that managed to characterise detention. On the other hand, every record had at some level described rainfall-runoff. Possibly the lack of studies on detention factors is explained by the aforementioned difficulties in measuring flow rate.

Some of the research included in this summary from the N total records have not been discussed in the previous sections. The reason is that relevant aspects of these works may have already been discussed, thus avoiding repetitions, or the works only focused on quantifying the performance of a vegetated roof model compared to a conventional one, without comparatively varying any structural, dynamic or environmental parameters of the VR. The n parameter shows how many independent experiment events were recorded inside the same record N. Table 3 summarises the data by record, table 4 by climate and figure 17 graphically georeferences the outcomes. In the tables, uncertainties are calculated as standard errors of the mean.

N#	**Authors**	**Year**	**City**	**Climate**	***n***	***C***	***RR***
1	Loiola *et al.*	2019	Rio de Janeiro	Am	6	0.467 ±0.092	0.533 ±0.092
2	Watrin *et al.*	2019	Belém	Am	16	0.266 ±0.047	0.734 ±0.047
3	Silva *et al.*	2019	Rio de Janeiro	Aw	12	0.246 ±0.025	0.754 ±0.025
4	Persch *et al.*	2021	Santa Maria	Cfa	201	0.184 ±0.027	0.816 ±0.027
5	Arboit *et al.*	2021	Santa Maria	Cfa	36	0.541 ±0.051	0.459 ±0.051
6	Liberalesso *et al.*	2021	Santa Maria	Cfa	280	0.223 ±0.010	0.777 ±0.010
7	Castro *et al.*	2020	Porto Alegre	Cfa	38	0.172 ±0.034	0.828 ±0.034
8	Laar and Grimme	2006	Rio de Janeiro	Aw	2	0.520 ±0.130	0.480 ±0.130
9	Savi and Tavares	2018	Curitiba	Cfb	65	0.406 ±0.029	0.594 ±0.029
10	Bonsere	2019	Toledo	Cfa	12	0.620 ±0.032	0.381 ±0.032
11	Oliveira *et al.*	2009	Vargem Grande	Cfa	2	0.445 ±0.005	0.555 ±0.005
12	Bacovis and Nagalli	2013	Curitiba	Cfb	3	0.890 ±0.061	0.110 ±0.061
13	Klein	2017	Florianópolis	Cfa	105	0.250 ±0.033	0.750 ±0.033
14	Silva	2014	Rio Claro	Aw	15	0.162 ±0.057	0.838 ±0.057
15	Mendonça and Melo	2020	João Pessoa	BSh	32	0.216 ±0.057	0.785 ±0.057
16	Souza	2019	Campo Mourão	Cfa	3	0.085 ±0.057	0.915 ±0.057
17	Costa	2016	Toledo	Cfa	2	0.475 ±0.266	0.526 ±0.266
18	Maronez and Carraro	2017	Medianeira	Cfa	1	0.500 ±0.206	0.500 ±0.206
19	Baldessar	2012	Curitiba	Cfb	22	0.374 ±0.059	0.626 ±0.059
20	Barros	2013	Caruaru	As	20	0.402 ±0.055	0.598 ±0.055
21	Kreutzfeld	2018	Toledo	Cfa	13	0.595 ±0.033	0.405 ±0.033
22	Ferreira	2015	Campo Mourão	Cfa	5	0.183 ±0.083	0.817 ±0.083
23	Tassi *et al.*	2014	Santa Maria	Cfa	43	0.361 ±0.045	0.639 ±0.045
24	Moruzzi *et al.*	2014	Rio Claro	Aw	15	0.219 ±0.049	0.781 ±0.049
25	Duarte	2018	Cerro Largo	Cfa	17	0.404 ±0.058	0.596 ±0.058
26	Santos	2019	Dois Vizinhos	Cfa	25	0.362 ±0.059	0.638 ±0.059
27	Pedrosa	2021	Rio Verde	Aw	8	0.639 ±0.148	0.361 ±0.148
28	Jobim	2013	Santa Maria	Cfa	350	0.408 ±0.070	0.592 ±0.070
29	Pessoa	2016	Santa Maria	Cfa	51	0.300 ±0.018	0.700 ±0.018
30	Ohnuma *et al.*	2014	São Carlos	Cfa	14	0.522 ±0.046	0.478 ±0.046
31	Silva	2010	Santa Maria	Cfa	3	0.447 ±0.225	0.553 ±0.225
32	Souza	2018	Campo Mourão	Cfa	2	0.074 ±0.004	0.926 ±0.004
33	Sanchez	2013	Viçosa	Cwa	7	0.446 ±0.042	0.554 ±0.042
34	Louzada	2016	Natal	As	8	0.614 ±0.125	0.386 ±0.125

Table 3 – Summary of average C and RR coefficients of vegetated roofs by record reviewed.

Climate	***N***	***n***	**Mean C**	**Mean RR**
Am	2	22	0.320 ± 0.045	0.680 ± 0.045
Aw	5	52	0.285 ± 0.039	0.715 ± 0.039
As	2	28	0.462 ± 0.055	0.538 ± 0.055
BSh	1	32	0.216 ± 0.057	0.785 ± 0.057
Cfa	20	1203	0.306 ± 0.018	0.694 ± 0.018
Cfb	3	90	0.414 ± 0.052	0.586 ± 0.052
Cwa	1	7	0.446 ± 0.042	0.554 ± 0.042

Table 4 – Summary of average C and RR coefficients of vegetated roofs by climate.

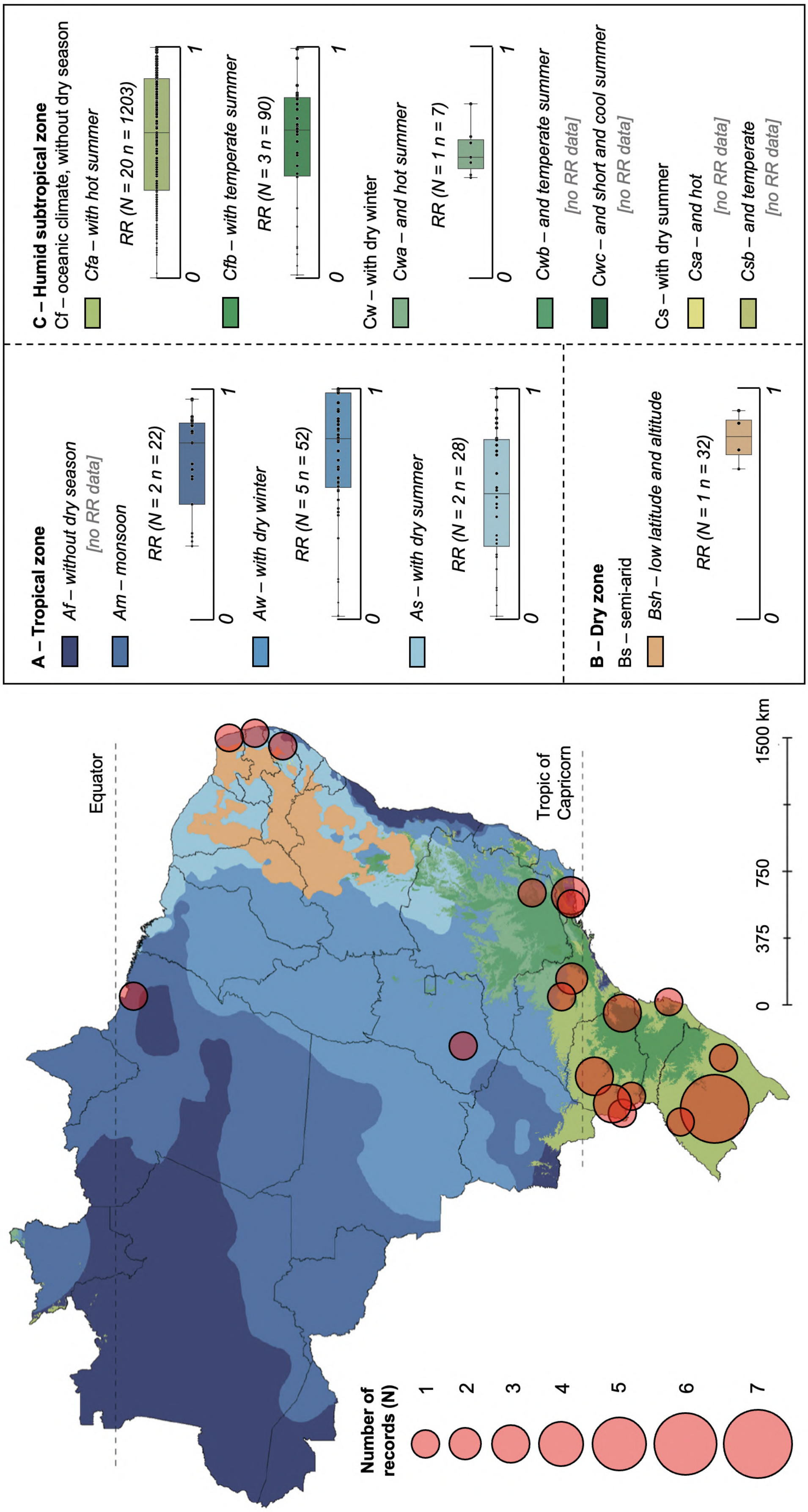


Figure 17 – Graphical summary georeferencing the research origins by climate according to the Köppen-Geiger classification and boxplots for summarising *RR* values. Map based on Alvares *et al.* (2013).

In the presented graphical summary, the lack of research in many of Brazil's climate regions according to the Köppen-Geiger classification is noticeable. The vast majority of characterised events (n) are concentrated within the subtropical climate regions (Cfa, Cfb and Cwa), representing 91% of the total events. The tropical areas (Am, Aw and As) have only 7% of the total events and the semiarid areas (BSh) only 2%. Not only that, but the Af tropical zone, the Cwb, Cwc, Csa and Csb subtropical zones have no studies been recorded at all. This inequality in research may reflect the economic inequality in the country, as Southeast and South have higher economic indexes as well as a larger population.

By the boxplot summary one can perceive that the retention rates (RR) tend to improve the further to the Equator the climate zones are. This can be a consequence of temperature, solar radiation, air humidity, and all environmental factors that have been reported as changing evapotranspiration and evaporation. The more a VR can recover its retention capacity in between rainfall events, the better is its retention performance. However, no work has been recorded analysing vegetated roofs *in situ*. Soulis *et al.* (2017) highlight that experimental conditions may not reflect the reality of VR, thus it is a blind spot yet to be addressed.

Within the qualitative analysis presented, some gaps and trends can be identified. The ability to measure runoff as a real-time sensing technique can support the characterisation of detention indicators such as peak runoff delay and attenuation. But most of the experiments here described were not able to reach this point. Among the structural factors investigated, no study managed to quantify the influence of substrate depth by clearly displaying rainfall-runoff correlations. The substrate material, roof area and drainage systems affecting factors still need further investigation, as very few studies managed to characterise its influence on the hydrological performance of VR. In terms of drainage system performance, it is worth mentioning the possibility of colmatation (or clogging) in the geotextiles, a phenomenon that needs long-term experiments and still lacks being done in Brazil. Slope, on the other hand, seems to be well understood by experimentalists and is negatively correlated with RR.

In terms of dynamic factors affecting rainfall-runoff in VR, gaps and trends can be highlighted. Vegetation and antecedent soil moisture content have been investigated by many of the presented records, but it is a field that still needs exploring. Brazil's biodiversity is immense and many studies concentrate on using succulent plants, which may be interesting by their drought resistance and for temperate climates, but does not help recharging the roof's retention capacity. Native species should be further explored, as their benefits are extended beyond only hydrological aspects, reaching the ecological sphere. Unmanaged vegetated roofs influence on hydrological aspects are yet to be explored, and may bring interesting outcomes.

Evapotranspiration is also a scarcely explored affecting factor. This phenomenon is specially interesting as it can bring results not only for the water cycle but for the energy budget on VR. Evapotranspiration should be further explored, and methods for quantifying it need to be validated and developed. Recent research has been using infrared (IR) cameras for quantifying heat changes due to ET (see ZOU; YANG; QIU, 2019, QIU *et al.*, 2021, KRASOWSKI; WADZUK; JACKO, 2021), which is an innovative trend that may be able to quantify different scales of BGI.

Regarding the environmental affecting factors, final gaps and trends should be mentioned. Most of the experiments characterised rainfall (depth, intensity, duration) and also antecedent dry weather periods. This is an indication of the researchers' awareness that the hydrological performance of VR is deeply intertwined with its surroundings. This trend shows the necessity for investigating the VR water performance in every climate, given that there are big urban centres in each of these. To wrap up, though it is difficult to establish a correlation, many of the experiments managed to at some level verify the seasons influence on VR performance. This should be further explored and is an especially difficult theme given its need for long-term experiments.

5.6 Conclusion

An exhaustive review of the state-of-the-art of the internationally indexed, nationally indexed and grey literature for rainwater management performance of vegetated roofs was presented. Qualitative aspects of these reviews were shown in terms of research findings, such as methodologies used and influencing factors analysed. Quantitative aspects were presented, using the Rational Method for extracting and crystallising a standard indicator of retention performance, the RR, from each of the $n = 1,434$ events characterised along the $N = 34$ records. Trends and gaps have been identified and future research suggestions highlighted, in order to incentivise further innovative experiments in Brazil.

The review clearly demonstrates the average positive effect vegetated roofs have on retention and detention of rainwater. Not only that, by generating an average retention rate coefficient for each climate, such summarisation can be the input for national and international standards, thus supporting the creation of science-based public policies. The use of mean coefficients can mask variations in the roof structure and dynamic factors, which is a limitation of this study. Yet, for a large-scale use where there may be little control and supervision of every small structural factor, average values may be handy for estimating macro performances.

In order to reach the UN Sustainable Development Goals, Nature-based Solutions are a necessity for the urban environment. Green roofs are a key structure to be mainstreamed, but outdoor experiments under real rainfall conditions still need replication in order to improve knowledge on VR performance. Hence, the authors incentivise future investigations on the vegetated roof hydrological performance, which is demonstrated to be relevant not only for changing the urban water cycle for better, but also urban energy efficiency, urban ecology and overall urban well-being.

6 Experimental runoff measurement in vegetated roofs

> Nature to be commanded must be obeyed.
>
> Francis Bacon in:
> *Novum Organum*, 1620

6.1 Introduction

Nature-based Solutions (NbS), as defined by the International Union for Conservation of Nature (IUCN) are "actions to protect, sustainably use, manage and restore natural or modified ecosystems, which address societal challenges, effectively and adaptively, providing human well-being and biodiversity benefits" (COHEN-SHACHAM *et al.*, 2016). Among the range of NbS, some of the most widely known are wetlands, bioretentions, stormwater planters, swales, vegetated roofs and vegetated walls (EGGERMONT *et al.*, 2015). The term NbS is a novel nomenclature for the already known Low Impact Developments (LID), Blue-Green Infrastructure (BGI) or Sustainable Drainage Systems (SuDS), however the concept tries to demonstrate clearly the payoffs and trade-offs humans get from implementing these systems. As Cohen-Shacham *et al.* (2016) put, NbS made "a subtle yet important shift in perspective: not only were people the passive beneficiaries of nature's benefits, but they could also proactively protect, manage or restore natural ecosystems as a purposeful and significant contribution to addressing major societal challenges."

A way to express and quantify these trade-offs between humans and its environment is via the NbS provision of Ecosystem Services (ES), which are defined as "the benefits people obtain from ecosystems" (MA, 2005). As Almassy *et al.* (2018) present, NbS can provide cultural services, provisioning services, habitat and supporting services and regulating services. But as Mengist, Soromessa and Feyisa (2020) indicate, the necessary attention is not given to Regulatory Ecosystem Services (RES) as its benefits may not be as tangible. There may not be an immediate and easy way to perceive their connection to human well-being, in addition to being complex to quantify (MENGIST; SOROMESSA; FEYISA, 2020). In this sense, methods for quantifying RES benefits can generate scientific data to support decision-makers towards mainstreaming Nature-based Solutions.

Among the main regulatory services provided by NbS are its potential for regulating water dynamics in cities and its capacity for managing flood risk (SAHANI *et al.*, 2019). These are especially necessary for densely built cities, which can benefit from systems that retain and slow down rainfall runoff, improving rainwater management as advocated by the Sponge Cities model (HAMIDI; RAMAVANDI; SORIAL, 2021). Hence, research for investigating the Regulatory Ecosystem Services provided by NbS towards water quantity performance is a foremost theme and also a research gap to be explored. In order for these experiments to be undertaken, real-time sensing and a low-cost experimental setup is a relevant toolbox to support researchers on quantifying these systems' performance.

In terms of fluid mechanics, the water dynamics in a NbS system can be described by inlets and outlets in relation to a control volume. In a vegetated roof, water inlet in the control volume can happen via direct rainfall or irrigation; water outlet can happen via runoff, soil evaporation or plant evapotranspiration. In a bioretention, water inlet in the control volume can be via direct rainfall, irrigation, surface runoff from the catchment area or capillary rise; water outlet can happen via excess water runoff, infiltration, soil water evaporation or plant evapotranspiration. These fluxes are illustrated in figure 18. These examples are not restricted to vegetated roofs and bioretentions, but to any NbS that involve water quantity to be investigated.

Analysing these phenomena described, it is noticeable that the water flow rate is a necessary measurement to quantify water performance in NbS. For vegetated roofs, water runoff is measured in terms of flow rate (STOVIN; VESUVIANO; KASMIN, 2012), which also applies to bioretention excess water runoff and surface runoff inlet. Having instruments to inexpensively and in a real-time manner measure flow rate is a must, and its applications can be relevant for a range of practical purposes. Quantifying the water dynamics can be relevant for understanding heat dynamics, as evapotranspiration removes heat from surface (BROADBENT *et al.*, 2019); can be relevant for irrigation control; for the correct selection of plant species in landscaping (FARRELL *et al.*, 2013); to support water quality measurements, among other aspects.

Measuring flow rate can be expensive, inaccurate and equipment may demand close supervision and regular maintenance. As indicated by Naveen *et al.* (2020), affordable sensors must be developed, aiming specially for inexpensive, reliable and easy to implement solutions. Pereira (2009) brings a comprehensive review on flow meter types and characteristics, recalling that now in the era of digital flowmeters a variety of methods is available.

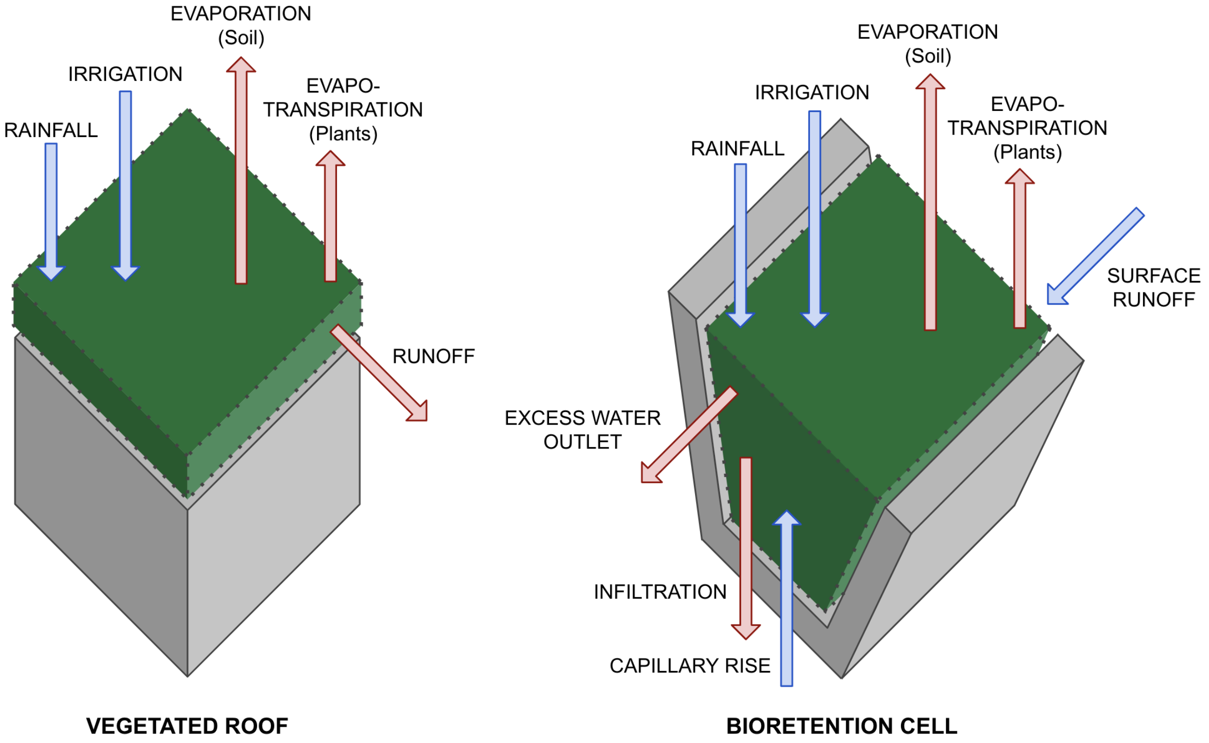


Figure 18 – Water flow in a control volume in vegetated roofs and bioretentions. Blueish arrows indicate inflow and redish arrows indicate outflow. The control volumes for each NbS are indicated by dotted lines. Bioretentions may have pervious or impervious bottom surfaces: if impervious, infiltration and capillary rise flows won't be present.

Baker (2005) also reviews available flow meters and categorises them into different methods of measurement, involving *e.g.* orifice plate flow meters, nozzles, momentum-sensing meters, turbine flow meters etc.

Naveen *et al.* (2020) propose measuring flow rate through the displacement of a cantilever LED strip in the investigated pipeline; Loizou and Koutroulis (2016) bring a state-of-the art review on water level sensors, and propose a novel capacitive water level measurement system, which can be used for measuring water flow if associated to a tank. Dijkstra and Uittenbogaard (2010) correlate flow rate with flexible plastic strips positions subject to water currents; Dinardo, Fabbiano and Vacca (2013) investigate the vibrations in pipelines using accelerometers to improve flow rate measurements; Hill, Perotto and Yoon (2015) use rain gauges and measure runoff from vegetated roofs via tipping buckets, meaning that for each bucket that tips after filled, it counts each tip, having the precision of about the bucket's volume.

As noticeable in the aforementioned flow rate measuring methods, it is possible to transform the physical variable being measured: flow rate can be measured directly or indirectly in a variety of different ways. Evapotranspiration in vegetated roofs, for example, can also be estimated indirectly by measuring the weight loss of a physical model through time (WALTER *et al.*, 2001), as a lysimeter does, or can be estimated using thermography (KRASOWSKI; WADZUK; JACKO, 2021). For flow rate, a range of different experimental setups can be used to attain measurements as close as possible to the phenomenon behaviour.

In this sense, the present work brings an indirect method for measuring flow rate using an ultrasonic sensor and a weir tank, converting a flow rate measurement into a water level measurement. The method is innovative, given that many previous authors indicate methods for measuring water level, but using state-of-the-art open source ultrasonic sensors attached to a weir tank to convert water level into flow rate is a novel approach. It can be implemented not only in laboratory experiments, but also in real structures built in public places. The aim of this article is to present this low-cost method for real-time measurement of water flow rate in NbS structures, useful both for inlet or outlet flow.

The scope of the present work involves evaluating the method in a vegetated roof prototype experiment constructed at the University of São Paulo, Brazil, and further evaluating its capacities. For section 6.2, hence, the present paper brings the working principles of the sensor and experimental setup, along with describing step by step the data collection and processing from this above-mentioned pilot experiment. Section 6.3 presents and discusses the pilot experiment results, bringing challenges that were successfully addressed and difficulties found; and a demonstration of the method's feasibility for application in a bioretention experiment. The paper presents conclusions and further work in section 6.4.

6.2 Methods

Low-cost sensors can be a good alternative for commercial sensors, but demand special attention to detail. As indicated by Naveen *et al.* (2020), a flowmeter ideally should have an adaptable design and avoid fatigue characteristics. Though the ultrasonic sensor selected is not waterproof, meaning it can rust when operating under humid conditions, the module exposed to weathering can be replaced easily and inexpensively.

As a low-cost method for measuring flow rate, an Arduino-based hardware was built and evolved from many years of testing and prototyping (PEREIRA *et al.*, 2021). The ultrasonic sensor used here is the US-025 ultrasonic sensor operated by the ESP12e8266 control module for data logging and communication, with a user software interface that enables wireless data collection.

6.2.1 Sensor working principle

The US-025 ultrasonic sensor is a recently developed module and there is still scarce information available regarding its working details. But its principles are the same as the HC-SR04 ultrasonic sensor, which is a widely used instrument for a variety of applications. Thus, the working principle of the US-025 is described based on the HC-SR04.

The aforementioned ultrasonic sensors infer the distance by measuring the time (t) between releasing a sound pulse (trigger) and its return (echo) as indicated by Panda *et al.* (2016). This process is described in figure 19, which depicts the ESP12e8266 module interacting with the sensor. By using the propagation speed of sound in the air (c), it is possible to find the distance ($d(t, c)$) between the sensor and the water level, as indicated in equation 8. Dimensions in the SI system are indicated between square brackets. The US-025 has a crystal oscillator which transforms the resonant frequency of a piezoelectric quartz into a highly precise constant frequency electric signal. This mechanism creates a highly precise clock for inputting time span (t) in the equation. The trigger signal generated by the sensor is an eight-pulse sound wave with a duration of t'.

$$d\ (t, c) = \frac{t \times c}{2} \quad [m] \tag{8}$$

Special attention must be given to the sound speed, highly dependent of the air temperature, air humidity and pressure, that makes crucial the temperature control when long monitoring periods are used. If the humidity and pressure effects can be neglected the sound speed varies according to equation 9, where Θ indicates the dry air local temperature.

$$c = 331.45\sqrt{\frac{\Theta}{273.15}} \quad [m/s] \tag{9}$$

From the readily available online datasheets for the HC-SR04 sensor, the sensor is indicated to work between an offset of 2 cm to 400 cm and has an effectual angle α of 15 degrees (see Fig. 22). That means it is respectively the distance an object has to be in order to be recognized and the maximum angle the object can be placed measuring from the center of the sensor. It is capable of measuring up to millimetre precision, but this aspect will be further discussed in this article as well as sound speed variations.

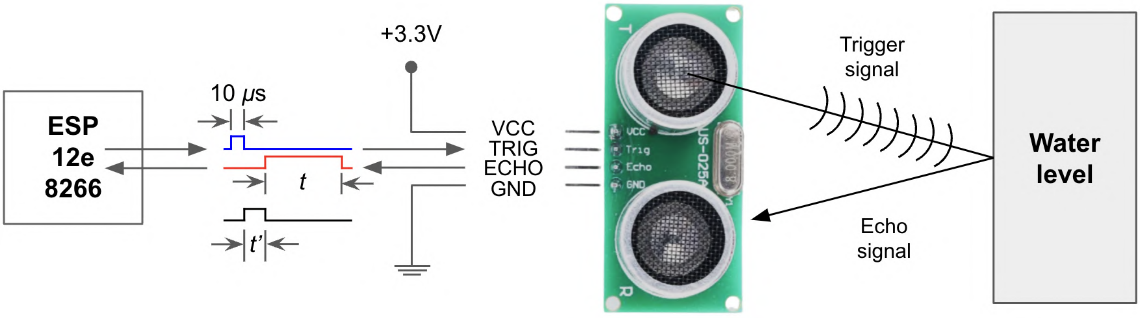


Figure 19 – Working principle of the US-025 sensor.

6.2.2 Microcontroller-based data logging

The ESP12e8266 is a small wireless module, measuring 24mm by 16mm, and has a built-in WiFi antenna. It operates at 3.3V, which is the main reason for using a US-025 instead of a HC-SR04 in the hardware setup, given that the HC-SR04 operates at 5V. The necessary tension is reached by adding a 3.7V 18650 battery and a diode, as indicated in figure 20, which also gives the setup the ability to work in places without easy access to power sources. A push button is added for the user to interact with the microcontroller and the USB Serial Converter FTDI FT232RL module is needed once for uploading the code into the module.

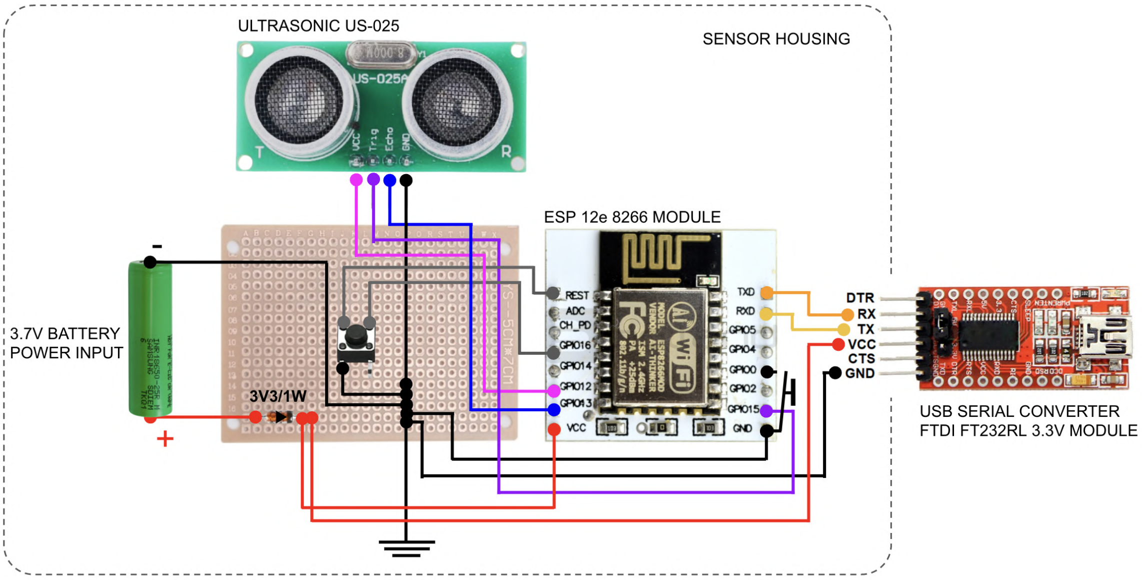


Figure 20 – Pictorial diagram of the circuit used.

A simplified flowchart of the code used is given in figure 21. Via the push button, the user can interact with the microcontroller, making it work for: (i) only capturing data from the ultrasonic sensor to save energy, turning off between readings, or (*ii*) making it try to connect to a known WiFi network and via its IP address the user can utilise an interface for performing actions such as collecting the logged data, erase data, configure the timesteps for data collection etc.

The proposed setup can work using cellular data networks or fully using the Internet of Things (IoT) if a permanent WiFi network is in reach. For the first option, a network can be created with a smartphone only for collecting data stored offline inside the ESP12e8266 internal memory and for the second option the sensor can store the captured data in a server and data is fully remotely collected. The T seconds indicated is the time step between data collections, which results in data resolution: a balance should be made between the required resolution and the battery consumption. The measured battery performance for the hardware to collect data at power saving mode a $T = 30s$ time step is about a month.

Besides environmental variables effects, there are also random interferences on the ultrasound signal that need to be treated during data acquisition. Considering that each sample is taken along 10 or 20 microseconds, the sampling process can be repeated a certain number of times until the result reaches a desired stability, for example, limited by a threshold of the standard deviation (SD). The reading routine can be adapted to perform the Welford algorithm for the running SD (KNUTH, 1998).

6.2.3 Proposed setup

The sensor hardware is housed within a protective plastic box, attached to the weir tank by self locking nylon zip ties for easy removal. Ideally the plastic box should be hermetic to prevent water from getting in. The sensor should be facing the water and oriented parallel to the liquid surface. The sensor housing and the weir tank assembled can be seen in figure 22. The figure also shows the position of both the triangular weir and a stone barrier which should separate the inflow and outflow. The contribution of this barrier is to attenuate surface waves if water inflow generates turbulence as the sensor precision is high and small surface disturbances will be captured by the setup. The stone barrier height (H) should be higher than the maximum water level ($L(h)$) height, that is $H > P + h_{max}$, where P is the height of the notch vertex (red dot in Fig. 22) with

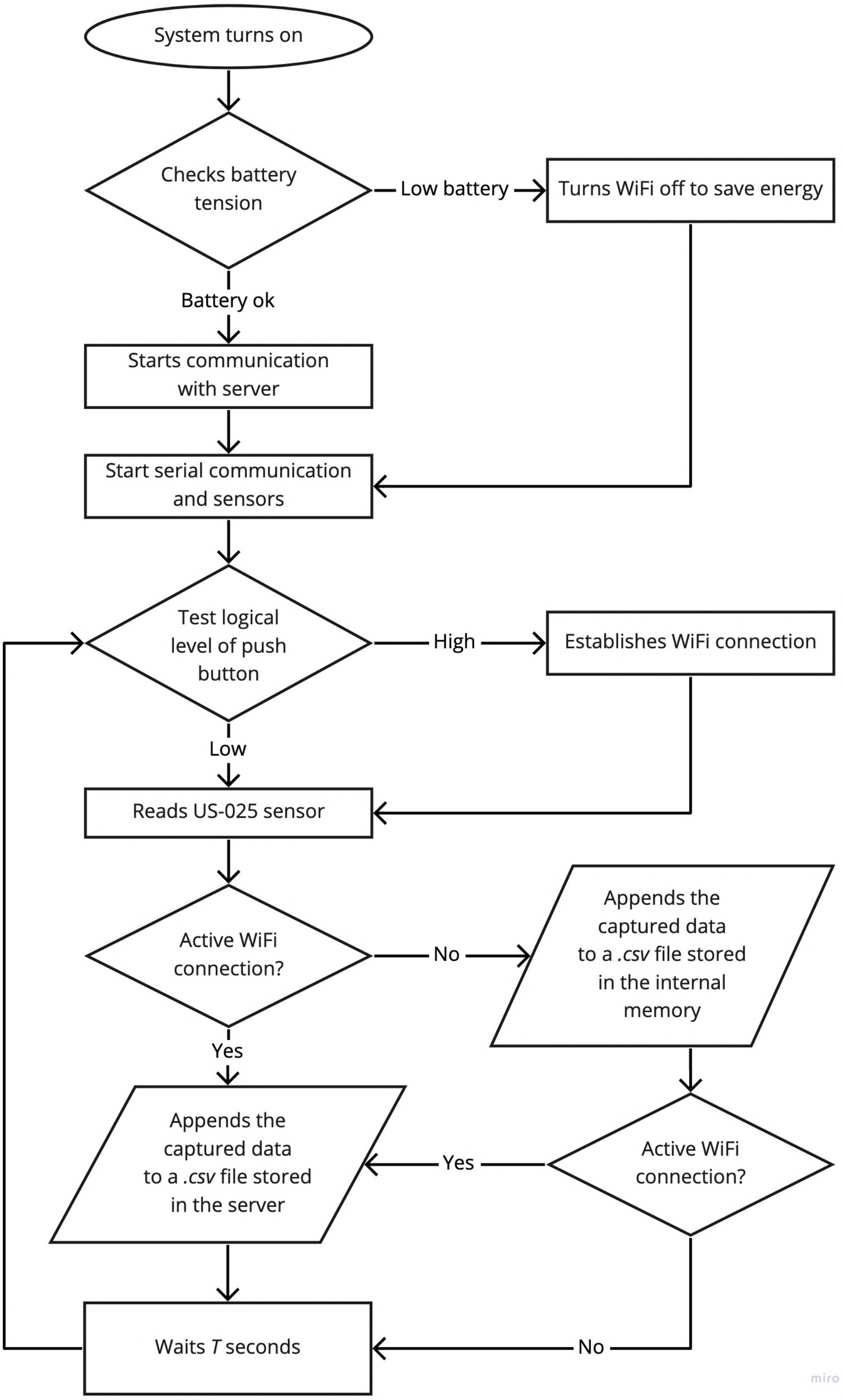


Figure 21 – Code flowchart.

respect to the tank's floor and h_{max} is the maximum height of water the weir is designed to accommodate.

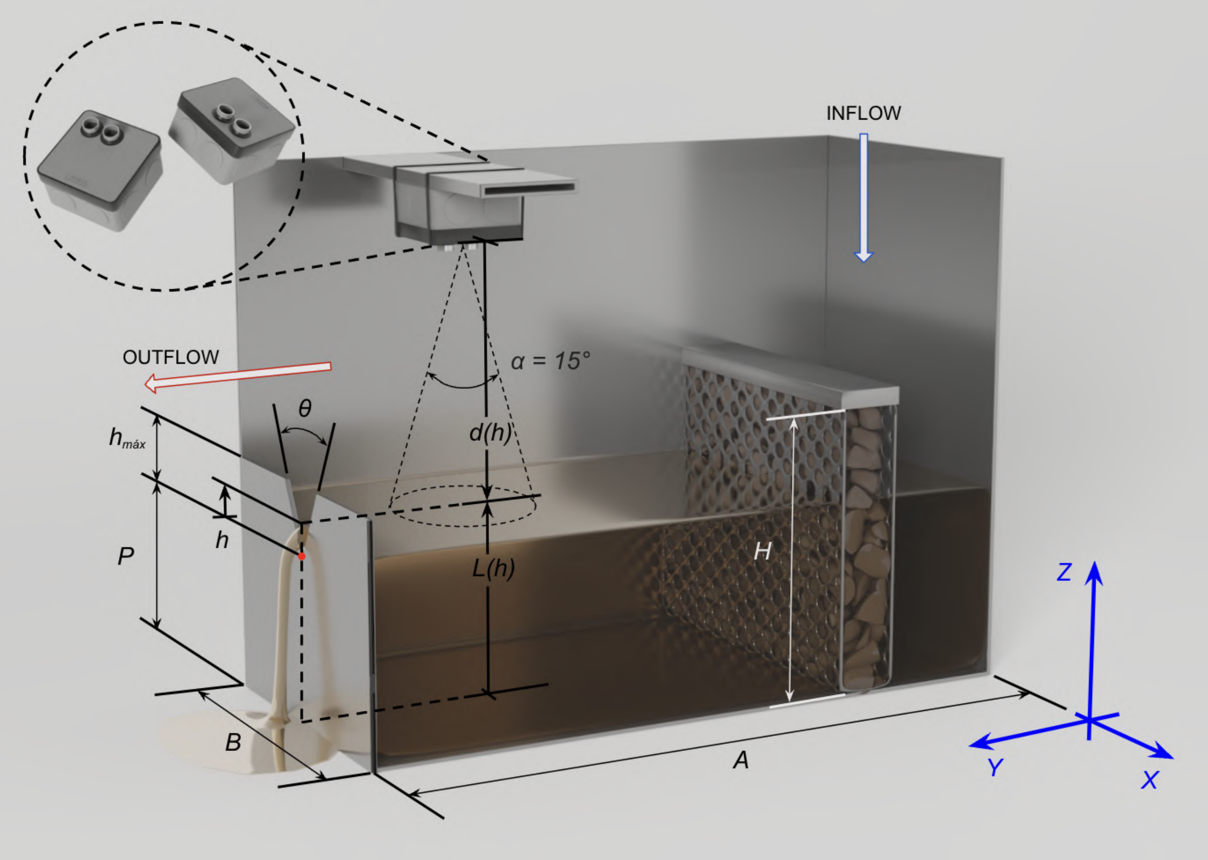


Figure 22 – 3D rendering of the ultrasonic sensor housing and triangular-notch thin plate weir tank. Source: illustrated by Henrique Capanema, adapted by the authors.

The proposed ultrasonic sensor setup is adaptable to any flow rate range, given that the weir tank is designed accordingly. Shen (1981) brings detailed aspects for triangular-notch thin plate weirs, an indicated weir design for small flow rate measurements ($q < 30\ell/s$). Ideally the plate should be made of a metallic material such as steel or aluminium or with acrylic, and the notch's crest surface should be fabricated with a 45 degrees angle (β) and an ε of around 1 mm (Fig. 23).

From Shen (1981), the flow rate function ($q(h, \theta)$) for triangular-notch thin plate weir is given in equation 10, where the integration process is here further derived (HATTAB; MIJIC; VERNON, 2019). The variable h is the water level measured from the weir notch vertex and θ the weir notch angle. Following figure 6, assuming a thin horizontal strip of elementar height dz and length x, considering it working as a small orifice, the elemental flow rate dq will be:

$$dq = C_d(\theta) \times V_t \times da \tag{10}$$

Where $C_d(\theta)$ is the runoff coefficient usually approximated to a constant $C_d = 0.61$, as Hattab, Mijic and Vernon (2019) further discusses; V_t is the theoretical velocity of the fluid which is trivially given by the Torricelli Equation as $V_t = \sqrt{2gz}$, with $g = 9.81\ m/s^2$ being the Earth's gravity acceleration; and da is the elemental area highlighted in blue in figure 23, $da = x \times dz$. Integrating for z from 0 to h:

$$q(h,\theta) = \int_0^h dq = \int_0^h C_d\ \sqrt{2gz} \times dz \tag{11}$$

Hence, using geometry and integrating for z:

$$q(h,\theta) = (\frac{8}{15} \times 0.61)\sqrt{2g}\ tan(\frac{\theta}{2})h^{5/2}[m^3/s] \tag{12}$$

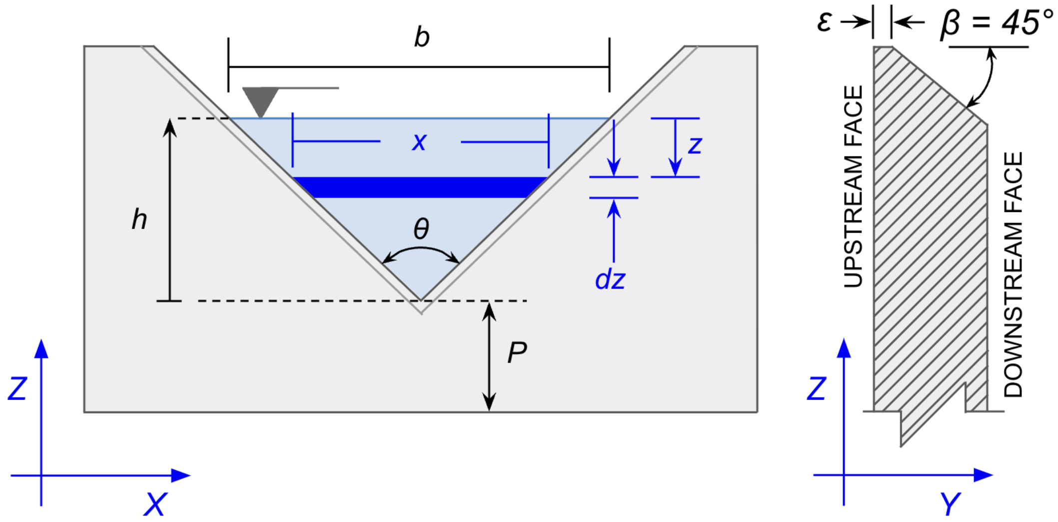


Figure 23 – Triangular-notch thin plate weir flow rate and section detail.
Source: adapted by the authors from Shen (1981) and Hattab, Mijic and Vernon (2019).

The constants A, B, P, H, h_{max} and θ, illustrated in figure 23, should be designed according to the maximum flow rate capacity of the setup, which should be estimated beforehand by the experimentalist. The notch angle θ can be found by forcing a maximum estimated design flow rate $q(h,\theta) \equiv q_{design}$ and a maximum chosen design weir height $h \equiv h_{design}$ in equation 12.

In practice, the ultrasonic sensor will read the distance $d(h)$, which is not trivial to convert to water level ($L(h)$) if a full IoT system is not implemented: if the experimentalist needs to remove the sensor to read its data by interacting with the internal push button, the position of the sensor may slightly change every time it is removed. To address this problem, it is indicated plotting the water level dynamics and graphically finding the weir notch vertex position (red dot in Fig. 22). For that, as indicated in equations 13 and 14, the distance from the sensor to the vertex (d_P) can be found when inflow ends after the outflow alighted through the weir, thus the water level stabilises at $L(h) = P$.

$$lim_{h \to 0^+}\ d(h) = d_P \tag{13}$$

$$lim_{h \to 0^-}\ L(h) = P \tag{14}$$

Hence, in order to finally find the full setup flow rate $Q(h, \theta)$ see equation 15, where i is a timestep with T seconds:

$$Q_{t=i}(h, \theta) = \begin{cases} [(L_{t=i}(h) - L_{t=i-1}(h)) \times A \times B]/T, & 0 < L(h) \leq P \\ q_{t=i}(h, \theta), & P < L(h) < P + h_{max} \end{cases} \tag{15}$$

6.2.4 Pilot experiment

To assess the practicality of the proposed ultrasonic flow rate sensor setup, a pilot experiment was conducted. As seen in figure 24, two masonry prototypes were built at the Civil Construction Engineering Department of the Polytechnic School of the University of São Paulo - Brazil. One is a ceramic tiled roofing system and the other is an extensive vegetated roof. Along with the ultrasonic sensors and weir tanks, a weather station was installed on top of the ceramic tiled roof in order to capture rainfall depth and duration. The station used is a Vantage Vue made by Davis Instruments, which has a tipping bucket rain gauge. The station precision is 0.1mm of rainfall depth.

For a given characteristic rainfall event, the experiment used the triangular-notch weir tank to measure both prototypes' runoff. It is a common experiment that can characterise the roofs performance towards rainwater management, normally associated with its retention and detention capacities. Retention stands for how much a vegetated roof can store from the input rainfall by saturating its substrate pores; detention illustrates how much it can delay and attenuate the peak runoff. If well characterised for different climates, substrate depths, substrate materials and vegetations, these parameters can help demonstrate the ability of these Nature-based Solutions to work as Sustainable Drainage Systems.

To evaluate if the combined water level ultrasonic sensor and weir tank can generate robust results, it is possible to use the ceramic tiled roof results. As the ceramic tiled roof

Figure 24 – Vegetated roof building prototype and ceramic tiled roof building prototype, triangular-notch weir tank with ultrasonic sensor and Vantage Vue weather station.

won't retain almost any rainwater, the runoff from the CT prototype measured by the proposed setup should be similar to the rainfall intensity measured by the weather station.

6.3 Results and discussion

6.3.1 Results and setup reliability

A rainfall-runoff series was captured during a short and intense summer rain event. In figure 25 it is possible to observe that, as expected, the rainfall flow rate through time is directly reflected in the ceramic tiled roof measured runoff. For the vegetated roof another phenomenon happened: as a sponge, it retained water and also detained the flow rate by diminishing and delaying the peak runoff, which demonstrates its rainwater management ability.

The runoff measured for the CT was compared to the rainfall intensity measured by the weather station and results were compatible. As seen in figure 26, a linear regression for both measurements demonstrates a high adherence between the instrument results. Statistical analysis is undertaken using Python and the visualisation with *seaborn* and *matplotlib*. During the pilot experiment it was found that fluctuations in water level measurements may have been due to rainfall falling directly into the tank and for higher flow rates a slight volumetric expansion of the tank was observed, due to its malleable construction material. It is, therefore, suggested to account for a lid when building such a tank and also account for structural reinforcements to avoid volumetric expansion during higher flow rates.

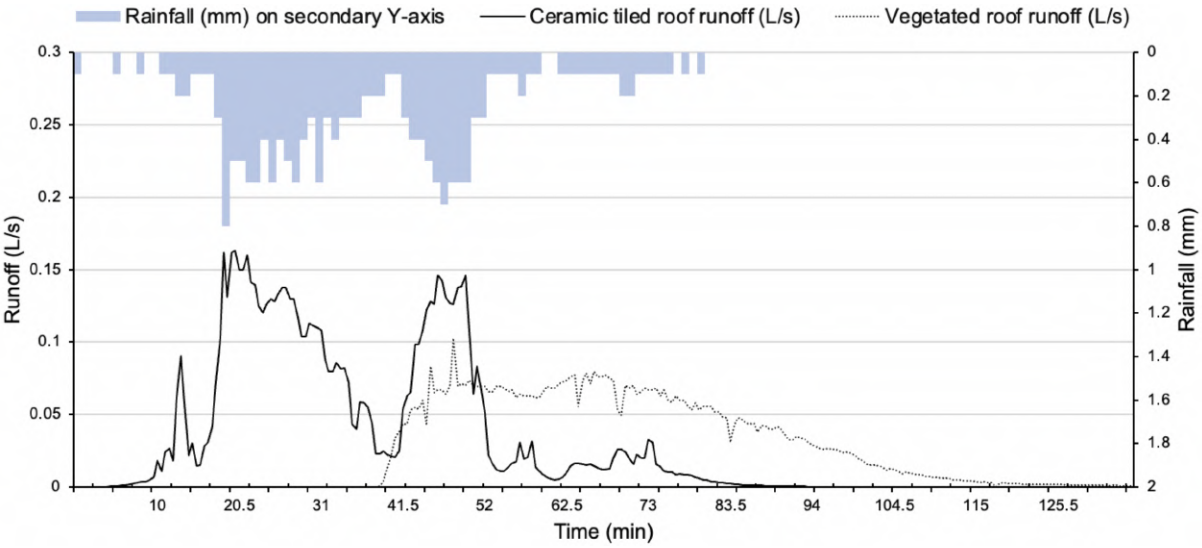


Figure 25 – Rainfall-runoff for the vegetated roof (VR) and ceramic tiled roof (CT) under the proposed experiment.

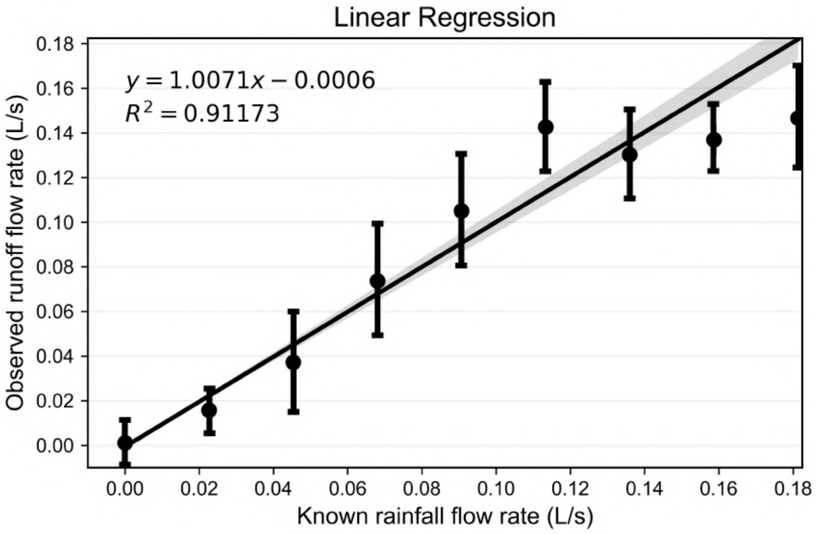


Figure 26 – Central linear regression tendency of flow rate measured with the proposed setup compared with the same flow rate measured with a weather station under the pilot experiment conditions using the CT prototype. Shaded area represents a 95% confidence interval.

The capacity of the proposed setup for flow rate measurement in real-time is critical if the experimentalist has to observe real rainfall events. In controlled experiments — *e.g.*

where rainfall can be simulated by irrigation systems — the ability to measure in real time may not be as imperative, but for NbS structures it is interesting to observe real events, as many of these involve a complex set of environmental phenomena happening at the same time. A rainfall event can change air temperature, air relative humidity, radiation, provoke a large superficial runoff and last for a long duration, which can be difficult and costly to model and simulate.

6.3.2 Sound speed correction

As mentioned above, some corrections should be used regarding variable environmental conditions. Panda *et al.* (2016) propose a simplified equation to consider air temperature ($\Theta[^{\circ}C]$) and relative humidity ($\phi[\%]$), as shown in equation 16 for a corrected speed of sound $c^{*}(\Theta,\phi)$:

$$c*(\Theta,\phi) = [331.296+(0.606\times\Theta)]\times\{1+[\phi\times 0.9604\times 10^{-6}\times 10^{0.032\times(\Theta-(0.004\times\Theta^{2}))}]\} \quad (16)$$

To compare results, a correction for captured distance was undertaken using the new c^{*}. Thus, a correction factor for the speed of sound (γ) was implemented, where:

$$\gamma \equiv \frac{c^{*}}{c} \quad (17)$$

Relevance of this investigation is exemplified by summer rainfall events. In the subtropical climate of Brazil, they are normally associated with frontal rainfall, when temperature increases minutes before the beginning of the rainfall event and so does relative humidity. To simplify the use of the correction factor, the first γ when the event begins (for $t_0 = 0$) is calculated. Subsequent timesteps were corrected via a derived correction factor (γ^{*}) for a corrected height reading (h^{*}), as seen in equations 18 and 19. This corrected height is thus input in equation 15 for a corrected flow rate.

$$\gamma^{*}_{t=i} = 1 + (\gamma_{t=i} - \gamma_{t_0=0}) \quad (18)$$

$$h^{*} = h \times \gamma^{*} \quad (19)$$

In this way, only variations in the speed of sound within the rainfall event need to be calculated for each timestep. However, the authors compared both results of flow rate: with speed of sound corrections and without and the difference between both is irrelevant.

For this case, the difference was irrelevant because flow rate was measured in roughly uniform temperature and relative humidity, as useful data starts to appear when runoff starts to flow, that is after the temperature and relative humidity had already increased. Whereas for experiments where temperature and relative humidity are not uniform, the correction for sound speed should be taken into account.

6.3.3 Sensor costs

As the triangular-notch weir tank setup can vary a lot in terms of dimensioning, it is not useful to estimate its costs. But regarding the sensor, it can remain the same for any given weir tank setup, even if using other geometries of weirs such as rectangular ones. The components currently cost roughly as follows: ultrasonic sensor US-025 costs about U$D 0.93; the module ESP12e8266 costs about USD 1.10; the module USB/SERIAL converter FTDI FT232RL costs about USD 1.14; the 3.7V 18650 battery costs about USD 5.00 and other general electronic components top up about USD 5.00 more. Therefore the total sensor cost is about USD 13.17, not taking into account the sensor housing.

A commercial sensor can be much more expensive. Flowmeters available in the market that can offer the same precision cost from USD 190.00. Arduino-based flowmeters such as the YF-S201 can also be cheap, but will not give the same precision. The proposed setup is versatile and adaptable to different flow types and scales. The US-025 can perform well under the described experiment conditions and operates successfully for at least six months without replacement.

6.3.4 Use for other NbS

Other experiments using the same setup can be performed if dimensioning is undertaken correctly. Figure 27 shows a variation of the proposed system being operated by the authors for water quantity investigation in a bioretention cell. Framing is made of reinforced concrete, which addresses the problem of volumetric expansion if the tanks are full, and the inlet weirs are rectangular, which is adequate for greater flow rates. Differently from the vegetated roofs in which their contribution area is the roof's footprint, bioretentions can collect the surface runoff from large contribution areas.

Figure 27 – Bioretention using the same method for water quantity characterization: inlet with a rectangular-notch acrylic thin plate weir surrounded by a concrete framing and outlet with a triangular-notch steel thin plate weir in a concrete tank.

6.4 Conclusion

In this work, a setup for measuring water flow rate in Nature-based Solutions was presented, along with the mathematical characterisation and the complete demonstration of software and hardware design. The results show the system as a cost-effective, reproducible and adaptable alternative to commercial flowmeters. It is capable of measuring a range of flow rates and ideal for both laboratory and field applications, *e.g.* quantifying the water performance of public structures *in situ*. Statistical analysis demonstrated that it has excellent precision when compared to a rain gauge flowmeter and its operation can be supported by IoT for remote data logging.

The setup using ultrasonic sensors can support practitioners and researchers for quantifying the real benefits of NbS in terms of not only water quantity, but also many related Regulatory Ecosystem Services. In this sense, the present work describes a tool that can help better understand the effectiveness and benefits of Blue-Green Systems, helping its mainstreaming as public policies based on robust scientific research.

As further work, long-term performance analysis should be undertaken for the sensors and sensor housing, specially for operation under hostile weather conditions. Furthermore, working towards a smaller hardware for the sensor and its housing can also bring benefits for making its installation easier and less evident, especially for use in public places.

7 Effects of substrate depth in the vegetated roof runoff

> In the domain of natural science, the aid of the experimental method becomes indispensable whenever the problem set is the analysis of transient and impermanent phenomena, and not merely the observation of persistent and relatively constant objects.
>
> ---
>
> Wilhem Wundt in:
> *Principles of physiological psychology*, 1873

7.1 Introduction

Tropical and subtropical cities tend to go through a considerable amount of intense rainfall events along any given typical year (VÖRÖSMARTY *et al.*, 2013), especially during summer (STEVAUX *et al.*, 2009). These intense rainfall events become an even greater problem given the way cities are currently built and due to recent accelerated urbanization (DENG *et al.*, 2009). Mainstream urban planning covers up most of pervious areas, turning basins into more and more impervious surfaces (JACOBSON, 2011; SHUSTER *et al.*, 2005), preventing infiltration and evapotranspiration (WANG *et al.*, 2022).

This form of occupying and using the natural surface exceedingly changes the hydrological cycle (BAPTISTA; NASCIMENTO; BARRAUD, 2011). As a result of impervious soil coverage, surface runoff increases and reaches floodplains in less time (HAN; BURIAN, 2009). These events tend to become hazardous as floodplains are occupied by humans, turning flood risk management a rising concern in a warming climate (MIGUEZ *et al.*, 2015).

In this sense, finding ways of better managing rainwater runoff is imperative and decentralization can be a possibility (DIERKES; LUCKE; HELMREICH, 2015). Towards this direction, Nature-based Solutions (NbS) are a pathway to be followed, as Blue-Green structures can generate a range of Regulatory Ecosystem Services (RES) (KRAUZE; WAGNER, 2019). Among these, as pressure and competition on ground level glebes use is commonly high in densely populated cities, vegetated roofs (VR) stand out (VESUVIANO; STOVIN, 2013). Roof areas can represent in compact built urban areas up to 50% of impervious surface (DUNNETT; KINGSBURY, 2014; VESUVIANO; STOVIN, 2013).

Vegetated roofs are a type of Nature-based Solution that can locally manage rainfall, retaining a portion of rainfall, delaying and attenuating its peak runoff (STOVIN, 2009; JOHANNESSEN; MUTHANNA; BRASKERUD, 2018). These are RES of water regulation, which give these structures the ability to capture water at the point where it precipitates, a mechanism which bases the Sponge City urban model (HAMIDI; RAMAVANDI; SORIAL, 2021). Green roofs, or vegetated roofs can not only provide water quantity regulation, but also water quality (BERNDTSSON, 2010), among many other Ecosystem Services (ES) (OBERNDORFER *et al.*, 2007; SHAFIQUE; KIM; RAFIQ, 2018).

7.1.1 Water budget and theoretical background

A summary of main water inflows and outflows on a vegetated roof control volume are depicted in the proposed diagram of figure 28, based on (CHUI; LIU; ZHAN, 2016). The VR is seen as a water vessel, in which rainfall (R) inflows and can be stored in one of three volumes: $V1$, $V2$ or $V3$. The volume $V1$ is the unavailable water zone. It is composed of hygroscopic water closely bound to the soil particles, not useful for plants (PÉNÉ; N'DIAYE; N'GUESSAN-KONAN, 2021; DEMIRKESEN, 2001). $V2$ is the plant available water (PAW) zone and is composed of hygroscopic and capillary water. The capillary water is able to move by capillarity through the substrate pores (DEMIRKESEN, 2001). This volume is gradually lost by plant evapotranspiration (Q_{ET}). The rate by which plants remove water from the substrate is highly influenced by local solar radiation, air temperature and humidity (GETTER; ROWE; CREGG, 2009; FERRANS *et al.*, 2018; GAROFALO *et al.*, 2016).

The moisture content μ is somewhere inside the $V2$ boundaries. It is relevant to note that the higher the initial moisture volume, the lower relative retention will be possible (LIU *et al.*, 2021). Volume $V3$ is the runoff volume, happening when soil field

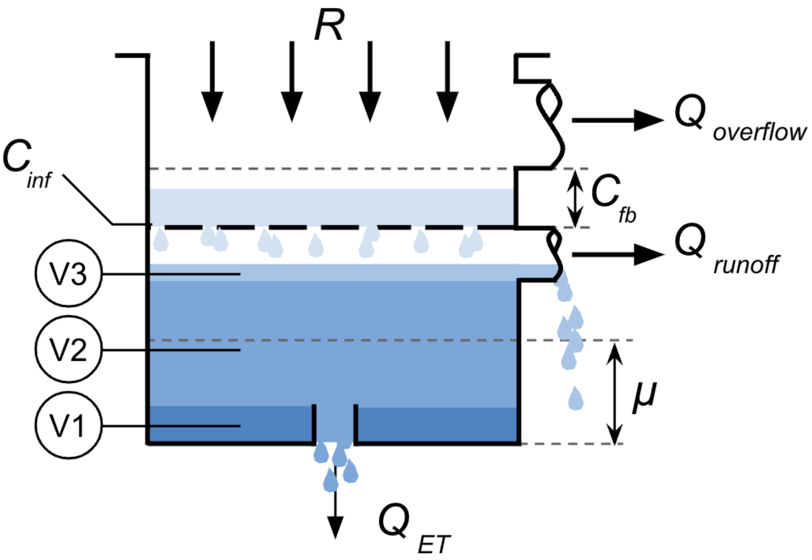


Figure 28 – Proposed conceptual model for a vegetated roof water dynamics based on Chui, Liu and Zhan (2016) and Garofalo *et al.* (2016).

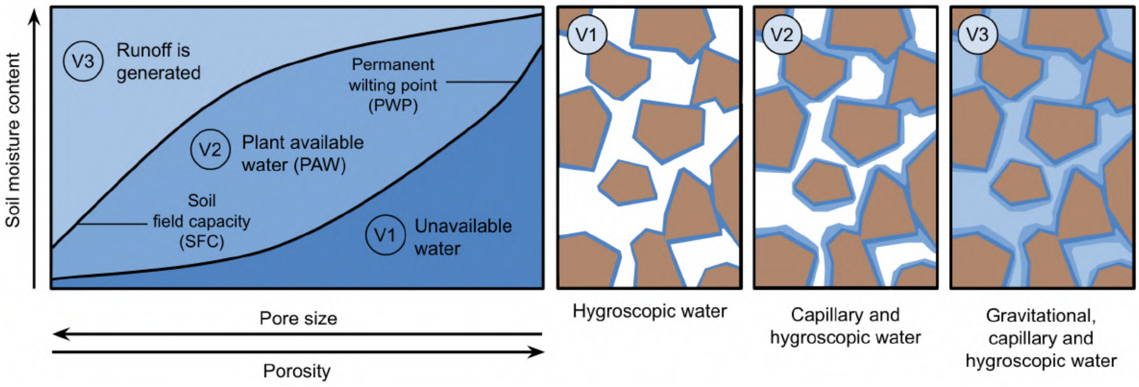


Figure 29 – Soil moisture content relation to substrate particles. Adapted from Li *et al.* (2021) with concepts from Lofrano (2018) and Demirkesen (2001).

capacity is reached and excess gravitational water starts forming (PÉNÉ; N'DIAYE; N'GUESSAN-KONAN, 2021; DEMIRKESEN, 2001). After this point, soil saturation is reached and runoff (Q_{runoff}) begins. Total substrate retention capacity is represented by volumes $V2 + V1$. This soil dynamics is seen in figure 29.

Furthermore, if a rainfall event is sufficiently intense, the soil infiltration rate capacity (C_{inf}) may be surpassed, generating superficial puddling. This volume of water temporarily stored on the green roof surface can be trapped within the roof freeboard framing (C_{fb}). After reaching the top of the frame, it becomes overflow ($Q_{overflow}$). The overflow is particularly relevant for higher slope vegetated roofs, where if the infiltration capacity is too low it can lose water for overflow and have the same performance of a regular tiled roof.

7.1.2 Factors influencing water quantity performance

Influencing the VR water performance there are both structural factors and roof conditions at the moment of the rainfall event. As main structural factors, as demonstrated by Liu *et al*. (2019), the substrate material, its depth, the vegetation choice and the roof slope are relevant factors for the general roof stormwater management performance. But the roof conditions are also relevant, especially regarding water moisture content (LIU *et al.*, 2019; PENG; SMITH; STOVIN, 2019; VOYDE; FASSMAN; SIMCOCK, 2010).

The vegetation and surrounding environmental conditions count when understanding the soil moisture content dynamics (POË; STOVIN; BERRETTA, 2015). As pointed out by Voyde, Fassman and Simcock (2010), the evapotranspiration (ET) accounts for 20% to 48% of moisture lost. Pöe, Stovin and Berretta (2015) describe the ET process of water capture, in which plant's roots collect PAW (see fig. 29) and release it through the xylem towards the leave's stomatal cavities, which will thus release it to the atmosphere.

7.1.3 Previous studies

Recent studies in tropical and subtropical regions of Brazil are scarce and mainly use small scale laboratory models and adopt succulent or grass plants in their research, but demonstrate a relevant capacity of VR water management in this geographical region. Arboit *et al.* (2021) used small scale models to evaluate the evapotranspiration and runoff rates in a subtropical climate of Brazil. Results for runoff demonstrate that the species used, *Sedum rupestre*, did not provide better water retention performances than a roof module without any vegetation. This can possibly have happened because of these plants' succulency and their Crassulacean Acid Metabolism (CAM), which helps them lose less water and thus recharge less the soil retention capacity by consuming less the PAW.

Vacari *et al.* (2019) analyzed small scale green roof models with grass vegetation coverage, shrubs and a mixture of both. Results demonstrated no statistically significant differences from vegetation compositions, but a significant retention rate for all of them. The authors indicate that substrate composition may play a role in the results. Loiola, Mary and Silva (2019) analyzed modular tray green roof systems towards their hydrological performance using succulent plants. The work demonstrates a relevant peak runoff delay and a hydrograph abatement for the VR modular system.

Castro *et al.* (2020) evaluated water quantity and quality performance of VR models in the south of Brazil. Runoff measurements were conducted in low time resolution, only every 3 hours, and demonstrated high retention rates in the VR models, ranging from above 50%.

The methods involved in the previous studies and the vegetation types used are the main differences to the present research. The present work analyzes laboratory built real scale constructions to compare the rainfall-runoff, generating more robust and closer to reality data along a real-time sensing sensor setup. The present work also innovates on investigating unmanaged and spontaneous vegetation in green roof testbeds and in the aforementioned prototypes, a novel approach to vegetation management for subtropical climates. The use of native and spontaneous species on VR structures can have a beneficial effect on restoring the substrate capacity to retain stormwater due to its local adaptability and is therefore relevant to be investigated. Very few studies have been conducted, which also incentivize and demonstrate the need for further research.

7.1.4 Subtropical climate peculiarities

As of environmental influences, the evapotranspiration rates and rainfall events are the main concerns regarding the water balance in vegetated roofs (POË; STOVIN; BERRETTA, 2015; PENG; SMITH; STOVIN, 2019). Previous studies show that there has been very little VR water quantity performance investigation under tropical and subtropical climates (BLANK *et al.*, 2013; GRULLÓN-PENKOVA; ZIMMERMAN; GONZÁLEZ, 2020) but it is an increasingly investigated topic (LIU *et al.*, 2021). Geographical differences for the VR performance towards water management are relevant, as pointed out by Poë, Stovin and Berretta (2015). Locatelli *et al.* (2014) show that retention rates are higher in warmer climates if compared to temperate climates, where the bulk of VR studies are concentrated (BLANK *et al.*, 2013). Hakimdavar *et al.* (2014) demonstrate how the higher incidence of storm events also influences water retention, diminishing the VR performance, and the parameters that most influence this phenomenon are rainfall depth and event duration.

In this sense, given these peculiarities and the lack of studies in subtropical climates, there is a gap to be addressed. There is a need for local analysis, in the sense that it is qualitatively known how VR performs, but quantification in the subtropical areas is yet insufficient. Therefore, the present experimental investigation is undertaken in São Paulo, Brazil. The city is under a transitional zone between tropical and subtropical climates within the country, as the Köppen Geiger climate classification indicates (ALVARES *et al.*, 2014). Martinelli (2010) classifies São Paulo as a Cwa (Humid subtropical zone, with dry winter and hot summer) on larger scale referencing maps, in close transition to Aw (Tropical zone, with dry winter).

South America is home for developing countries which are yet standardizing Blue-Green Infrastructure (CASTILLO; CRISMAN, 2019). Therefore, results are immensely relevant in order to support the correct design and planning towards mainstreaming these structures. Extensive and lightweight roofs are a possibility for decentralizing water management, as they are less demanding for the building structures, making it possible to install them in un-retrofitted buildings (SILVA; FLORES-COLEN; ANTUNES, 2017). If extensive roofs can yet generate relevant water retention and detention in a subtropical area, this can be a way forward towards sustainable drainage.

To address this hypothesis, the main objective of this work is to quantify the extensive VR retention and detention performances in terms of rainwater capture, peak runoff delay and peak runoff attenuation under the subtropical area of São Paulo. To further expand the results, the work also aims at demonstrating how substrate depths and previous soil moisture can influence the retention and detention performances of VR to the light of unsaturated soil mechanics.

7.2 Materials and methods

In order to reach the characterization of the hydrological performance of extensive vegetated roofs, two complementary experiments are set up. The first, experiment A, compares the rainfall-runoff of two masonry building prototypes, one with a vegetated roof and another with a commonly used ceramic tiled roof. The second, experiment B, compares the rainfall-runoff of four testbeds with varying vegetated roof substrate depths.

The complete experimental setup is illustrated in figure 30 and photographed in figure 31. Experiment A lasted for 70 days and experiment B for 10 days.

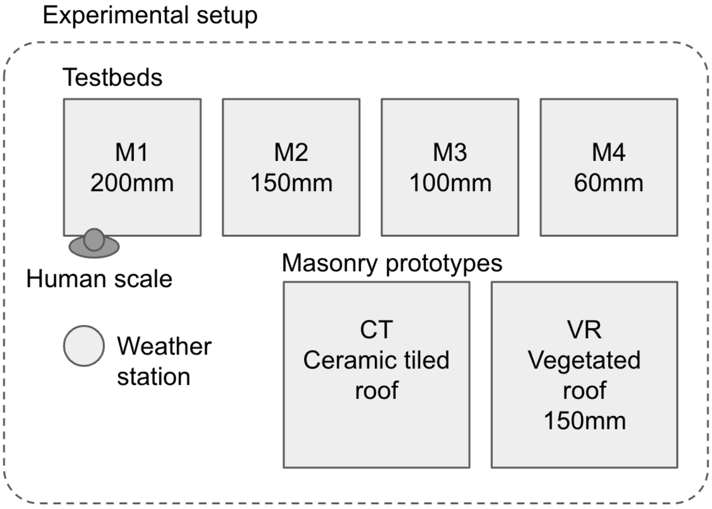


Figure 30 – Illustration of the experimental setup.

Figure 31 – Experimental setup. Buildings on the back are the unmanaged vegetated roof (VR) and the ceramic tiled (CT) masonry prototypes. Testbeds on front are the unmanaged M1, M2, M3 and M4 models from right to left, with respectively 200 mm, 150 mm, 10 0mm and 60 mm substrate depth.

7.2.1 Runoff data capture

For both experiments, a common phenomenon to be characterized is the roofs' runoff, which is flow rate based. As indicated by Naveen *et al.* (2020), regular commercial flowmeters tend to be expensive or only able to read in specific conditions. Arduino-based flow rate sensors, though inexpensive, may also not provide the adequate precision for such a small discharge. To address this issue, a triangular notch weir tank was attached to each prototype and testbed outlet in order to accurately capture the runoff.

A triangular notch thin plate weir can be used for measuring small flow rates ($q < 30L/s$) and is, thus, adequate for the proposed application. Attaching this weir to a tank and measuring its water level can generate sufficiently accurate flow rate estimations (HATTAB; MIJIC; VERNON, 2019). Based on equation 20, as in Shen (1981) and Hattab, Mijic and Vernon (2019), if the water level is above the weir notch vertex the rate of pouring water is:

$$q = (\frac{8}{15} \times 0.61)\sqrt{2g}tan(\frac{\theta}{2})h^{5/2} \ [m^3/s] \tag{20}$$

Where θ is the triangular notch angle, g the Earth's gravity acceleration, h the water level measured from the weir notch vertex, as seen in figure 32.

To infer the flow rate for any water level (L) in the weir tank, equation 21 is used. In these equations, t is the time, i is a generic timestep counter, A and B are the tank dimensions, T is the time of a timestep i in seconds, and Q_{runoff} is the final flow rate:

$$Q_{runoff,\ t=i} = \begin{cases} [(L_{t=i} - L_{t=i-1} \times A \times B]/T \ [m^3/s], & 0 < L \leq P \\ q_{t=i} \ [m^3/s], & P < L < P + h_{max} \end{cases} \tag{21}$$

Figure 32 shows the US-025 ultrasonic sensor positioning, which should be parallel to the water level (NAIR; JOLADARASHI; GANESH, 2019). The ultrasonic sensor sends a trigger sound pulse and measures the time taken until the pulse echoes back, inferring the distance by the speed of sound as seen in Panda *et al.* (2016). A kinetic dumping barrier made of loose stone is added to diminish the surface waves from the runoff mechanical energy.

Finally, in order to find the total rainfall volume during a given event, equation 22 is used, presented in its continuous and discrete forms:

$$Q_{runoff} = \int_0^t Q_{runoff,t=i}dt \ [m^3] \ \ or \ \ \sum_i (Q_{runoff,t=i} \times T) \ [m^3] \tag{22}$$

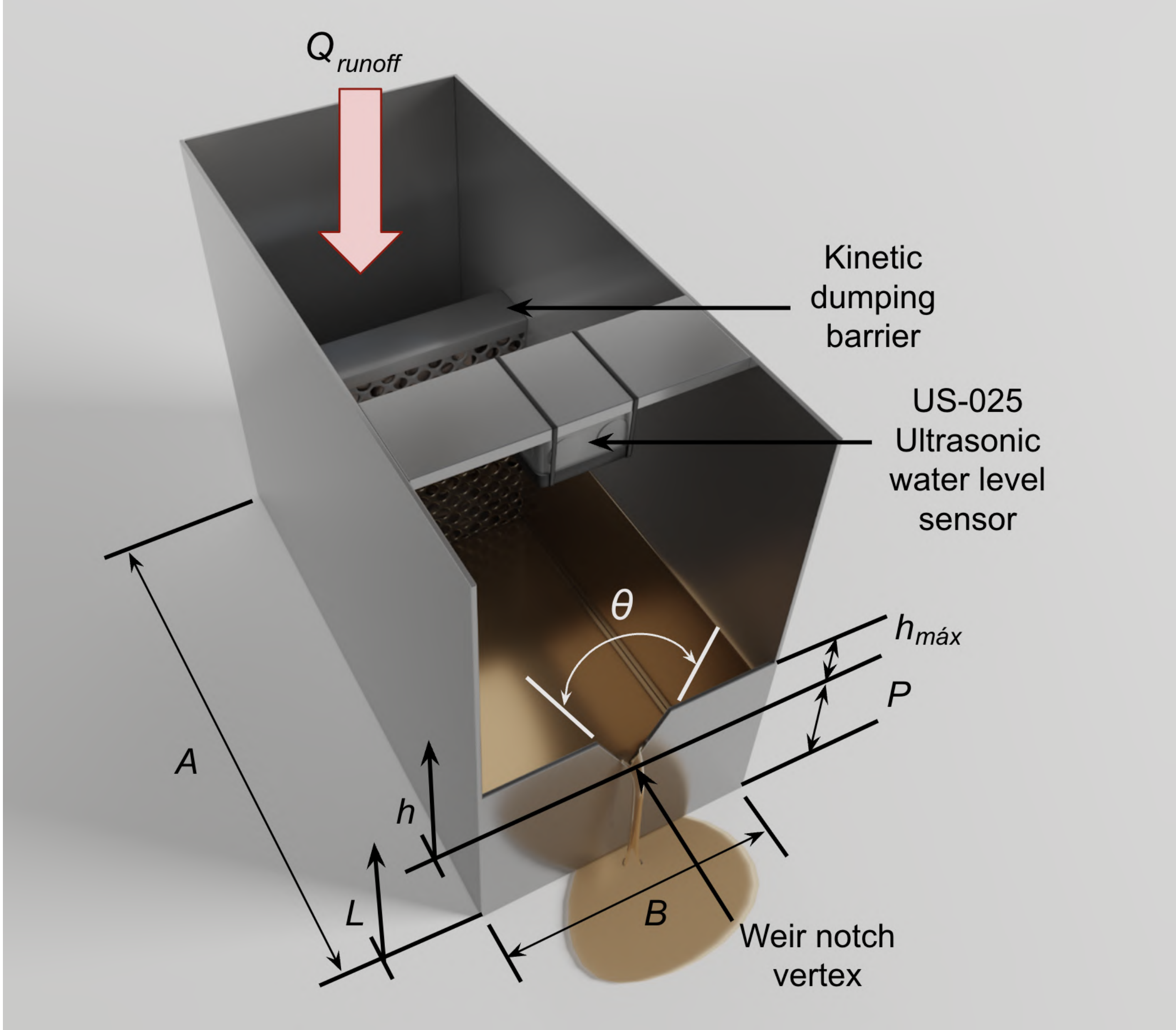


Figure 32 – Triangular notch thin plate weir tank dimensions. Illustrated by Henrique Capanema, adapted by the authors.

7.2.2 Rational Method

The Rational Method was used in order to characterize rainfall retention rate for each green roof event. As Loiola *et al.* (2019) point out, it is a method classically applied to micro-drainage and used in small urban catchment areas, and is demonstrated in equation 23.

$$Q = C \times i \times A_{roof} \tag{23}$$

In the equation, Q represents peak hydrograph; i is a design rainfall intensity; A_{roof} the roof area and C is a dimensionless runoff coefficient. This coefficient depends on the catchment surface conditions, use and occupation, varying from zero to one. It tends to zero when surface runoff is low, that is, in permeable surfaces such as forests and parks;

and tends to one when surface runoff is high, that is, in impervious surfaces such as asphalt. Thus, equation 24 presents C:

$$C = \frac{Q_{runoff}}{R}, \qquad\qquad C \in [0, 1[\tag{24}$$

Where R is the total rainfall (m^3). To use a more intuitive coefficient, the present work adopts RR as the complimentary coefficient to C, representing the retention rate. RR (equation 7) represents the proportion of the total rainfall retained by a green roof, varying from zero to one:

$$RR = \frac{R - Q_{runoff}}{R} = 1 - C, \qquad\qquad RR \in]0, 1] \tag{25}$$

7.2.3 Experiment A

The first experiment characterizes the rainfall-runoff of two prototypes, one with a 15cm deep extensive vegetated roof (VR) and another with a ceramic tiled (CT) roof. Both prototypes are 3m x 3m, built outdoors using masonry and simulating a real scale building with a door and a window, as seen in Ferraz (2012).

The VR prototype is a ten-year unmanaged and un-irrigated roof. Its vegetation after such time has become dominated by an invasive grass species, turning into a spontaneous but homogeneous culture. As indicated by Dunnett, Nagase and Hallam (2008), if totally unmanaged, a roof can become fully controlled by aggressive species that may decrease the roof biodiversity.

Real-time sensing is undertaken for runoff rates using the aforementioned setup, and other sensors also collaborate. Two different rain gauges capture rainfall data, one an *in-situ* Vantage Vue weather station with a $1min$ resolution (DAVIS INSTRUMENTS, 2021) and another laboratory made rain gauge about $400m$ distant with a $5min$ resolution. Not all data was available from the *in-situ* station, thus the other close-ranged rain gauge was used. A HOBO solar radiation sensor S-LIB-M003 (ONSET, 2022b) with a H21-USB data logger (ONSET, 2022a) collected data regarding sunlight intensity. The S-LIB-M003 is a Silicon Pyranometer with a measurement range of 0 to $1280W/m^2$ over a spectral range of 300 to $1100nm$, with a $\pm 5\%$ accuracy.

Five relevant characteristic rainfall events during a summer period from Nov/2021 to Feb/2022 were chosen (Events A1 to A5) from a larger range of collected data. These represent different rainfall intensities, durations and time gaps from previous rainfall events. Such parameters illustrate different demands for a vegetated roof, as seen in (LIU *et al.*, 2019), and thus may generate different relevant performance outcomes.

Knowing the rainfall rate (inflow) and the runoff rate (outflow), an estimate of the vegetated roof retention can be made, which is the roof capacity to store water (STOVIN, 2009). After this water budget realization, an analysis of the vegetated roof detention capacity is undertaken. The detention characterizes the ability of the VR in delaying and decreasing the peak runoff (STOVIN, 2009). As it is expected that the retention and detention rates will vary depending on the previous soil moisture conditions Liu *et al.* (2019), a second experiment under more controlled conditions is built.

7.2.4 Experiment B

The second experiment has the capacity to characterize runoff for different substrate depths and soil moisture contents. Four 1.4m x 1.3m testbeds are built with pine wood and machined aluminum profile structure (Models M1 to M4). In order to simulate rainfall events, an irrigation system is installed. The system consists of a Rain Bird controller that can open and close solenoid valves at programmed intervals, the piping system and a set of 15 calibrated drip nozzles for each testbed (RAIN BIRD, 2003).

Rainfall events were simulated using the irrigation system, which applied a constantly uniform irrigation equally over the models. The same constant irrigation was input at different controlled events (Event B1, Event B2, Event B3) when varying the soil moisture content. This moisture content variation was achieved by letting all testbeds dry without irrigation, increasing this antecedent dry weather period (ADWP) for each event. Testbeds were left without irrigation for 24h in Event B1; for 48h in Event B2 and for 72h in Event B3. Extensive roofs which have shallow substrate can lose their available water quickly, thus the dry gaps for each event were short: 0 hours, 24 hours and 48 hours.

Soil moisture content data was collected using a Extech MO297 portatile pinless moisture meter and an MO290-EP extension moisture probe with dual sharp 8.5cm pins (EXTECH, 2009; EXTECH, 2014). The sensor can work within a 13% to 99% moisture range and provide an accuracy of ±5%. It is known that for such loose and porous substrates used in green roofs the moisture meters can give significant reading variations

(HILL; PEROTTO; YOON, 2015). Thus, having many readings is necessary for reaching a mean value closer to the substrate reality. For that, an experiment under controlled conditions where rainfall events can be simulated becomes useful, as one only moisture meter can be used to infer data in a variety of points along the testbed surface before the irrigation starts.

Vegetation in the testbeds is left unmanaged, generating space for spontaneous individuals to grow. It is used as substrate a mixture of (in vol.) 64% mixed organic compost, ashes, crushed and composted pine and eucalyptus bark; 12% coconut coir fiber dust; 12% mixed grain sand and 12% mixed grain vermiculite.

7.2.5 Data analysis and error

Experimental data has used statistical data analysis when necessary and errors related to the methods used were propagated. For experiment A, solar radiation data is represented as its mean intensity and a confidence interval of 95% around its average. For experiment B, moisture content and irrigation rates were characterized via its mean and a standard error. Experiment B tendency lines are a two-period moving average in order to smooth out runoff sensor measurement imprecisions and get closer to reality.

Errors are based on nominal instrument uncertainties indicated by the manufacturer or estimated as half the equipment precision or resolution. Errors are propagated whenever an arithmetic operation between measurements containing errors is made, based on Tellinghuisen (2001).

For summing up the inflow measurements, if using weather station data or irrigation data, the process is the same. Let R be the sum of each $R_{t=i}$ inflow for each timestep i in an event. The error δR is given in equation 26:

$$\delta R = \sqrt{\sum_{I} (\delta R^2_{t=i})} \; [mm] \tag{26}$$

Where $\delta R_{t=i}$ is the measurement error for the inflow at a given timestep i.

For finding the runoff $Q_{runoff,\ t=i}$ (or outflow) error for a given $t = i$ timestep, the error is coupled to the weir tank error. The triangular notch weir tank flow rate error is derived from the error of the variable h, which is δh. Equation 21 can be written in the form of equation 27, where k is constant when varying only h:

$$Q_{runoff,\ t=i} = k \times h^{5/2}_{t=i}, \qquad P < L < P + h_{max} \tag{27}$$

How $Q_{runoff,\ t=i}$ varies for any $h_{t=i}$ variation is answered by partially deriving for h, which yields equation 28:

$$\frac{\partial Q_{runoff,\ t=i}}{\partial h_{t=i}} = \frac{5}{2} \times k \times h_{t=i}^{3/2}, \qquad P < L < P + h_{max} \tag{28}$$

Hence, dividing by Q_{runoff}, the error δQ_{runoff} will be the equation 29:

$$\delta Q_{runoff,\ t=i} = Q_{runoff,\ t=i} \times (2.5 \times \frac{\delta h_{t=i}}{h_{t=i}}), \qquad P < L < P + h_{max} \tag{29}$$

In terms of relative errors, a 1% error in the water level means a 2.5% flow rate error for the zone where water is pouring from the weir, or $P < L < P + h_{max}$. This error does not take into account the error of θ. The water level error for the proposed setup is associated with the ultrasonic sensor error and data acquisition frequency, which for the present work yielded $\delta h = 0.2\ mm$ for any $t = i$.

For the zone where $0 < L \leq P$ errors are propagated from an arithmetical multiplication of errors associated with a sum of errors. As L is a function of h, its basic error is the same $\delta L = 0.2\ mm$ for any $t = i$. This process is seen in equation 30:

$$\delta Q_{runoff,\ t=i} = Q_{runoff,\ t=i} \times \sqrt{\left(\frac{\sqrt{\delta L_{t=i}^2 + \delta L_{t=i-1}^2}}{|L_{t=i} - L_{t=i-1}|}\right)^2 + \left(\frac{\delta A}{A}\right)^2 + \left(\frac{\delta B}{B}\right)^2}, \quad 0 < L \leq P \tag{30}$$

To find the total δQ_{runoff}, the sum of errors propagation is used. Hence, equation 31 is used to find the total error for the total runoff volume of a rainfall event:

$$\delta Q_{runoff} = \sqrt{\sum_i (\delta Q_{runoff,\ t=i}^2)} \qquad [m^3/s] \tag{31}$$

7.3 Results and discussion

Each of the two experiments generated relevant results. The main findings are separated in two sections, describing patterns observed and applicable correlations for each investigation.

7.3.1 Experiment A

From the bulk of events captured, a set of representative events were selected. These events in experiment A are Event A1 to A5, as seen in figure 33. The figure shows both solar radiation dynamics during the event days and previous days as well as total daily rainfall. The events are characterized in table 5, where a return period is calculated using the intensity-duration-frequency (IDF) equation of São Paulo (DAEE-CTH, 2018).

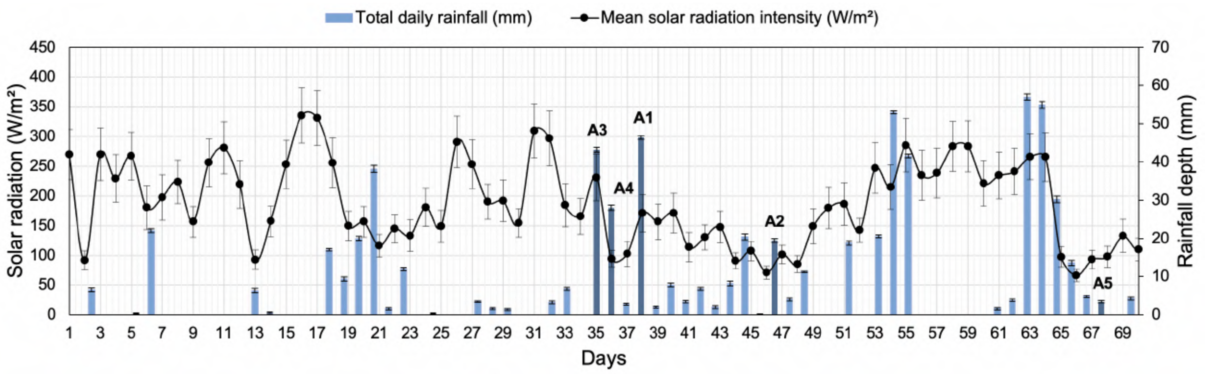


Figure 33 – Rainfall and solar radiation dynamics during the experiment duration, highlighting in darker hatch the events analyzed, Events A1 to A5.

	Rainfall intensity at Peak 1 (mm/min)	**Rainfall intensity at Peak 2 (mm/min)**	**Rainfall duration (min)**	**Total rainfall (mm)**	**Mean rainfall intensity (mm/min)**	**Gap from previous rain event (h)**	**IDF return period (years)**
Event A1	0.8 ± 0.1	0.7 ± 0.1	90.5 ± 0.5	37.60 ± 0.84	0.418 ± 0.010	26.82 ± 0.04	1.46
Event A2	0.8 ± 0.1	No peak 2	120.0 ± 0.5	17.40 ± 0.71	0.145 ± 0.006	41.80 ± 0.04	1.01
Event A3	0.3 ± 0.1	No peak 2	80.5 ± 0.5	21.40 ± 0.39	0.268 ± 0.005	50.63 ± 0.04	1.03
Event A4	0.2 ± 0.1	0.1 ± 0.1	200.5 ± 0.5	20.80 ± 0.55	0.104 ± 0.003	3.90 ± 0.04	1.00
Event A5	0.1 ± 0.1	0.1 ± 0.1	200.0 ± 0.5	3.40 ± 0.41	0.017 ± 0.002	26.63 ± 0.04	1.00

Table 5 – Rainfall characteristics for each event.

Among the events analysed, event A1 is representative of high intensity summer evening rainfalls, having the highest intensity of all events analyzed and a short duration. Event A1 has also happened at the end of a sequence of concentrated intense rainfall events. Event A2 is representative of medium intensity rainfalls that last for many minutes, having all 15 of its previous days seen precipitation. Event A3 is representative of rainfall events right after dry periods, having 12 of its previous days not seen any rain or very little precipitation. Event A4 is representative of a medium intensity event a day after an intense precipitation, as the last rain event happened less than four hours before. Event A5 is representative of small intensity and long duration events. Events A1, A4 and A5 had two separate peak rainfalls. These events had their peaks analysed separately. Events were defined by a gap of at least two hours without rainfall.

Figure 34 shows the rainfall hydrographs for events A1 to A5 and the runoff for the vegetated roof (VR) prototype and ceramic tiled (CT) prototype. For all events, it is noticeable that the weather station captures rainfall about the same time the runoff is being captured by the CT weir tank. However, VR runoff delays not only to start, but its peak is also delayed and attenuated.

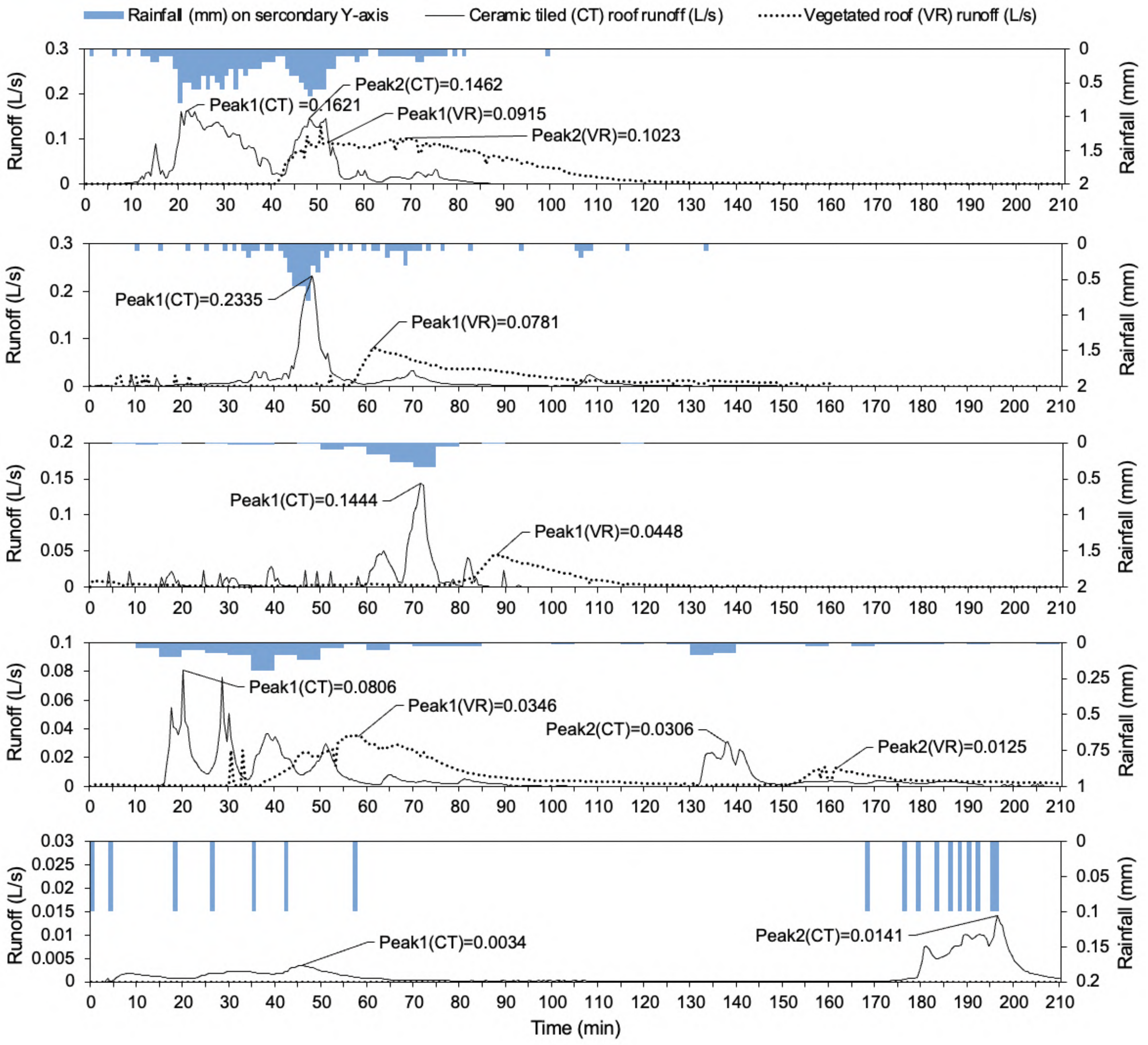


Figure 34 – (a-e) Rainfall-runoff hydrographs for five characteristic events, A1 to A5.

Tables 6 and 7 show a water balance for each event, respectively for the CT and VR prototypes. For all events, the ten-year unmanaged VR was able to retain considerably more rainfall than the CT. In Event A5, the CT proportionally retained a relevant amount of water, but that is because E5 was a very small rainfall depth event, in which the simple soaking of tiles already consumed most of the rainfall. Also, for the same A5, the VR prototype collected 100% of the rainfall, which shows there are low intensity events that can generate no runoff for vegetated roofs.

Besides Event A5, the event in which the proportion retained was higher was A3. A direct indication that an intense event right after a dry period may be where the VR

	Rainfall (L)	**Runoff (L)**	**Retention (L)**	**RR (1)**
Event A1	511.36 ± 8.08	501.6790 ± 0.0063	9.68 ± 8.08	0.019 ± 0.016
Event A2	228.48 ± 6.61	227.6452 ± 0.0042	0.84 ± 6.61	0.004 ± 0.029
Event A3	151.34 ± 8.33	143.1728 ± 0.0025	8.17 ± 8.33	0.054 ± 0.055
Event A4	172.55 ± 11.78	166.6702 ± 0.0017	5.89 ± 11.78	0.034 ± 0.068
Event A5	46.24 ± 1.86	36.7002 ± 0.0001	9.54 ± 1.86	0.206 ± 0.041

Table 6 – Water budget for each rainfall event, comparing the ceramic tiled roof (CT) retention performances.

	Rainfall (L)	**Runoff (L)**	**Retention (L)**	**RR (1)**
Event 1	440.01 ± 8.06	289.5352 ± 0.0060	150.47 ± 8.06	0.34 ± 0.19
Event 2	196.60 ± 6.60	147.6277 ± 0.0030	48.97 ± 6.60	0.25 ± 0.35
Event 3	130.22 ± 8.33	66.3227 ± 0.0015	63.90 ± 8.33	0.49 ± 0.71
Event 4	148.48 ± 11.78	91.6693 ± 0.0015	56.81 ± 11.78	0.38 ± 0.09
Event 5	39.78 ± 3.97	0.0 ± 0.0	39.79 ± 3.97	1.00 ± 0.14

Table 7 – Water budget for each rainfall event, comparing the vegetated roof (VR) retention performances.

should have a higher performance. This is because most of the water saturating the soil has been removed by ET.

The event that retained proportionally less rainwater was A2: a medium intensity event right after many days of rain and a low solar radiation period. The low solar radiation is an indicator of low ET, which is the main mechanism for desaturating the roof. Events A1 and A4 had similar performance, showing that a one day gap may not be relevant for any major changes in runoff retention.

Table 8 demonstrates a compared detention performance between both CT and VR prototypes. For any event with two peaks (Peak 1 and Peak 2), it is straightforward to notice that the second peak (Peak 2) always has a smaller or equal peak runoff attenuation and delay effect. That is because the VR is already exceedingly saturated. Despite not having the best retention performance, A2 was the most attenuated peak, followed by A4 which also did not have the best retention performance. That is because both had smaller rainfall intensities and greater rainfall duration, yielding less water pressure to generate runoff. Greater peak runoff delay was obtained in Event A4 for the same reason.

Taking into account the VR roof area of $11.7m^2$, the retention value can be calculated in mm. For event A1, the VR retained $12.9mm$; event A2 retained $4.2mm$; event A3 retained $5.5mm$; event A4 retained $4.9mm$ and event A5 retained $3.4mm$.

	Peak 1			**Peak 2**		
	Attenuation		**Delay**	**Attenuation**		**Delay**
	(L/s)	**(%)**	**(min)**	**(L/s)**	**(%)**	**(min)**
Event A1	0.0705 ± 0.0405	43.5 ± 0.3	30.5 ± 0.5	0.0439 ± 0.0362	30.0 ± 0.3	20.5 ± 0.5
Event A2	0.1554 ± 0.0531	66.6 ± 0.3	14.0 ± 0.5	No peak 2	No peak 2	No peak 2
Event A3	0.0996 ± 0.0311	42.7 ± 0.2	15.0 ± 0.5	No peak 2	No peak 2	No peak 2
Event A4	0.0460 ± 0.0177	57.0 ± 0.2	37.0 ± 0.5	0.0180 ± 0.0064	58.9 ± 0.2	24.0 ± 0.5
Event A5	0.0034 ± 0.0006	100 ± 0.0	-	0.0141 ± 0.0027	100 ± 0.0	-

Table 8 – Compared detention performance for each rainfall event and peaks.

7.3.2 Experiment B

Experiment B results are shown in figure 35, for three different events: Event B1, Event B2 and Event B3. Events differ by the antecedent dry weather period (ADWP). The runoff was measured for a steady 0.0325 L/s irrigation income. Within any same graphic, patterns are observable. It is noticeable that on average greater soil depths yields also longer delays for runoff to start and the smaller is the peak runoff reached. It is also noticeable that the shallow 6 cm (M4) and 10 cm (M3) can overlay or switch positions, indicating what can be a minimum threshold performance.

Along the three observed events, there are also patterns to highlight. From one event to another, as soil moisture content decreases, the delay for runoff to start increases. The *plateau* all curves reach is not parallel to the X-axis, but is inclined. For a longer experiment, runoff would eventually equal the inlet irrigation when full soil field capacity is reached.

Comparing the detention performance for each event under different soil moisture conditions yields the analysis in tables 9-11. The moment when runoff starts is considered to be when flow rate first reaches a 1 mL/s threshold. Each model peak runoff for the imposed irrigation of 0.0325 L/s is calculated as the average runoff between 45-50 min, which will increase as the full soil field capacity is reached.

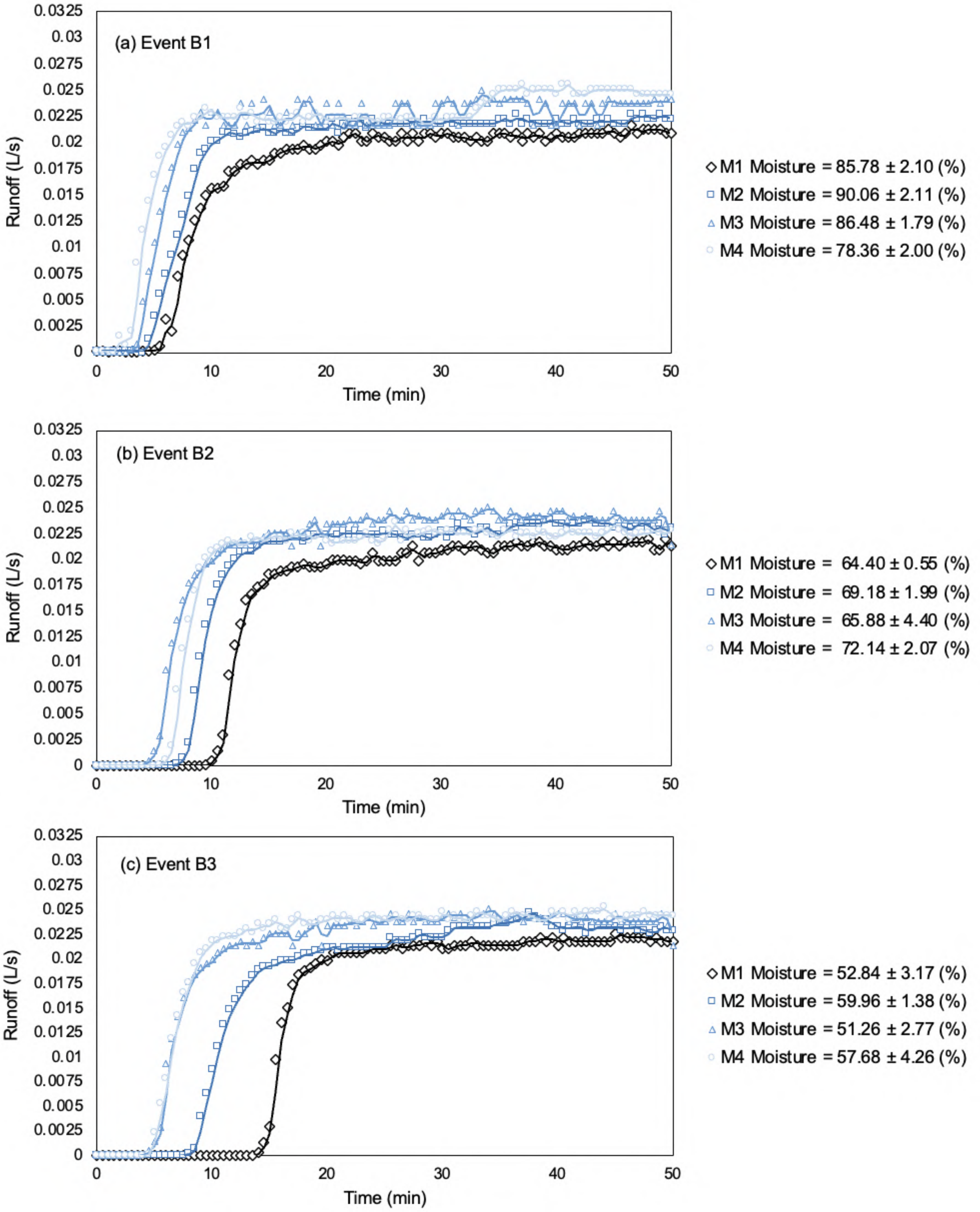


Figure 35 – (a-c) Runoff obtained for different substrate depths (Models M1 to M4) and different soil moisture contents during controlled simulated rainfall events (Events B1 to B3) with same intensity and duration.

Tables 9-11 quantify the phenomena demonstrated in figure 35. quantify the phenomena demonstrated in figure 8. In the experiment as a whole, the proportion of total irrigation retained (RR) varied from 0.340 ± 0.005 (Event B1, Model M4) to 0.548 ± 0.006 (Event B3, Model M1), depending on substrate depth and previous moisture content. Runoff starting time was also delayed from 2.5 ± 0.5 min (Event B1, Model M4) all the way to 14.5 ± 0.5 min (Event B3, Model M1).

	Model M1 (20cm)	**Model M2 (15cm)**	**Model M3 (10cm)**	**Model M4 (6cm)**
ASMC (%)	85 ± 7	90 ± 7	86 ± 7	78 ± 7
Time runoff starts (min)	6.0 ± 0.5	4.5 ± 0.5	4.0 ± 0.5	2.5 ± 0.5
Retention (L)	46.44 ± 0.49	40.95 ± 0.49	35.48 ± 0.49	33.15 ± 0.49
RR (1)	0.476 ± 0.006	0.420 ± 0.005	0.364 ± 0.005	0.340 ± 0.005

Table 9 – Retention and detention obtained for event Event B1.

	Model M1 (20cm)	**Model M2 (15cm)**	**Model M3 (10cm)**	**Model M4 (6cm)**
ASMC (%)	64 ± 7	69 ± 7	66 ± 8	72 ± 7
Time runoff starts (min)	10.5 ± 0.5	8.0 ± 0.5	6.5 ± 0.5	6.5 ± 0.5
Retention (L)	50.28 ± 0.49	42.08 ± 0.49	41.43 ± 0.49	40.49 ± 0.49
RR (1)	0.516 ± 0.006	0.432 ± 0.005	0.425 ± 0.005	0.415 ± 0.005

Table 10 – Retention and detention obtained for Event B2.

	Model M1 (20cm)	**Model M2 (15cm)**	**Model M3 (10cm)**	**Model M4 (6cm)**
ASMC (%)	53 ± 7	60 ± 7	51 ± 7	57 ± 8
Time runoff starts (min)	14.5 ± 0.5	9.0 ± 0.5	5.0 ± 0.5	5.0 ± 0.5
Retention (L)	53.40 ± 0.49	44.81 ± 0.49	36.46 ± 0.49	34.96 ± 0.49
RR (1)	0.548 ± 0.006	0.460 ± 0.006	0.374 ± 0.005	0.359 ± 0.005

Table 11 – Retention and detention obtained for Event B3.

The correlation between initial soil moisture content and substrate depth and the consequences on relative retention and on the time when runoff starts can be seen graphically in figure 36, a correlation matrix. Positive strong correlations are shown between the proportion of rainfall retained and substrate depth and also to the delay in time runoff. This means that as substrate depth increases, so does rainfall retention and the time for runoff to start, which is corroborated by works such as Liu *et al.* (2019) and VanWoert *et al.* (2005). However, expanding these findings, the figure shows that substrate depth has a greater influence in the retention amount than in the detention delay. An also strong and positive correlation is observed between the proportion retained and the time runoff starts. This means that the more rainfall the substrate retains, the greater is the runoff delay, almost directly proportional. On the other hand there is a negative correlation between antecedent soil moisture content (ASMC) and the proportion retained as well as to the time runoff starts. This indicates that as ASMC increases, the proportion retained decreases, which is in harmony with Liberalesso *et al.* (2021) and Soulis *et al.*

(2017), but also in harmony with Persch *et al.* (2021) that shows this correlation is weak. This also indicates that as ASMC increases, the delay for runoff to start decreases, which is physically coherent. However, the ASMC wasn't correlated to the substrate depth, which is counterintuitive, as it was expected that the deeper the substrate the more it would be able to retain. This can be explained by the fact of the vegetated roofs being unmanaged: higher substrate depths also had greater biomass and thus greater evapotranspiration rates. This is a very interesting outcome pointing to the possibility that in unmanaged green roofs ASMC loses correlation to substrate depth, also indicating that vegetation can be more effective in restoring the substrate retention capacity. Deeper depths will indeed retain more moisture, but its unmanaged vegetation will also grow and proliferate more, meaning it will then release more water as ET. Full research data is available in Mendeley Data (GOBATTI AND LEITE, 2022).

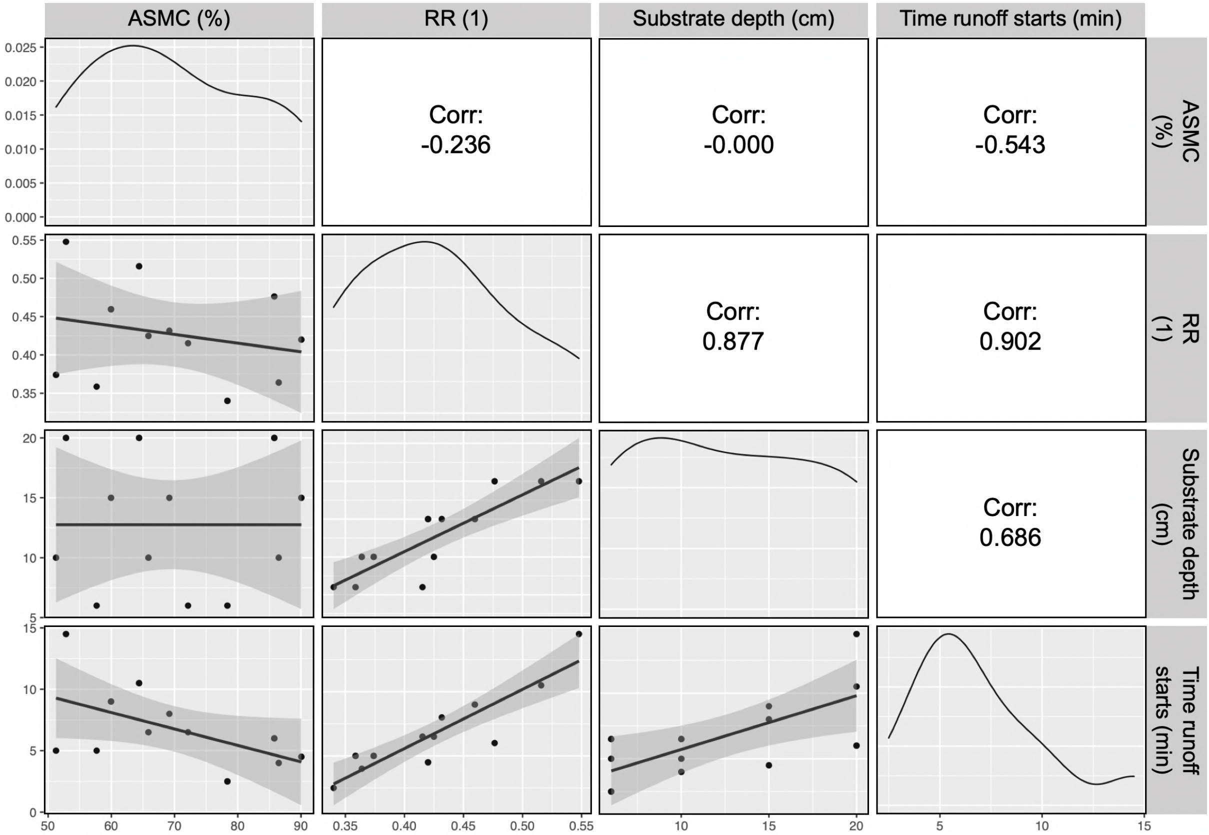


Figure 36 – Correlation matrix for substrate depth, soil moisture content, relative retention and the time runoff starts for a $0.0325 L/s$ irrigation under experiment B conditions.

7.3.3 Unsaturated soil mechanics

Results of experiment A demonstrate and quantify a phenomenon which is highly useful for rainwater management. The VR not only captures water within its substrate, but also delays runoff arrival to the urban rainwater drainage system. A conceptual representation of this phenomenon can be seen in figure 37.

The results of experiment B also yield an interesting unsaturated soil mechanics development. Despite the experimental errors and measurement uncertainties, it is possible to observe that none of the runoff curves presented in figure 35 equal the inflow simulated rainfall of $0.0325L/s$. As soil dries out, the capillary water present in the soil is gradually lost. The hygroscopic water represents, thus, a bigger proportion of soil moisture content as this moisture decreases. A less water saturated substrate means a higher air saturated substrate. This signifies that rainwater (or irrigation) has to rebuild the gravitational paths around the soil particles. But this path construction takes time and energy.

This finding gives a relevant insight to previously well-established ASMC correlations like in Tucci (2005). In his work, the author associates soil moisture only with rainfall depth in the previous five days from an event. Soil moisture content, however, may thus be more closely correlated to rainfall intensity and duration in previous days, as this correlation would better account for the time water takes to actually saturate the soil pores.

In figure 38 it is possible to see this conceptual phenomenon represented. The time t_2 represents the moment in which full field capacity is reached and the runoff is exactly equal to the inflow. Results in this work have been captured up until an intermediate time time $t_1 = 50\ min$. Runoff will increase at different rates, as shallow soil should be easier for water to flow through and deep soil more difficult.

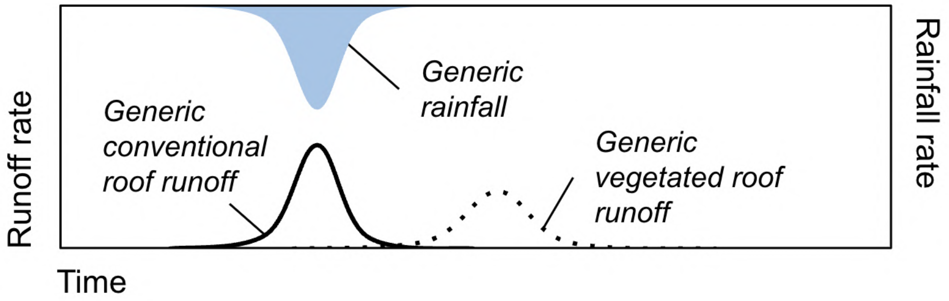


Figure 37 – Conceptual representation of phenomena observed in experiment A: a rainfall generating different runoff behaviors.

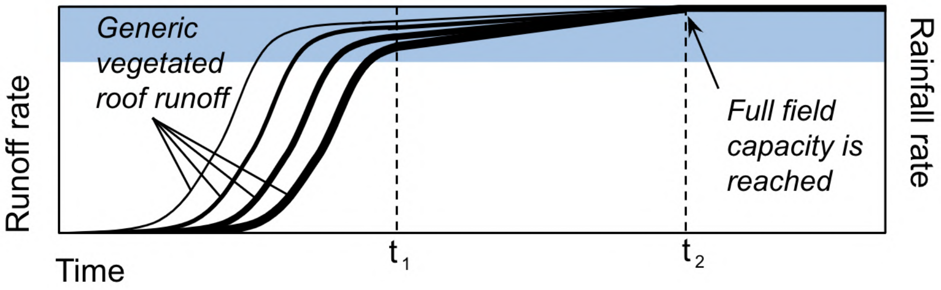


Figure 38 – Conceptual representation of phenomena observed in experiment B: thicker lines represent thicker substrate depths.

Hence, it is observed that the soil field capacity is not a sharp line and is not reached when simply gravitational water starts running off. Despite there may be runoff and thus gravitational water, for the full field capacity to be reached it takes time. That is, within the same block of soil (or green roof) there can be zones with gravitational water, capillary water and only hygroscopic water simultaneously.

Experiment B thus, points to the possibility that a large number of previous days with a slow but steady rainfall intensity can reduce the soil retention capacity more than a short and intense previous day of rain, which explains a lot of the outcomes observed in the Event A2 from experiment A, in comparison to Event A4 from experiment A. As seen in figure 33, Event A2 had a steady sequence of rain events for 15 days, and Event A4 only one previous day of intense rainfall. Although both events measured a similar rainfall intensity, the VR on Event A2 retained 35% less rainwater.

7.4 Conclusions

The present work characterized the influence of vegetated roofs in the runoff of a building scale. A robust laboratory analysis was carried out for unmanaged extensive lightweight vegetated roofs with varying structural parameters and initial conditions under a subtropical climate. Main conclusions for prototype experiments were: in comparison to the CT prototype (*i*) the VR prototype retained 34% to 100% of rainwater; (*ii*) delayed 14 to 37 minutes the peak runoff and (*iii*) decreased by 30% to 100% the peak runoff.

For testbed results, it is shown that: (*i*) runoff start is delayed as substrate depth increases for a same irrigation event; (*ii*) runoff start is also delayed as previous soil moisture decreases as energy is demanded for water to push air from substrate and create pathways around substrate particles; (*iii*) within a model, increases in its soil moisture content represented up to 13% less retention performance and 59% less peak runoff delay.

The experiment results show that retention and detention performances are highly dependent on the initial conditions of the VR for a rainfall event. Namely, substrate depth generated the greatest influence on runoff, and ASMC also influenced, but to a lesser extent. The moisture content is, furthermore, a consequence of the surrounding temperatures, humidity, solar radiation and of the plants ET rate.

Further work to implement the aforementioned results into urban rainwater systems is needed in order to observe whether the positive outcomes are maintained or changed. The present work results are representative of summer periods in subtropical areas, a moment when solar radiation is higher, generating higher soil desaturation. But also a moment when rainfall events are more intense and more frequent. To address this limitation and provide general results and recommendations, further work for winter periods is necessary and will be undertaken.

Vegetated roofs can have a great urban impact towards a sustainable and decentralized drainage future. Along with its many benefits, many dwellers and architects are choosing vegetated rooftops. But for a real impact on urban scales, VR should become a public policy and be largely adopted. For that to be possible, a standardization is necessary, which, including Brazil, many mainly tropical and subtropical countries still do not have. Towards a proper standardization, it is imperative not only to know qualitatively the VR performance, but also to quantify it. Hence, these results may contribute not only to the incorporation of VR in architectural projects, but also to an urban scale application.

8 Unmanaged subtropical green roof vegetation

> Natural phenomena undisturbed
> by man point the way to the
> realization of a new technique.
>
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>
> Viktor Schauberger in:
> *Living Water*, 1973

8.1 Introduction

The human built environment can represent a dramatic change to natural cycles and habitats when compared to its previous local natural space. Densely occupied cities can become places of dispute for land use, as pointed out by Vesuviano and Stovin (2013), making it difficult for installing ground-level Nature-based Solutions (NbS) such as bioretentions, street trees and public parks. Structures such as vegetated roofs, as pointed out again by Vesuviano and Stovin (2013), can address these pressures on land use, as they can be installed in rooftops, and at the same time generate a variety of Ecosystem Services (ES) such as rainwater retention and detention (OBERNDORFER *et al.*, 2007).

Ecosystem Services are defined by the International Union for Conservation of Nature (IUCN) as ≪the benefits people obtain from ecosystems≫ (MA, 2005), which is a novel approach to attempt quantifying the interdependence between human nature and its surrounding nature. This approach was thus encompassed by the term "Nature-based Solutions", defined by the European Commission (EC, 2015) as ≪Solutions that are inspired and supported by nature [...].≫

In this sense, getting inspiration from nature and supporting its processes demand systematically observing nature in order to work together with natural phenomena. Thus, it is relevant to clearly state what natural and artificial processes are for this paper and Lacerda *et al.* (2013) summarise it in a simple manner. The authors argue that artificial and natural are only different orientations: while artificial artefacts are produced (or caused) by humans with a definite aim, natural artefacts are a consequence of nature. A naturally occurring artefact may live a long-lasting life if natural conditions are favourable, and an artificial artefact may be built where intense maintenance will be needed for its permanence.

The same applies for vegetation on top of a roof. Many extensive vegetated roofs are built using grasses, sometimes exotic and invasive species, and owners often desire the control of weed growth. On the other hand, it is possible to better understand what these spontaneous individuals are and thus better use their benefits to the urban ecosystem, as Lundholm (2016) points out. Hence, the artificial vegetated roof artefact, a human creation, can then be the stage for natural vegetation to spontaneously grow and, thus, diminish costs of maintenance, increasing the provision of ES such as biodiversity, habitat for species, aesthetic appeal, rainwater management, diminishing irrigation, gardening and fertilisation costs (DUNNETT, 2015).

8.1.1 Vegetated roofs

Vegetated roofs are not a novel structure. Osmundson (1999) defines them as any vegetation or garden that is separated from the soil by a building. There are different types of vegetated roofs that are normally classified by their substrate depth, which, from shallowest to deepest, are extensive, semi-intensive and intensive. As Dunnett, Nagase and Hallam (2008) point out, the intensive types of vegetated roofs may not be so interesting as the main society needs are light-weight, ecologically harmonic and aesthetically appealing roofs, in order to allow a wider range of people to actively use it. The common layer composition of these roofing systems is indicated below (Fig. 39).

Each layer can have its specific characteristics depending on the configuration of the green roof, which is not homogeneous worldwide. As a relevant aspect, though, that underlies any vegetated roof is its substrate composition, which usually incorporates a specific range of materials. Ampim *et al.* (2010) bring a concise review of substrate materials and their properties, classified among natural and mineral components, artificial or modified mineral components, recycled or waste and plastic foam materials and finally organic materials. Mulching is also an interesting addition, as it can help the substrate lose less water from evaporation (CIANCIARUSO *et al.*, 2006).

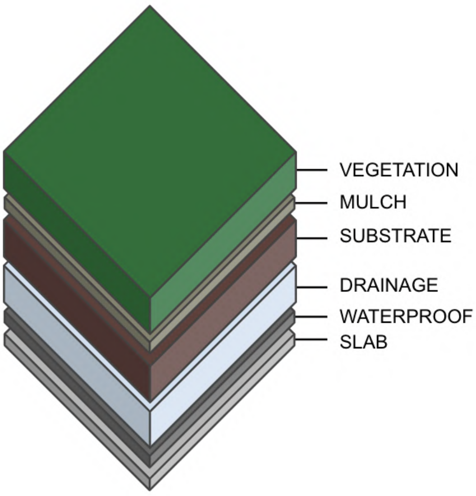

Figure 39 – Vegetated roofs typical layers and slab structure support.

8.1.2 Spontaneous vegetation aspects

Lundholm (2016) demonstrates how vegetated roofs are artificial structures, though also highlighting that after its construction there is spontaneity involved and the level of human management will dictate the roof dynamics. By characterising levels of organisation from autopoiesis and spontaneous dynamics to engineered systems, the author brings novel approaches to designing systems towards self-regulation and criticises highly managed green roofs.

The green roof vegetation can have a great impact on the system performance regarding for example water retention and thermal inertia (DUNNETT; NAGASE; HALLAM, 2008). Thus, plant characteristics and selection are a relevant aspect on vegetated roof systems, investigated by the author. In his research, the author points out the dangers of relying on spontaneous colonisation if the main objective is related to biodiversity heterogeneity. Systems may become too homogeneous because of the greater adaptability and aggressiveness of some of the species. The work shows that although greatest plant survival and diversity occurred at 200mm depth, colonising species greatest diversity happened at 100 mm depths.

Dunnett (2015) sheds light to not only early colonisation, but also vegetated roof succession. In his article, Dunnett illustrates vegetated roofs as dynamic ecosystems and points towards the need for self-regulating systems, in order to attain long-time response to environmental perturbations. Nagase, Dunnett and Choi (2013) show that a reduction in substrate depths may also lead to a reduction in plant colonisation.

In a research with the same focus, Catalano *et al.* (2016) analyse vegetated roofs unmanaged for 30 years. It is highlighted that spontaneous colonisation is an awe-important and beneficial phenomenon for vegetated roofs, as it is also relevant to ground botanical selection into local plant communities.

Catalano *et al.* (2018) analyse green roof norms and guidelines from Germany, Switzerland and Italy. In these norms, it is demonstrated a lack of analysis regarding ecoregions and plant traits. The research indicates the necessity of addressing ecological aspects when designing green roofs that work towards environmental compensation. Thus, from the aforementioned works, it becomes clear that research in different climates should be addressed, as local environmental conditions are greatly relevant.

8.1.3 Tropical and subtropical climates

Previous research approaches mainly concentrate on temperate climate conditions (GRULLÓN-PENKOVA; ZIMMERMAN; GONZÁLEZ, 2020), and the few recent studies undertaken in tropical and subtropical climates also highlight the need for improvement in understanding spontaneous dynamics for their local conditions. Hence, the present work aims at systematically characterising the first months of vegetation dynamics in unmanaged laboratory green roof models, as early stages are fundamental for improving the understanding of green roof vegetation arrangements and their resilience (DUNNETT, 2015). Thus, this work brings a relevant original contribution as it takes place in a subtropical environment, a region lacking cohesive and robust data to systematically characterise the growth and identify spontaneous green roof species for further usage.

It is expected that shallower substrate depths will hamper the progression of planted species up to a depth threshold when depth is not relevant anymore. It is also expected that spontaneous species that can better deal with drought and less water availability may progress better than the planted species for the shallower substrate depth. Though, investigation is necessary to observe if even a shallow substrate depth can satisfactorily accommodate a variety of species and become a proper habitat for them. Such finding can be relevant for deriving botanical selections for shallow vegetated roofs colonisation, which incentivises these lightweight roofs mainstreaming (SILVA; FLORES-COLEN; ANTUNES, 2017).

8.2 *Materials and methods*

To accomplish the research objectives, a laboratory investigation was undertaken in São Paulo, Brazil. It is a transition climate between tropical and subtropical regions of the country, as seen in the Köppen Geiger climate classification (Alvares *et al.*, 2013). On a larger scale, Martinelli (2010) classifies the city of São Paulo as a Cwa (Humid subtropical zone, with dry winter and hot summer), in a close transition with Aw (Tropical zone, with dry winter). Testbeds were built and on top of them a method for systematically sampling and characterising its vegetation dynamics was constructed.

8.2.1 Experimental setup

The experiment was carried out in four 1,40x1,30m outdoor vegetated roof testbeds, each one with different substrate depths, whereas all other structural parameters were identical. The experiment lasted for 110 days. Their distribution and substrate depths are here identified (Fig. 40). The models are able to measure a variety of parameters, including water and thermal performance, but focus will be given only to the vegetation dynamics in this work.

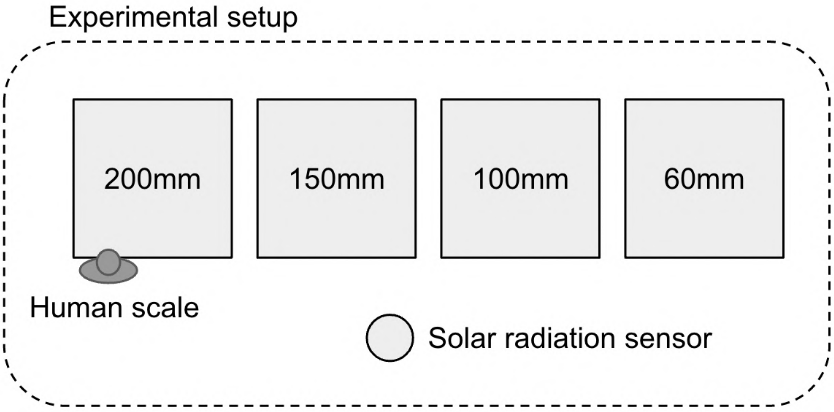

Figure 40 – Testbeds outdoor experimental setup, substrate depths and solar radiation sensor positioning.

Recalling the green roof structure (Fig. 39) from bottom-up, models were built using machined aluminium square profiles of 30mm as structure and varnished pine wood to frame the substrate and simulate a slab. A low permeability HDPE (High-Density Polyethylene) geomembrane with 0.5mm thickness was used as a waterproof layer. A geodrain membrane is used as a drainage layer. For substrate composition a proportion of different materials was used (Table 8) and a geotextile layer of $100g/m^2$ separates the substrate from the drainage layer. Mulching uses dry decayed leaves from trees around the laboratory, a practice that can represent a human vector for seed dispersion. Finally for the vegetation layer, an equal distribution of 33 *Arachis repens* seedlings per square metre was planted as initial landscaping. The slope of the testbeds is 3%. A solar radiation sensor is placed close to the testbeds (Fig. 40).

Material	Proportion	Benefits and drawbacks
Mixed substrate with organic compost, ashes, crushed and composted pine and eucalyptus bark	64% (vol.)	Has abundance of nutrients, great water retention and high microbial counts, but is very heterogeneous, possibly having toxicity concerns and can store a seed bank if composting wasn't done properly
Coconut coir fibre dust	12% (vol.)	Has good water retention, but is low in nutrients
Mixed grain sand	12% (vol.)	Structures the substrate providing anchorage and improves soil retention, it does not, however provide nutrient income
Mixed grain vermiculite	12% (vol.)	Is lightweight, but deteriorates quickly and does not retain water very well

Chart 8 – Substrate materials used, their proportion and its positive and negative aspects.
Source: adapted by the authors from Ampim *et al.* (2010).

An irrigation system was installed to keep soil with a high moisture content rate. A Rain Bird controller is used to start the system at 6AM every day and a set of 20 drip nozzles distribute water equally over the testbed.

8.2.2 Point-intercept method

To assess the dynamics of planted and spontaneous species, laboratory sampling is made by means of a perpendicular grid of 100 mm equidistant lines placed on top of the testbed using a Polyethylene thread. A final overview of a planted testbed with automatic irrigation and the implemented grid lines is here depicted (Fig. 41).

Figure 41 – Final testbed with the grid for point-intercept method.

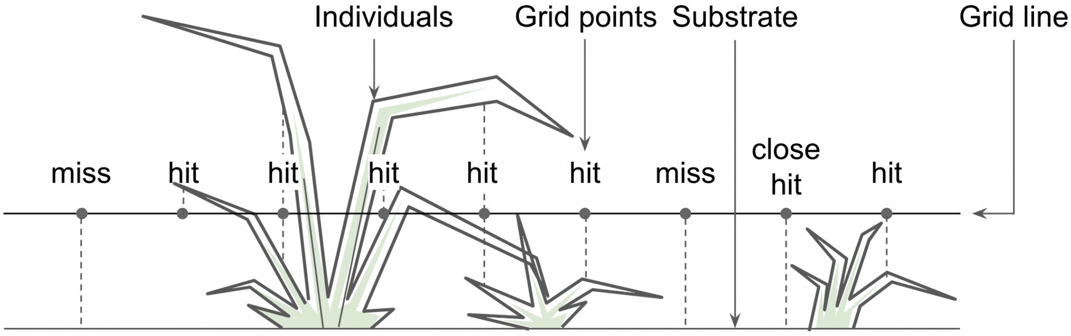

Figure 42 – Illustration of the point-intercept method.

Source: adapted by the authors from Chojnacky and Milton (2008).

At each intersection between a horizontal and a vertical grid line, another line perpendicular to the testbed surface is searched to find any intersections between this line and any vegetation. This is the Point-intersect method, as described by Mueller-Dombois and Ellenberg (2015) and Caratti (2006). A visualisation of the method is here illustrated (Fig. 42).

The intersections are a representative and neutral sample of the whole testbed surface and intersections can quantify the *Arachis repens* progression as well as any other spontaneous plants. Plants that do not intersect with the grid points will not appear in the results. To improve the model resolution, the authors considered a full intersection when plants intersect with the grid point and a half intersection when plants are very close to the grid point but do not intersect. In the first months, data was collected weekly and in the final months data was collected monthly. Plant coverage is roughly estimated by dividing the total number of grid points by the total number of intersected grid points at each day of laboratory data collection. The data collection began a couple of weeks after the first planting; it is expected, thus, that spontaneous species will appear already in the first readings.

8.3 Results

Results for the progression of interceptions along the experiment days and for plant coverage can be seen in figure 43. It is possible to notice that total plant coverage (which involves both planted and spontaneous species, on secondary Y-axis with dashed lines) has progressively increased through time. Highlight should be given to the substrate with 10cm depth, which had better plant coverage throughout the whole experiment, a result that resonates with Dunnett, Nagase and Hallam (2008) findings.

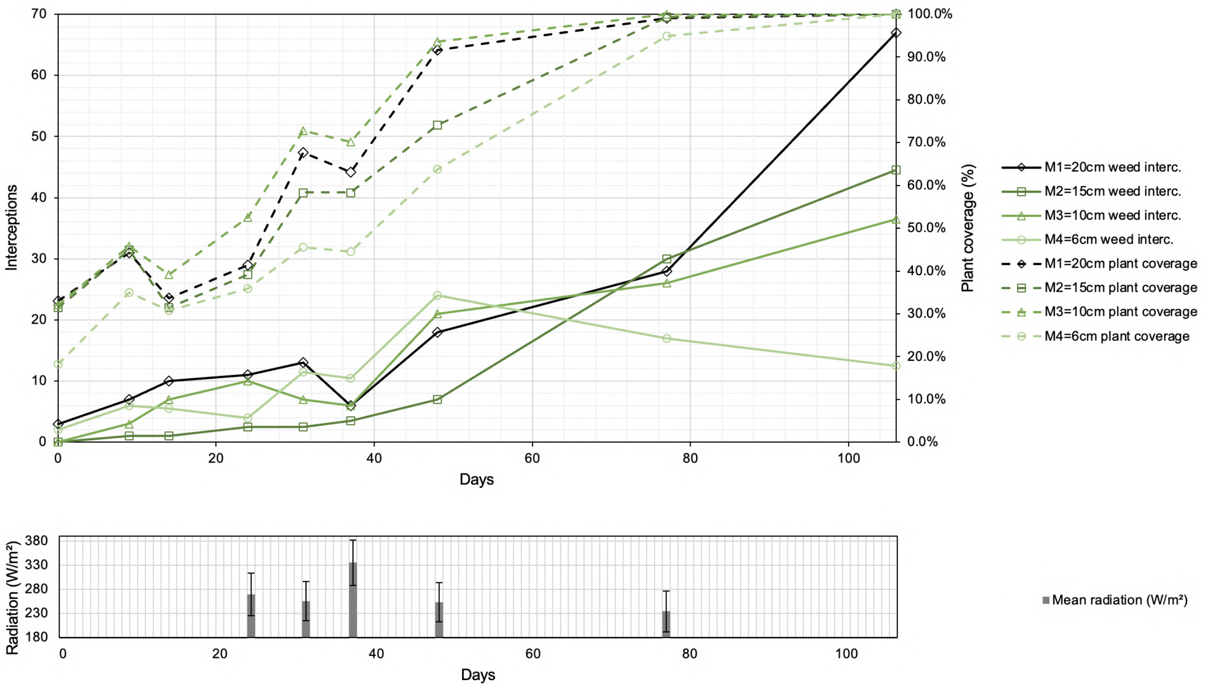

Figure 43 – The top graph shows the number of interceptions of spontaneous species (main Y-axis) per day and plant coverage (secondary Y-axis) per day; and the bottom graph shows the average solar radiation during some of the data collection days.

In terms of spontaneous vegetation, the graph (Fig. 43) demonstrates how weed interceptions progress (primary Y-axis with solid lines). It is noticeable that the shallower substrate depths have initially, in the first 40 to 50 days, had greater quantities of spontaneous weed intersections. A phenomenon that happened possibly because there were still gaps in the planted grasses, and these gaps in the shallower substrates had stayed for longer. But as time progressed, the deeper substrate depths became better environments for spontaneous vegetation.

The graph on the bottom (Fig. 43) shows the solar radiation measured *in situ* for some of the experiment days. Radiation and plant coverage have close correlation. Graphs show an evident decrease in plant coverage on day 37, which is also accompanied by a day of evident higher solar radiation mean. It is known that *Arachis repens* grass species can move their leaves to regulate radiation exposure depending on light conditions, thus this result may shed light into how plant coverage can change in account of that phenomenon. Error bars are estimated as 95% confidence interval from standard deviation.

The qualitative part of the experiment, identifying the species that voluntarily colonised the roofs, as well as the planted *Arachis repens* is further demonstrated (Table 9). Noticeably, botanical families with greater diversity of species were the *Asteraceae* and *Fabaceae*. However, the families with higher numbers of individuals were the *Commelinaceae* and *Poaceae*. Full experimental data is available at Mendeley Data repository (GOBATTI, LEITE AND HUTTENLOCHER, 2022).

Family	Species	Common name
Asteraceae	*Bidens pilosa*	Spanish needle
	Galinsoga parviflora	Gallant soldier
	Sonchus oleraceus	Sow thistle
	Vernonia sp.	Bitterleaf
Commelinaceae	*Commelina benghalensis L.*	Benghal dayflower
Euphorbiaceae	*Acalypha sp.*	Red cat's tail
	Euphorbia graminea Jacq.	Grassleaf spurge
Fabaceae	*Arachis repens*	Creeping peanut
	Fabaceae	Fabaceae
	Leucaena leucocephala	Jumbay
	Rhynchosia tomentosa	Twining snoutbean
Poaceae	*Zea sp.*	Corn
Rubiaceae	*Richardia brasiliensis*	Brazilian clover
Urticaceae	*Pilea microphylla*	Artillery plant

Chart 9 – Species identified in the experiment.

Figure 44 – Some of the spontaneous species identified. From left to right, top to bottom: *Zea sp.*, *Bidens sp.*, *Richardia sp.*, *Leucaena sp.*, *Acalypha sp.*, *Galinsoga sp.*, *Euphorbia sp.*, *Commelina sp.*

Results demonstrate that the shallowest substrate depth model, which could retain less water, initially hamper the spreading of species but provide sufficient conditions for spontaneous individuals to grow. A diversity of voluntary individuals rapidly grows (Fig. 44), and the first spontaneous species quickly colonise the models (Fig. 45).

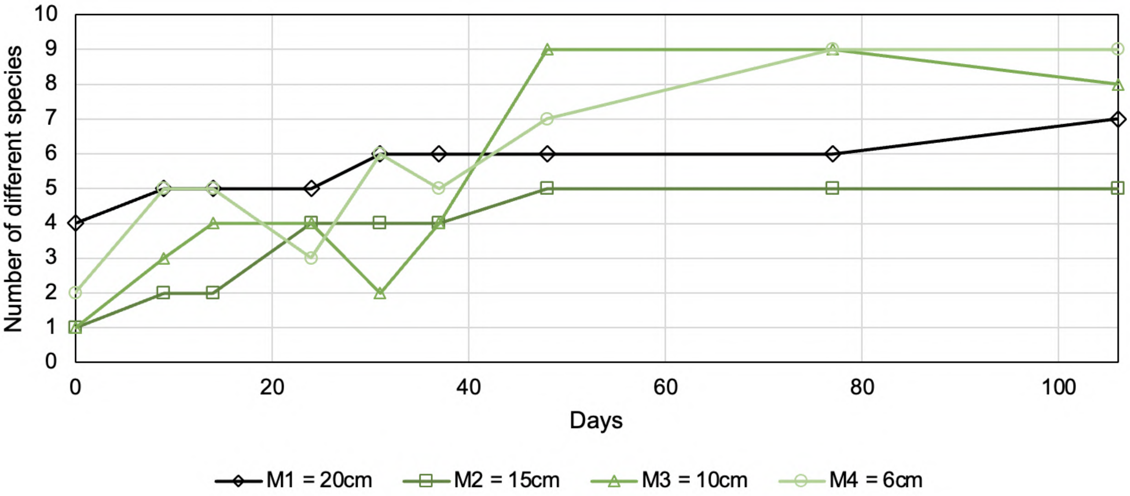

Figure 45 – Total plant diversity in the experiment.

8.4 Discussion

Vegetated roofs are a dynamic ecosystem that can change significantly depending on the surrounding environmental conditions (DUNNETT; NAGASE; HALLAM, 2008). Rainfall may not have influenced the present experiment much as there was a regular water income from the artificial irrigation system, but solar radiation did have an influence. The *Arachis repens* has an intricate system for closing and opening leaves, as seen in figure 46. This was observed to indeed be the reason why in higher radiation days the total plant coverage tends to diminish, as the A. repens movements modify to great extent their footprint.

Figure 46 – *Arachis repens* with open leaves (left) and closed leaves under high radiation (right).

The progression of spontaneous vegetation had close correlation to the plant coverage, especially from the *Arachis repens* initial culture. Contrary to what was expected, that is, the higher plant coverage with the lesser number of weeds, the opposite was observed. Weed interceptions grow as total plant coverage grows (Fig. 47). This may be explained by framing this analysis on the first months of growth, where there are still many gaps in the plant coverage being occupied by weeds, growing all together with planted individuals. Possibly this correlation changes when analysing a consolidated vegetated roof. Despite that, it is interesting to observe that as total plant coverage increases, the rate at which weeds appear increases the deeper the substrate. However, shallower substrates tend to house spontaneous individuals earlier.

Weeds may appear dispersed by wind, propagated by animals or from the soil seed bank (AMPIM *et al.*, 2010). It was possible to observe that in the last weeks, diversity

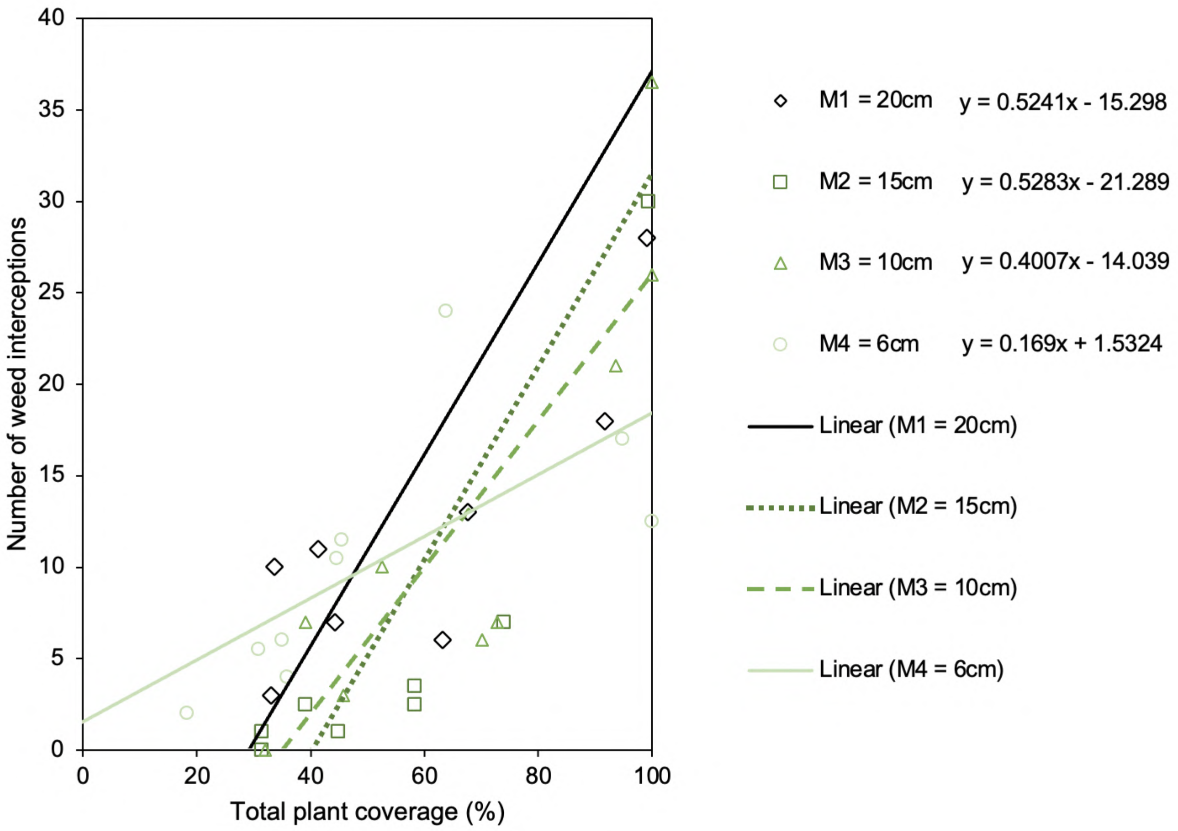

Figure 47 – Correlations between plant coverage and number of weed interceptions on each model using linear regression.

stopped increasing, though weed quantity continued growing. That indicates possibly a small set of individuals gaining preference, which may diminish the relative diversity to the total number of plants. The *Commelina benghalensis L.*, *Leucaena leucocephala* and the *Zea sp.* species had a high number of individuals in the end, being possibly the more aggressive groups. In this way, maintenance and pruning cannot be ignored for spontaneous vegetated roofs, controlling these groups.

Plants have traits and mechanisms that can facilitate their colonisation capacity of such small substrate vegetated roofs. Oliveira, Rodrigues and Oliveira (2021) indicates that plants with adequate root architecture for shallow substrates, and species that have pollinators and good vegetative propagation may have a better development. The authors also mention the ability of plants with succulency properties, which can make a specific photosynthesis process that enables them to colonise arid regions and also have stomata that close during the day, saving more water. Trichomes are a structure that can also help reflect part of the excessive radiation, decrease the thermal amplitude at the plant surface and capture water from the atmosphere, a trait that was observed in plants such as *Zea sp.* in the experiment.

Zea sp. colonised the roof during the last days of the experiment, but quickly represented a great proportion of total intersections. Another trait that seemed to support this aggressive colonisation was a mechanism which is also present in bromeliads: the ability to store water in their central tank (Oliveira, Rodrigues and Oliveira, 2021). Plants in the 60mm substrate demonstrated worse appearance regarding colour and leaves seemed less healthy, often with leaves more easily eaten by predators. Thus, the 100 mm demonstrated to be the lightest weight with great biodiversity and better initial succession and plant coverage, a finding which is coherent with previous research.

A limitation of the present research is that the botanical species here characterised may not simply be used anywhere. Species which are in harmony with a given ecosystem may be invasive to another. To address this limitation, it is suggested to investigate not species, but their mechanisms and capacities, which can be found in other native species in the area in which a desired spontaneous roof is being designed.

8.5 Conclusion

The present research showed an initial growth analysis of vegetated roofs with different substrate depths up to the point when total plant coverage was reached. The spontaneous dynamics and planted individuals' dynamics were characterised through time, generating quantitative and qualitative data. Spontaneous plants managed to colonise the roofs, though this colonisation has deep interconnection to planted individuals' dynamics. The work indicates the need for long-term research, which is planned to be undertaken for a range of seasons.

Under the experiment conditions, such as automatic irrigation, the shallow substrate roof of 6 cm has demonstrated to be a sufficient condition for biodiversity to propagate, however it had a generally worse performance in comparison to the other substrate depths. The 10 cm depth, though not the lightest analysed, may be a balanced solution between creating a better environment and still being lightweight.

Shallower roofs had greater diversity of species, as heterogeneity is a natural mechanism for collectively dealing with environmental pressures. These findings give rise to the need for analysing vegetated roof plants as communities and not only as individuals. Further work may also seek to indicate ecological relationships among individuals and not only plant mechanisms. Findings are relevant for practitioners and designers looking for green roof systems that can better adapt to local environmental pressures. Moreover, they also reinforce a more sustainable approach by demonstrating relevant vegetation growth and diversity in situations of minor maintenance and demonstrate potential for naturalist landscaping aesthetic interest.

9 Discussion

> Though all this may be true,
> flowers fall even if we love them,
> and weeds grow even if we hate
> them, and that is all.
>
> Sōtō Zen Master
> Eihei Dōgen Zenji
> (道元禅師, 1200-1253) in:
> *Shōbōgenzō*,
> tr. Gudo Wafu Nishijima, 1992

The present dissertation quantified the hydrological performance and plant dynamics of vegetated roofs under the humid subtropical climate of São Paulo. It was shown that the VR can have a positive effect on rainwater retention, peak runoff attenuation and peak runoff delay. By varying substrate depths, it was observed that even the shallower of the vegetated roofs still produced an expressive effect in the aforementioned indicators and deeper substrates produced a proportionally greater effect. In terms of vegetation dynamics, *Arachis repens* species managed to satisfactorily colonise the shallower substrate depths, but took longer to reach a considerable soil coverage. A successful progression of spontaneous species was also observed in all different substrates, which maintained a high biodiversity.

In this sense, the primary, secondary and tertiary research propositions stated in the first chapter were confirmed, albeit with limitations. The hydrological performance of a VR is highly correlated with permanent and dynamic structural and environmental factors. The plant dynamics is also deeply correlated to the level of maintenance in the VR, and a minimum management is necessary to upkeep biodiversity. Nevertheless, for any type of VR investigated, under any of the rainfall conditions and during the whole period of vegetation dynamics observed, the roofs presented strong capacities of generating Regulatory Ecosystem Services of habitat for species and rainwater management.

As for unexpected findings, there are some to point out. In chapter 5, it was exceptionally interesting to observe the different methods experimentalists in Brazil found to measure flow rate. Scientists used pressure, image recording, weighing and a range of solutions to find out retention and detention indicators. A flow rate method has been developed and tested for VR runoff quantification in the present work, which addressed the lack of inexpensive flow rate sensing instruments. In Chapter 6, where this method was tested on a pilot experiment, the flow rate sensing setup demonstrated to be exceedingly satisfactory for the proposed application. Chapter 7, the main chapter of this dissertation, concentrated the most interesting findings. It was unexpected to observe how unmanaged VR makes the soil moisture content lose correlation with substrate depth: vegetation grows according to water availability and increases transpiration, thus always removing the available moisture content. It was also interesting to observe the different substrate depth runoff curves, which made reviewing unsaturated soil mechanics aspects necessary in order to better understand the outcomes. Correlating the intensity of the rainfall event to the micro-dynamics of soil saturation unexpectedly enlightened the fact that rainwater has to take its time to fully soak a substrate. Finally, chapter 8 also brought unexpected results for vegetation. It was impressive to verify that the $10cm$ substrate had a very satisfactory result both on spontaneous and planted vegetation dynamics. The biodiversity of voluntary flora arriving was greater than expected, but the biodiversity of fauna also visiting the roofs was extraordinary.

To its significance, this study can shed light into interesting urban planning possibilities. The less structurally demanding shallow substrates can already promote some retention and detention. If a shallow roof can sufficiently delay the rainwater arrival to the public pluvial water system, then maybe greater substrate depths can be wasteful. To reach that conclusion, a scaling study should be undertaken, which can be started using the results presented in this work using the rational method. In this sense, the present investigation suggests for the city of São Paulo the use of a 10cm substrate to accomplish both hydrological, fauna and flora related Ecosystem Services in a sufficient way. Investigations on real VR should also be undertaken, and real scale VR may also provide the ability of varying substrate depths within one same roof, which can be immensely interesting.

A megalopolis of implications can be derived from the use of vegetation as a building envelope. To say the least, social and economical change can be a product of the change in paradigm of building cities not only for the human-nature, but for Nature as a whole. The examples of “Teto verde favela” (Fig. 48) and “RevoluSolar” (Fig. 49) show interesting consequences of VR applications. In the hot climate of Rio de Janeiro, dwellers use active air conditioning for cooling down indoors. But the surcharge in the precarious electric infrastructure increases fire risk, thus VR installation implies decreasing fire risk. For solar panels, VR can also increase the panel's performance by decreasing heat excess that reflects from the Sun to the bottom of the solar panels. More about these projects and their findings can be found in the figures' sources.

Figure 48 – Vegetated roof installed in the community of Parque do Arará in Rio de Janeiro, in the northern zone city slums, part of the "Teto verde favela" project.
Source: Robin (2019).

For vegetated roofs to reach a large-scale application public policies are necessary. Ways of incentivising the use of these roofs should be part of the urban planning process, as well as ways to train professionals and make innovative and affordable technologies available. The large application of such technologies should also be accompanied by norms and standardisation processes. This can support professionals to safely design and build these structures, as well as support the public sector to maintain quality control.

The use of Nature-based Solutions in the urban fabric should be a transdisciplinary process. The present work brought regulatory services quantifications and insights, and attempted to interrelate both roof and its environment as well as water, heat and vegetation. Nevertheless, many other optics should come into play for better understanding and evaluating the large-scale application of such technologies.

Figure 49 – Solar panels over a VR installed by the RevoluSolar project.

Source: Bildsten and Zárate (2019).

10 Conclusions

> Uniformity is not nature's way,
> diversity is nature's way.
>
> ---
>
> Vandana Shiva for:
> *The New Internationalist*, 1995

This chapter is divided into two sections. Section 10.1 will review the main specific conclusions of each of the main research chapters that are submitted to journals, namely chapter 5, chapter 6, chapter 7 and chapter 8. Section 10.2 brings a concise general conclusion addressing the main research questions brought up in chapter 1 and main outcomes of the present body of work.

10.1 Specific conclusions

In chapter 5, through an exhaustive review of the literature for water performance of vegetated roofs in Brazil, research gaps and trends were identified. The chapter outcomes were:

- → National literature written in Portuguese was summarised and translated for the international scientific community;
- → Though there is some experimental data available regarding the hydrological performance of VR, most experiments lack a quality approach regarding experimental setup or data analysis.
- → As internationally indexed literature was scarce, grey literature had to be explored;
- → Measuring flow rate was a difficulty in many of the works found, thus innovating towards inexpensive flow rate sensors can benefit the scientific community;
- → Research on the hydrological influences of substrate depth that clearly indicate rainfall runoff coefficients has never been done.

Thus, it is concluded that the scientific community can benefit from a robust and systemic hydrological experimental research for vegetated roofs in the humid subtropical climates of Brazil.

This chapter based the submission of the article entitled “Vegetated roofs rainwater management experimental research in Brazil: a georeferenced exhaustive review of a continental-size country” to *Renewable and Sustainable Energy Reviews*, Elsevier, in 2022.

In chapter 6 it is analysed the accuracy and precision of combining an ultrasonic sensor for water level measurement and a weir tank, in order to measure flow rate. Results are found comparing the proposed setup under a representative natural rainfall event with an *in situ* weather station. The combined instrument is useful for characterising the prototypes and models used in the present work regarding their runoff. Both after a natural rainfall or an artificial irrigation. The main conclusions are:

- → The proposed system is a cost-effective, reproducible and adaptable alternative to commercial flowmeters;
- → The system can measure a range of flow rates using the same sensor, but changing the weir tank design in regard to its volume and weir angle;
- → Being an inexpensive sensor with IoT abilities assists the practitioner in terms of maintenance and ease for leaving it unattended collecting data in public places;
- → Statistical analysis showed the system has excellent precision when compared to a commercial rain gauge from a local weather station;
- → Ultrasonic sensor correction for temperature and humidity variations were irrelevant within a short summer rainfall event analysis, but may be relevant when longer events are observed.

Thus, the chapter demonstrates that the ultrasonic system can reliably measure runoff flow rates from the prototypes and models built for the present research.

This chapter based the submission of the article entitled “Real-time sensing and low-cost experimental setup for water quantity investigation in Nature-based Solutions” to *Blue-Green Systems*, IWA Publishing, in 2022.

After a first rainfall event with a successful data collection, chapter 7 associates the ultrasonic sensor for flow rate with other sensors and a more complex experimental setup towards a better representation of the retention and detention from vegetated roofs.

Two experiments are undertaken. Experiment A analyses the rainfall-runoff from an extensive vegetated roof (VR) masonry prototype and compares it to a ceramic tiled (CR) roof masonry prototype. The green roof in this experiment is unmanaged and does not have an artificial irrigation system. Experiment A conclusions are:

- → A comparative water budget between the VR prototype and the CT prototype shows an expressive water retention and detention from the vegetated roof;
- → The VR prototype managed to retain 34% to 100% of the rainwater, depending on the rainfall event analysed;
- → The VR prototype managed to delay 14 to 37 minutes the peak runoff, depending on the rainfall event analysed;
- → The VR prototype managed to decrease by 30% to 100% the peak runoff, depending on the event analysed;
- → The retention depth (mm of rainfall retained) for events that generated runoff lied between $4.2mm$ to $12.9mm$, depending on the event analysed.
- → Runoff in the VR prototype varies at each event, as it is highly dependent on the initial conditions of that given rainfall event, namely the internal substrate moisture content. The moisture content is, furthermore, a consequence of the surrounding temperatures, humidity, solar radiation and of the plants evapotranspiration rate;
- → Slow-steady rainfall decreases roof retention more than a short and intense one.

Given that retention and detention are highly dependent on soil moisture content, a second experiment was carried out. Experiment B analyses the rainfall-runoff in extensive vegetated roof (VR) models with different substrate depths. In experiment B, rainfall was substituted for a controlled irrigation system with a known flow rate input, vegetation was left undisturbed and soil moisture content was measured before each event. Irrigation was turned on until runoff reached a stable peak. Experiment B conclusions are:

- → As substrate depths increased, so increased the time necessary for reaching peak runoff;
- → As substrate depths increased, peak runoff rates decreased;
- → As previous moisture content decreased, the time necessary for reaching peak runoff increased;
- → Peak runoff rates remained the same after a long time, independent of previous soil moisture content or substrate depth;
- → Within the same model, increases in its soil moisture content can represent up to 13% less retention performance and 59% less peak runoff delay;
- → In unmanaged green roofs previous soil moisture lose correlation to substrate depth;

- → The hydrological performance of vegetated roofs, hence, is not only dependent on its structural factors (such as substrate depth, substrate composition, slope, vegetation type, drainage layer, geometry etc.) but also on its initial internal moisture conditions.

This chapter based the submission of the article entitled "Ten-years unmanaged extensive green roofs and the effects of substrate depth: a comparative water quantity performance investigation in Brazil" to *Journal of Hydrology*, Elsevier, in 2022.

Utilising the same experimental setup of VR models with different substrate depths, a third experiment, experiment C, was undertaken. In chapter 8 the first months of vegetation growth were documented quantitatively and qualitatively, in order to characterise planted and spontaneous dynamics using the Point-intercept method. The models were left unmanaged, but with abundant daily artificial irrigation. Experiment C conclusions are:

- → Total plant coverage was reached about 110 days after first landscaping;
- → The 100mm depth substrate had better plant coverage throughout the experiment;
- → Spontaneous plant interceptions grew as the total plant coverage grew, different from previous works. This phenomena may have happened because only initial conditions were analysed, a moment when there are yet many gaps;
- → 14 different spontaneous species colonised the models and were identified;
- → These voluntary individuals demonstrated interesting mechanisms for drought and excessive radiation resistance such as trichomes and central water retention tanks;
- → Shallower roofs had greater diversity of species, as heterogeneity is a known natural mechanism for collectively dealing with environmental pressures, if analysing plants not as simple individuals but as a community.

This chapter based the submission of the article entitled "Unmanaged tropical green roof spontaneous vegetation dynamics: effects of substrate depth" to *AGATHON International Journal of Architecture, Art & Design*, AGATHON, in 2022.

10.2 General conclusion

The research confirms the main hypotheses, adding limitations and practical implications. Vegetated roofs can indeed support the management of rainwater in the urban built environment and create habitat for a variety of fauna and flora species. Shallower and lightweight substrate depths indeed demonstrated a smaller contribution towards regulatory services of water retention and detention, but still managed to provide habitat for species without implying substantial loads for its sustaining slab. Spontaneous species could also successfully colonise the vegetated roofs, but the experiments demonstrated that some level of management is indicated. If not managed, some species may aggressively take on the whole ecosystem, turning a heterogeneous roof into a monoculture.

The research investigated the hydrological performance of vegetated roofs, a type of Nature-based Solution. There are many different optics to investigate and many different Ecosystem Services that NbS can provide. In order to achieve a strong urban transformation towards greener cities, it is mandatory to analyse all types of Nature-based Solutions for each case as a systemic intervention that can admit different forms. In some cases vegetated roofs will be the best option, but stormwater planters, wetlands, vegetated walls, community gardens and many other forms of Nature-based Solutions may be more interesting in other cases. Ecosystem Services can be the metrics to better enlighten which of the possible NbS is the best for each place.

Events analysed had small return periods and also low intensity, having no overflows been observed. It is relevant to indicate that in large return periods, that is in intense and not so frequent events, Nature-based Solutions may not provide services as interesting for drainage. If overflow starts happening, a vegetated roof will function as any other conventional roof. In this sense, it is important to note that the Green Infrastructure should always be thought as a collaborative tool to work together with Grey Infrastructure, not a substituting solution.

Extensive vegetated roofs with spontaneous species can provide relevant water regulation services and habitat for species in the humid subtropical urban environment, without occupying competitive ground level areas. But in many cases, the disordered use of engineering structures may cause underperformance. In this sense, it is relevant involve competent professionals in order to properly plan and design Nature-based Solutions. These technicians will be able to correctly account for less expected and not so frequent natural phenomena and also to correctly gear green and grey infrastructure together.

To work for real change, it is mandatory that we face the city as it is and not as we want it to be. Green infrastructure will not be mainstreamed overnight and small NbS may not be capable of dealing with events of large return periods under urban conditions. The correct understanding of this is crucial for an harmony between the given reality as it is and each of our individual utopias. The first step for a greener city is putting on your shoes and walking around your city as it is. What do you see?

11 Further work

> Science cannot solve the ultimate mystery of nature. And that is because, in the last analysis, we ourselves are part of nature and therefore part of the mystery that we are trying to solve.
>
> Max Planck in dialogue with
> Albert Einstein in:
> *Where is Science going?*, 1932

Further work is mainly related to sensor improvement, data logging improvement, extended periods of data collection, and interdisciplinary research in order to continue the present investigations.

Some of the sensors used did not read the expected phenomena. Soil moisture sensors were purchased for real-time data acquisition but did not function as planned. In this sense, adding sensors for real-time soil moisture content can positively impact the reliability of the outcome, as it would then be possible to read real rainfall events and not only simulated rain using an irrigation system. Observing real rainfall events can influence outcomes, as convectional rainfall may change, *e.g.* air pressure, wind dynamics, air temperature, and cloud presence can absorb shortwave radiation.

Still, further development of low-cost sensors can be positive for sensor improvement. Expensive commercial sensors can generate very reliable data but are costly to be installed for real-time data collection in public places. An extensive set of low-cost sensors can provide redundancy on data acquisition, thus reducing errors and generating reliable data, allowing their assembly in public places if the Internet of Things (IoT) is used. Such a setup can be useful for data acquisition from real structures.

As a still blank spot in this work for water and heat dynamics understanding, evapotranspiration (ET) is a demanding topic. For acquiring this data, lysimeters can be used to assess ET by measuring the model weight through time. However, this technique is challenging to implement in a real structure. Thus, innovative ways to address this subject have been appearing, and the use of infrared imagery can take a path.

Regarding data logging, further implementing IoT capabilities is also interesting. The present work was thoroughly carried out in a COVID-19 pandemic scenario, rendering difficult the access to the University laboratory facilities. Having real-time data acquisition and online data logging can be interesting to avoid unnecessary visits to the laboratory, but periodic checks on sensor working conditions cannot be underestimated.

The present work collected data from the summer and autumn periods. A year-long experiment should be undertaken to better express the real pressures these structures are subject to, as winter conditions may bring different conclusions.

As interdisciplinary research, there is a lot to be investigated. Environmental and Civil Engineering fields should exchange a lot with Botany, Ecology and Agricultural Engineering. There is still a lot lacking in understanding best practices for which plants to be used to colonise vegetated roofs in given ecosystems — more than that, understanding which morphological aspects and ecological mechanisms may help plants colonise these environments.

Social aspects of vegetated roofs need to be further understood. Better perceiving how low-income families can use such a structure in their homes is a must for mainstreaming the use of vegetated roofs. Also, Environmental Economic fields may be able to use Ecosystem Services to justify and quantify how to split the costs of a novel vegetated roof among the building owner, neighbours, and even local authorities.

Recalling the introductory discussion on scale transpositions, vegetated roofs may provide relevant retention and detention capabilities, but further investigation must be done for an urban scale rainwater management. Deep substrate depths may not be necessary, for example, to sufficiently retard the runoff peak discharge.

Hence, as future possible innovative researches:

- → Low-cost sensor development for real-time IoT data capture in real structures regarding water quality, quantity, soil moisture and heat.
- → Quantifying the evapotranspiration (ET) of Blue-Green Infrastructure using thermal infrared cameras. Drone and satellite data capture can be used.
- → Modelling the water and heat dynamics of Blue-Green Infrastructure and associating these two dynamics, especially regarding ET.
- → Plant mechanisms and plant morphology aspects that can provide bases for successfully colonising shallow substrate depth vegetated roofs.

- → Implementation and case studies of retrofitting buildings using vegetated roofs that did not need structural reinforcement or further roof waterproofing.
- → Vegetated roofs rainwater management from building scale to basin-scale analysis using computer simulation.

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APPENDIX A – Open access data

Full datasets collected during laboratory research and reviewing processes are publicly available via a Digital Object Identifier on Mendeley Data. Each dataset can be accessed in the respective URL provided below:

- → Chapter 5: dataset of quantitative and qualitative aspects of the works reviewed and values of C and RR indicators. Access via the DOI 10.17632/drwcvjwv3s.2.
- → Chapter 6: dataset of water level measurements for testing the accuracy of the proposed weir tank. Access via the DOI 10.17632/kdvw2vhxbf.2.
- → Chapter 7: dataset for Experiment A and dataset for Experiment B. Access via the DOI 10.17632/p942b9vkhs.2.
- → Chapter 8: dataset for Experiment C. Access via the DOI 10.17632/36cp9kzsrf.2.

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