Live Pole Drains for Cities (LPD4C)

An easy-to-build Nature-based Solution (NbS) alternative to conventional Sustainable Drainage Systems (SuDS)

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A thesis submitted for the Joint programme of
Master in Urban Climate & Sustainability

September 2022

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Publication type
Thesis

Completion year
2022

Number of pages: 120

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Title

Live Pole Drains for Cities (LPD4C): an easy-to-build Nature-based Solution (NbS) alternative to conventional Sustainable Drainage Systems (SuDS)

Degree: Master in Urban Climate & Sustainability

Abstract:

Rapid urbanization and the intensification of weather events due to climate change are only some of the drivers altering the water cycle in urban environments. Consequently, the total volume of stormwater runoff rises together with its frequency and severity, placing human life, infrastructure and environment under risks, increasing vulnerability against landslides and floods. Live Pole Drain (LPD), a less known Sustainable Drainage System (SuDS), is a plant-based drainage system deployed to drain the excess of surface water, to regulate the water budget in the soil, and to promote ecological succession and landscape restoration. Even though LPDs have a great potential for cities, they have not yet been explored in urban settings due to a severe lack of evidence on LPD eco-hydrological performance. Therefore, the aim of this thesis is to propose LPD as an original NbS alternative to conventional SuDS for regulating the water budget in the urban environment. In this context, the developed Live Pole Drain for Cities (LPD4C) framework (i) provides information on the main environmental criteria for LPD creation within cities; (ii) delivers guidelines for LPD design and construction; and (iii) delineates the steps to assess the eco-hydrological performance of LPD. Through a combination of eight environmental criteria in a spatial, multi-criteria analysis, results demonstrated that 28% of Glasgow City (Scotland) presents optimal conditions to accommodate LPDs. Among the vacant and derelict land owned by Glasgow's Local Council Authority, 48% of its surface area have great suitability to receive LPDs. Key findings of the eco-hydrological performance of LPDs observed during a pilot laboratory experiment showed that this Nature-based Solution is effective towards urban flooding mitigation. Particularly to LPDs hydrological performance, this research identified that LPDs, at certain design and environmental conditions, can decrease surface runoff up to 90% and water retention up to 54% when compared to fallow soil, while subsurface flow and percolation are increased up to 170% and 150%, respectively. This research also provided the design for the first LPD within a city. Through a combination of the opportunity sites for LPD creation map with the assessed eco-hydrological performance of LPD, the design showed that the LPD has a great hydrological potential under wetting soil conditions at an urban plot-scale. Interpretation of this analysis suggests that the designed LPD could be implemented to reduce the volume of surface runoff, while acting with functions observed in subsurface flow wetlands (i.e., phytoremediation). Moreover, this study successfully built pioneering evidence on LPDs eco-hydrological performance, which now supports LPDs as a suitable solution to mitigate urban flooding in cities. Within the LPD4C scope, the findings of this research support climate change adaptation in urban environments, especially to address natural hazards such as soil erosion, shallow landslides, and floods. The strategies and recommendations for further LPD adoption throughout cities herein presented can be useful for urban planners, environmental managers, policy makers, decision-makers, and contractors during the planning phase of projects seeking to manage flood hazards whilst enhancing the natural value of the urban environment. Specifically, this study delivered information for implementation of the first ever seen LPD in a city.

Keywords

Live pole drains, sustainable drainage system, nature-based solutions, urban flooding, surface runoff.

Originality statement. I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited and referenced, has not been submitted elsewhere in fulfilment of the requirements of this or any other award.

Signature

ACKNOWLEGMENTS

I would like to firstly thank the ERASMUS+ Programme consortium for the opportunity to take part in the MUrCS programme. To do a master’s degree in an international environment was something I was chasing for a long time, and MUrCS allowed me to fulfil my goal. Beyond *a thing to cross in a to-do list*, it was an adventure in which I could improve myself professionally and personally while having amazing experiences with people I got to know along the way.

My deepest gratitude goes to my supervisor Dr. Alejandro Gonzalez Ollauri for his continuous support, guidance and encouragement during the development of this study. Thank you for the many, *many*, hours in which we could exchange ideas to try to reach the best outcome possible for my research.

I would like to thank Prof. Rohinton Emmanuel for introducing me to the Operandum Project last year. During the internship, the first ideas for this research were drawn. I would also like to extend my gratitude to Dr. Denise Duarte, my second supervisor, and to Prof. Slobodan Mickovski for the support during this semester. Further, I want to thank Eefje Benschop and Lucie Podevin for the collaboration, help, and many hours shared in the lab. Without you, the lab experiment would not have been the fun experience as it was.

I offer a *special, full of shiny stars and colours* thanks to Sayontoni. *Girl*, living with you during MUrCS was one of the best experiences I had during these two years. Thank you for all the exchanges, company and your special sass. *I live for it!* My gratitude also goes to Arooj, Luke, Mushfik, Saloni and Samson for all moments shared during the MUrCS journey. Each of you have impacted my life in a very special way and I am glad I got to know you.

I want to thank my mother and sister for believing in myself and supporting me to achieve my goals. A special thanks to my friends Nicole, Natana and Cecília who have been supporting me for many years.

Finally, I am deeply grateful to Rodrigo. Thank you for the understanding, support and encouragement for me to take part on this master’s programme and during my studies. Thank you for making me laugh when things were *a bit hard.* Living apart during these two years was not easy but I truly believe that it made us stronger. *Amote.*

I dedicate it to my cat.

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1 INTRODUCTION

1.1 Rationale

Rapid urbanization and the intensification of weather events due to climate change are only some of the drivers leading to an unbalanced water budget in the soil. Specifically, alterations in the water cycle in urban environments are related to, but not only, two man-made interventions. First, changes in land cover together with removal of vegetation expose soil and affect the soil-plant-atmosphere continuum (SPAC), resulting in an excess of water in soil during rainfall events, increasing surface runoff, erosion, and slope instability. Second, strong impermeabilization of catchment surfaces decreases soil infiltration and storage of rainfall water. Consequently, the total volume of stormwater runoff rises together with its frequency and severity, placing human life, infrastructure and environment under risks, increasing vulnerability against landslides and floods. Thus, there is a need for mitigating and building resilience against the impacts of climate change through efficient drainage systems capable to balance the water budget in the soil, mitigating flood, landslide, and erosion hazards in the urban environment and elsewhere.

In this context, Nature-based Solutions (NbS) are an emerging concept which establish a green alternative to conventional grey infrastructure. The latter is mainly designed to control water quantity redirecting stormwater runoff away from urban environment as fast as possible though drainage, conveyance, and storage systems (Scottish Water, 2018) without providing any additional services or benefits to human communities. In addition, while conventional infrastructure is no longer able to cope with the increasing intensity and frequency of rainfall events and derived natural hazards by itself (Chen *et al.*, 2021), NbS are alternative solutions to drainage systems. NbS are inspired and supported by nature, offering solutions to sustainability challenges (European Commission, 2021). NbS provide environmental, social, and economic benefits (Zhang *et al.*, 2021), enhances biodiversity (Oral *et al.*, 2020) and helps building resilience against climate change within cities (Depietri and McPhearson, 2017).

Under the NbS' umbrella one could place the so-called Sustainable Drainage Systems (SuDS). SuDS are surface water drainage systems based on the principles of sustainable development and developed to offer a more comprehensive alternative for stormwater management than conventional drainage systems (Johnson and Geisendorf, 2019). SuDS aim to minimise the quantity and to manage the quality of surface runoff, while maximizing amenity and biodiversity opportunities at the local urban scale (Ballard *et al.*, 2015) through hydrological and ecological processes. As a sustainable strategy that has been applied

worldwide, SuDS are acknowledged by a range of terminologies including, but not limited to, Best Management Practices (BMPs) and Low Impact Development (LID) in the United States, Water Sensitive Urban Design (WSUD) in Australia and Sponge City in China (Fletcher *et al.*, 2015). Herein, the term SuDS is used to represent all the above systems, following policies and guidelines applied in the United Kingdom.

SuDS comprise the application of green roofs, infiltration and bioretention systems, swales, filter strips and drains, and wetlands (Ballard *et al.*, 2015) as components of a system designed to maintain water in an urban catchment for as long as possible, or to partially recover water fluxes and water quality back to the pre-development state. More than improving the hydrological conditions, SuDS are receiving greater importance due to increased acknowledgment of their positive effects on economic, social, and environmental aspects (Zhou, 2014; Seddon *et al.*, 2020). For example, SuDS can increase property value and promote community engagement in making a better place to live (Ashley *et al.*, 2018). They can enhance human contact with nature (O'Brien, 2015), delivering wider benefits by improving health and wellbeing (Panno *et al.*, 2017). Moreover and, though it is recognised that these NbS cannot lead to the formation of pristine environments (Rae *et al.*, 2019), SuDS can improve biodiversity by providing habitat and by potentially connecting isolated populations of flora and fauna (O'Brien, 2015). Therefore, implementing SuDS for sustainable drainage in urbanised areas is an opportunity to promote human wellbeing, to build resilience to climate change, to manage floods, erosion, and landslides, and to mitigate other impacts derived from climate change (e.g., heat island, biodiversity loss).

Also under the NbS' umbrella, Live Pole Drain (LPD) is a less known SuDS but with great potential for urban, rural, and remote natural areas. LPD is a plant-based drainage system deployed to drain the excess of surface water, to regulate the water budget in the soil, and to promote ecological succession and landscape restoration (Polster, 1989; Campbell *et al.*, 2008). LPD is built by placing tied cylindrical bundles of live woody cuttings (i.e., fascine; Sotir and Fischenich (2001)) with re-sprouting properties (i.e., plants capable of throwing shoots and roots from live cuttings and branches such as willow (*Salix* sp.), poplar (*Populus* sp.), and ash (*Fraxinus* sp.); Schiechtl and Stern (1997)) into a shallow trench. As rainfall occurs, stormwater runoff and debris reach and permeate the system, establishing an initial cover on site. Over time, the plant bundles start rooting in the LPD, leading to the establishment of a SPAC in the LPD (e.g., Rodriguez-Iturbe and Porporato (2005)) where there is water uptake — i.e., regulating the soil water budget through evapotranspiration — and nutrients uptake for further shoot and growth of new growths, and provision of overall mechanical stability to the LPD through soil-root reinforcement (e.g., Gonzalez-Ollauri and

Mickovski (2016)). In a later stage of maturity, LPD delivers landscape and ecosystem restoration providing co-benefits to humans and wildlife (O'Brien, 2015; Russo and Holzer, 2021).

LPD has been traditionally applied in rural sloping areas or remote areas (i.e., mountain slopes) as a soil bioengineering technique (e.g., Campbell *et al.* (2008) and Stokes *et al.* (2014)). Soil bioengineering solutions are mainly applied on unstable slopes (Schiechtl and Stern, 1997) and consider the application of live plants and parts of plants into the ground building structures that provide mechanical support to soil and act as hydraulic drains (Gray and Sotir, 1996). Moreover, these solutions are feasible, self-repairing, resilient, ecologically functional, and normally more efficient and cheaper than grey infrastructure (Mickovski, 2021). By employing plants as living building materials, bioengineering techniques improve soil conditions as a result of vegetation mechanical, ecological, and biological properties (i.e., root systems provide underground soil reinforcement while foliage and stems provide surface protection from scouring; Mickovski and van Beek (2009); Mickovski *et al.* (2009), Gonzalez-Ollauri and Mickovski (2017c)).

Despite the great eco-hydrological potential of LPD, it has not yet been explored in urban settings. LPD can be easily built and replicated — favouring community engagement throughout LPD's life cycle — and uses locally available materials without the need of heavy machinery, resulting in a low-cost opportunity to address problems of excess of soil moisture, surface runoff, erosion, and slope instability (Schiechtl and Stern, 1997; Campbell *et al.*, 2008). Since LPD provides benefits aligned with NbS and SuDS philosophies (Ballard *et al.*, 2015; European Commission, 2021), it is a promising alternative for urban environments facing erosion, landslide, and particularly, flooding hazards. Based on the latter, the city of Glasgow (Scotland) could profit substantially from the strategic implementation of LPDs. The city has one of the highest rainfall rates in the UK (Met Office, 2022) with a 68% risk of surface water flooding (SEPA, 2015).

However, to the author's knowledge, there is a severe lack of evidence on LPD's performance. This could be due to the lack of an integrated framework that collects the myriad processes within the LPD SPAC. In addition, standard protocols for LPD design and construction do not yet exist. Therefore, urgent research is needed to gain insights into the eco-hydrological performance of LPDs and their ability to provide co-benefits and ecosystem services to human communities, and to establish standard approaches of design and construction that enable upscaling and reproduction. This research seeks to fill these knowledge gaps. To do so, a LPD framework needs to be developed as it is crucial to set the basis for understanding the processes occurring at the LPDs SPAC, and how these

relate to the environment. Based on this, a later eco-hydrological performance assessment would be possible. Moreover, an LPD framework would set the foundations for the effective design and construction, informing urban planners, decision-makers, and contractors in future replications within an urban setting. For the latter, it is essential to identify the environmental criteria for finding opportunity sites for implementing LPDs within a city. This can be achieved combining spatial analysis and Multi-Criteria Analysis (MCA).

1.2 Aim and Objectives

Following the hypothesis that LPDs can be effective within cities, the overall aim of this research is to propose LPD as an original NbS alternative to conventional SuDS for regulating the water budget in the urban environment. To this end, a holistic framework depicting the eco-hydrological processes occurring at the LPD SPAC will be created. This framework will inform the key environmental criteria for LPD creation to facilitate land suitability assessments for LPDs within urban setting, encouraging their replication and upscaling as a suitable SuDS. In addition, the LPD framework will delineate the steps striving to assess the eco-hydrological performance of this NbS.

To attain this aim, the following objectives are set:

1. To develop the first LPD framework, which will inform LPD design, set the basis for land suitability assessment for LPD creation and for eco-hydrological LPD performance assessment.

Objective 1 will be achieved through a literature review identifying (i) the eco-hydrological processes and its variables, and their interactions within the SPAC; (ii) the LPD design and construction guidelines; and (iii) the environmental criteria and variables for LPD creation within the urban setting.

2. To devise and test an approach helping identify opportunity sites for LPD creation at urban scale.

Based on the gathered environmental criteria in Objective 1, Objective 2 considers the application of a Multi-Criteria Analysis (MCA) and secondary data to assess land suitability for opportunity sites for LPD creation at urban scale. For this objective, Glasgow (Scotland, UK) will be set as case study.

3. To assess the LPD performance through the key eco-hydrological processes.

Derived from the LPD framework defined under Objective 1, Objective 3 will be accomplished through a pilot laboratory experiment under controlled environmental conditions to collect primary data and to analyse the eco-hydrological performance of LPDs.

4. To evaluate urban land suitability and capacity to accommodate LPDs.
5. To provide further strategies and recommendations for future replications and upscaling of this NbS in the urban environment.

Objectives 4 and 5 will be achieved based on the findings from the previous objectives, providing strategies and recommendations on design and construction of LPD into urban settings and further studies contributing to the effective upscaling of this NbS.

1.3 Disposition of the Thesis

This dissertation is structured into six main chapters as follows:

Chapter 1 states the problem and its significance, provides an overview of the scope of the study, and describes the aim and objectives.

Chapter 2 presents a review of the available literature on LPDs, identifies knowledge gaps, and gathers information to create the LPD framework.

Chapter 3 outlines materials and methods applied throughout this research. It presents the case study area and provides details on data collection, data processing and data analysis.

Chapter 4 contains the results obtained under the spatial, multi-criteria analysis for LPD creation and under the LPD eco-hydrological performance assessment. The chapter also includes an integration analysis, which combines results found through applied methods to exemplify their applicability at an urban plot-scale.

Chapter 5 assembles the key findings of this research, comparing them with previous studies and reflecting on their upscaling and implications for urban planning practice to mitigate urban flooding. The chapter also highlights the limitations and recommendations for future studies on LPDs and expansion of the LPD framework.

Chapter 6 provides the conclusions of the study.

2 LITERATURE REVIEW

2.1 Live Pole Drain (LPD)

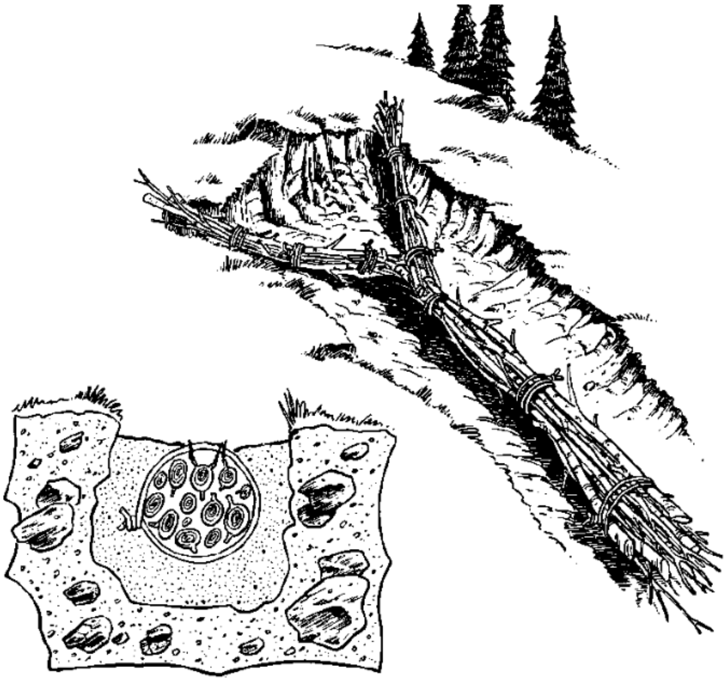
Live Pole Drain (LPD) is a plant-based, drainage system that aims to remove the excess of surface water and soil moisture, and to regulate the soil water budget. LPD is a soil bioengineering technique that has been reported as an effective measure to restore sloping landscapes (Campbell *et al.*, 2008; Stokes *et al.*, 2014). Yet, there is severe lack of evidence on LPD performance, and standard design and construction guidelines do not yet exist. As a result, LPDs are generally unknown by practitioners and researchers, and they have a limited adoption as SuDS.

Herein, the review of the available information on LPDs is based on textbooks, grey literature, and reports of previous successful implementations. It is worth noting that, to the author’s knowledge, scientific studies on LPDs do not yet exist. The literature review conducted herein will (i) help grasp basic features of LPDs; (ii) set the knowledge gaps that need addressing for effectively assessing the performance of LPDs; (iii) and determine the basis for their replication and upscaling into the urban environment.

2.2 LPD as a Soil Bioengineering Technique

LPDs are built from tied bundles of live, tree/shrub cuttings placed within a shallow trench. The bundles are normally fixed to the ground using live stakes or reinforcing steel bars (Sotir and Fischenich, 2001). Both cylindrical bundles — also known as live fascines — and stakes are made of live branch cuttings from woody plants with easy rooting and propagation properties, such as willow (*Salix* sp.), poplar (*Populus* sp.), and ash (*Fraxinus* sp.; Schiechtl and Stern (1997); Polster (2007)). While Polster (1997; 2003a; 2003b) defines LPD as a technique deploying live fascines in a herringbone pattern (Figure 2.1a), SRCD (2005) and Campbell *et al.* (2008) present LPD as a structure formed by three soil bioengineering techniques: lives fascines, pole drains and live staking (Figure 2.1b),. Depending on site conditions and on the purpose of the intervention, these three techniques might be applied separately or combined. When combined, they result in the so-called LPD. The definition of LPD from SRCD (2005) and Campbell *et al.* (2008) is adopted throughout this Thesis, since its broad characterisation gives comprehensive and detailed information.

(a)



(b)

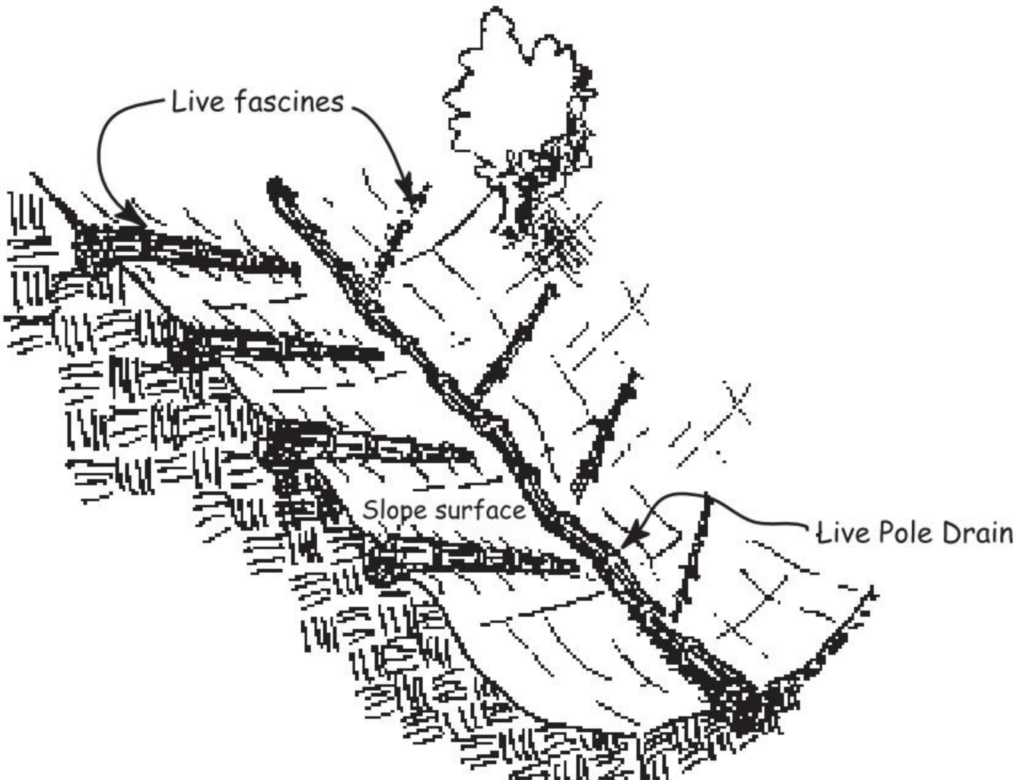


Figure 2.1 Live pole drain. (a) Herringbone pattern by Polster (2003a); (b) Herringbone pattern by SRCD (2005).

2.2.1 Live Fascines

Live fascines (Figure 2.1b; Figure 2.2) are cylindrical bundles of live woody cuttings with re-sprouting properties (i.e., plants capable of throwing shoots and roots from live cuttings and branches; Schiechtl and Stern (1997); Polster, (2003a)). The key functions of live fascines are (i) to retain debris, while (ii) enabling water to flow by diverting surface runoff and subsurface water through retention and infiltration, and (iii) to encourage plant development and landscape restoration. Live fascines are installed following the slope contours in slopes with low to moderate surface water flows. In areas with seepage and high surface water flow, live fascines are installed normal to the slope gradient (i.e., chevron pattern), helping to slow down surface runoff (SRCD, 2005; Campbell *et al.*, 2008). When directly deployed within shallow trenches on the slope, live fascines readily provide mechanical reinforcement to the surface soil (Campbell *et al.*, 2008). The latter increases slope stabilisation through soil binding once rooting from the cuttings starts (Schiechtl and Stern, 1997).

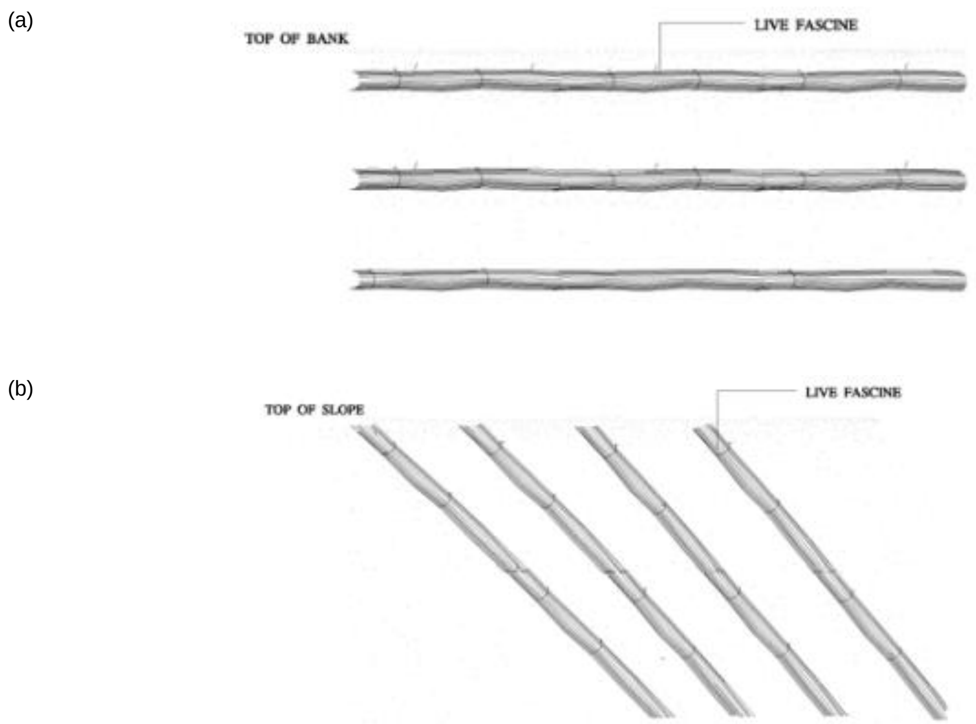


Figure 2.2 Live fascines. (a) Live fascines following slope contour; (b) Live fascines in chevron pattern. Source: SRCD (2005).

2.2.2 Pole Drains

Pole drains are, in essence, live fascines made of larger bundles. While live fascines are made of bundles with a cross-section diameter of 150-300mm, pole drains are made of bundles with a diameter of 300-500mm (Schiechtl and Stern, 1997; Campbell *et al.*, 2008). Pole drains are also deployed on the slope but following a different arrangement than for live fascines. This soil bioengineering technique is traditionally built following existing drainage paths or small gullies formed by seepage, with the aim of collecting and redirecting water flow down the slope. When combining a pole drain with live fascines, the latter connects obliquely with the former, resulting in a herringbone design (Figure 2.1a). Depending on site characteristics, additional live fascines can be deployed along the pole drain, improving drainage and landscape restoration (Figure 2.1b; SRCD (2005); Campbell *et al.* (2008)).

2.2.3 Live Staking

Live staking is a soil bioengineering technique consisting in inserting live stakes — also called live poles — made from live branch cuttings into the ground (Polster, 2013). Live stakes contribute to immediate mechanical reinforcement by providing a structural component able to reinforce the soil through the so-called pull-out force (Ennos, 1990), strengthening the soil by binding the soil particles once live stakes start rooting (Schiechtl and Stern, 1997). When applied in an LPD, live stakes are deployed between the bundles to anchor them firmly to the ground within the trench down the slope (Schiechtl and Stern, 1997). With further root development, live stakes assist to the removal of excess of soil moisture (Campbell *et al.*, 2008), debris retention, and soil-root reinforcement, contributing to drainage, erosion control, and additional slope stabilisation (Lindsay, F.; Mickovski, 2015).

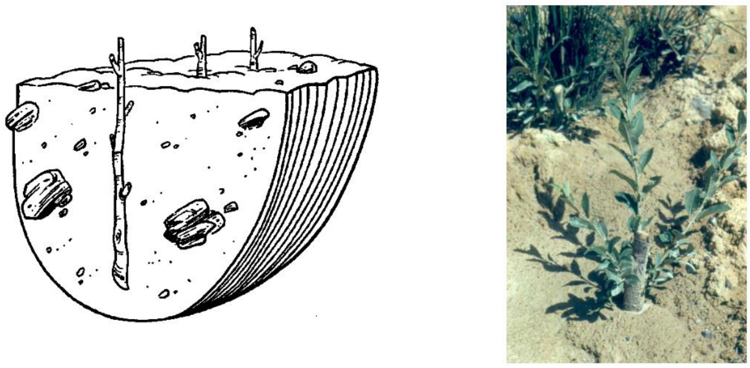


Figure 2.3 Live staking. Source: Polster (2013).

2.3 Lack of Evidence on LPDs

As independent soil bioengineering techniques, live fascines and live stakes have been studied separately. Li, Zhang and Zhang (2006) analysed the potential of live fascines to stabilise and restore riverbanks, endorsing that, with the presence of plants, soil shear strength increased significantly due to plant root's ability to bind soil particles together (e.g., Gonzalez-Ollauri and Mickovski (2017c)); and Recking *et al.* (2019) tested the performance of live fascines through laboratory tests simulating the early stages after implementation (i.e., when roots and resprouting had not yet started) for riverbank protection. These authors concluded that live fascines can be effective indifferent of the volume and rate of flow discharge.

Regarding live stakes, Prasad *et al.* (2012) corroborated that they can provide soil mechanical reinforcement immediately after deployment, providing further slope stability as the root system develops (e.g., Gonzalez-Ollauri and Mickovski (2016); Gonzalez-Ollauri *et al.* (2021)). Prasad *et al.* (2012) also noted higher suction and lower moisture in soil under live stakes than without intervention, concluding that live staking is effective upon decreasing the susceptibility of shallow slope failures. Kamchoom and Leung (2018) simulated the hydro-mechanical reinforcement potential of live stakes throughout distinct stages of stake development. The authors confirmed a strong relationship between live stake transpiration and slope stability due to an increased soil suction by plant uptake, resulting in slope stabilization. Although these studies confirm live fascines and live stakes' potential to improve soil stability and to restore landscapes, literature review demonstrates lack of research on these solutions working together as components of LPD as a bioengineering technique.

2.4 LPD as a Sustainable Drainage System (SuDS)

The key aim of LPD is to regulate the soil water budget, making LPD a potential good alternative to traditional urban-based SuDS. However, and as highlighted before, no research on LPDs as a soil bioengineering technique has been found. As a result, there is a substantial research gap on LPDs in general, and on their performance as NbS, in particular. However, previous research on other NbS with similar underlying features and processes, such as Subsurface Flow Wetlands (SFWs), could provide some insights into the multifunctional performance of LPDs.

In general, wetlands are vegetated bodies of water traditionally deployed to remove contaminants from municipal wastewater or stormwater runoff. Through assessment of phytoremediation performance (i.e., the use of plants to extract, mobilize or degrade contaminants; McCutcheon and Schnoor (2003); Jørgensen and Fath (2008)), Vervaeke *et al.* (2003) concluded that willows have the potential to degrade organic contaminants such as mineral oil and poly-aromatic hydrocarbons (PAHs) due to a dense root system stimulating microbial activity. Vymazal *et al.* (2020) also confirmed that wetlands are an advantageous NbS in the remediation of water coming from agricultural tile drainage. Xu *et al.* (2021) explored different types of substrates for simultaneous domestic sewage treatment and greenhouse gases' emission and mitigation, providing new insights into wetlands and their performance based on plant biomass and microbial community structure and diversity. As SuDS, wetlands can contribute to peak flow attenuation through an extended water retention time, together with the provision of co-benefits such as liveability and quality of life of the local community, landscape aesthetics, and wildlife habitat provision (Ballard *et al.*, 2015).

Subsurface Flow Wetlands (SFWs) may resemble LPDs in terms of their structure and functions. SFWs are built with a bed or channel containing an appropriated media as a substrate (US-EPA, 2000) for plant roots to grow and establish (Malaviya and Singh, 2012). It creates an environment in which water is treated through biological and physicochemical processes (i.e., retention, microbial decomposition, settling, plant uptake, and sedimentation; Maria and Liehr (2001)). Even though SFWs mainly strive to provide water treatment functions, differing from the primary objective of LPDs (i.e., regulation of the soil water budget and debris collection), there are similarities between both SFWs and LPDs to establish a baseline upon which build understanding of the features and function of LPDs. Accordingly, one can assume that LPDs will also provide a substrate for plant development and further processes related to eco-hydrological functions. For example, as a system evolving over time, underground plant biomass and root system may facilitate the adhesion of contaminants to the plant, with further pollutants' aerobic decomposition and sedimentation (Ballard *et al.*, 2015). Moreover, bundles of live cuttings could act first as a frictional structure decreasing surface water peak flow. As debris accumulate within the system, a sponge effect may result, retaining water, enhancing infiltration into the ground, and reducing surface runoff volume (Jones, 1996; Schiechtl and Stern, 1997).

2.4.1 LPD Eco-hydrological Processes for Performance Assessment

Identification and knowledge of the processes occurring at the SPAC within LPDs is essential to build holistic frameworks informing the assessment of the performance of this NbS. As a plant-based system developing throughout time, the ability of LPDs to provide eco-hydrological functions will likely change over the different stages of the LPDs lifecycle (Schiechtl and Stern, 1997).

In a broad concept to trees growth, Jacobs (1955) defined six plant development stages as juvenile sapling, pole, mature (early), mature, mature (late) and overmature, which are directly related to LAI (leaf area index). LAI is a determinant factor to estimate allometric relationships, photosynthesis, and tree growth potential (Barclay, 1998). When age-related, LAI peaks during the initial years of the mature stage and then declines (Meng, Bogaard and van Beek, 2014). As for the lifecycle of LPDs, one could divide it into (i) establishment (i.e., right after construction until sprouting); (ii) development (i.e., juvenile and pole phases); (iii) maturity (i.e., well-developed plant reaching the peaks of LAI and tree height); and (iv) senescent (i.e., overmatured phase). This research will focus on the first three stages in which most variability of eco-hydrological processes occurs, critically affecting LPD development and effectiveness.

Throughout LPDs lifecycle, the hydrological processes can be classified between those occurring under wetting (i.e., during or after rainfall events) and those occurring under drying (i.e., in the absence of precipitation) soil conditions. Processes occurring under wetting soil conditions are precipitation, surface runoff, infiltration, subsurface flow within bundles, water retention, and percolation. As precipitation occurs, stormwater runoff and debris reach and permeate within the LPD, which takes over surface runoff volume and peak flow and allows debris deposition. Under drying soil conditions, further debris sedimentation provides an initial cover to the system, fostering root development from the bundles and stakes. Additionally, plant water uptake, soil transpiration and percolation are processes acting as forcing functions in the removal of excess of water resulting in a balanced soil-water condition (Rodriguez-Iturbe and Porporato, 2005).

With the presence of vegetation, the ecological processes under wetting soil conditions are rainfall interception, throughfall and stemflow (Rodriguez-Iturbe and Porporato, 2005). Plant canopy intercepts the amount of precipitation reaching the ground, decreasing the volume of water permeating the soil. However, part of rainwater will pass through the leaves and reach the ground (i.e., throughfall) with a reduced energy of rain drops and hence reduced soil detachment by droplet erosion (Fu *et al.*, 2017; Vaezi, Ahmadi and Cerdà, 2017).

Concurrently, part of precipitation will be transported to the soil through the stem, leading to funnelling rainwater into the ground through an eco-hydrological process known as stemflow (Gonzalez-Ollauri, Stokes and Mickovski, 2020).

As bundles decay and belowground vegetation develops, a mass of fine roots binds soil particles — mechanically reinforcing the soil — while further roots system improves water drainage by loosening the soil and opening flow channels (i.e., preferential flow through macropores; Clothier, Green and Deurer (2008)), altering soil moisture conditions (Dhital and Tang, 2015). Through root system, plant water and nutrients uptake promote resprouting of live cuttings. Via the newly aboveground vegetation, evapotranspiration takes place during drying soil conditions, removing excessive soil moisture (Gonzalez-Ollauri and Mickovski, 2017a). With a well-developed LPD system, further processes such as phytoremediation, urban heat island mitigation and habitat provision through vegetation community contribute to the delivery of co-benefits and multifunctionally of this NbS.

2.4.2 LPD Design and Construction Guidelines

Adequate LPDs design is paramount to realise their eco-hydrological performance. However, little information exists on LPD design in the literature. Through the identification and review of the processes occurring at the SPAC of LPDs, different design criteria can be drawn to inform LPD construction and to ensure adequate eco-hydrological performance. Key design criteria are related to plant species selection, shape and drainage area required, size and number of cuttings and bundles, arrangement of bundles in the trench, etc.

Selection of the right plant species is essential to realise the full performance of LPDs throughout their service life. Preference should be given to plant materials retrieved locally from native species and healthy plant stock, rather than to exotic species (Polster, 1989; Schiechtl and Stern, 1997). This approach should encourage the adequate establishment of the vegetation cover and its adaptation to the local environment, facilitating natural ecosystem processes such as plant succession (Gray and Sotir, 1996), soil microbial colonisation, nutrients and water cycling, etc. Plants able to propagate from branch cuttings — i.e., capable of producing roots and shoots from cuttings — should be preferred, as they normally are fast growing and provide immediate soil hydro-mechanical reinforcement (Gonzalez-Ollauri and Mickovski, 2017c). Water tolerant species and with the ability to withdraw high volumes of water from the ground should be considered, too (Schiechtl and Stern, 1997; Campbell *et al.*, 2008). Schiechtl and Stern (1997) also emphasize the importance of selecting plant species with the ability to withstand mechanical forces acting

on stem or root, such as tolerance of high flow velocities, periodic flooding and sediment cover, and the ability to colonise soil through a dense root mass resulting in soil binding properties. Among the plant species available, willow (*Salix* sp.), alder (*Alnus* sp.), poplar (*Populus* sp.), elm (*Ulmus* sp.), ash (*Fraxinus* sp.), and bird cherry (*Prunus* sp.) are suitable candidates for LPDs, since they can cope with partial soil cover and permanent waterlogging conditions (Schiechtl and Stern, 1997).

Criteria related to the size (length and area) and shape (number of branches, herringbone, etc.) of LPDs should also be considered at the design stage to optimise its eco-hydrological performance. On one hand, building with natural and live materials requires space as soil-bioengineering measures cannot be implemented if the necessary area is not available (Schiechtl and Stern, 1997). On the other hand, no information on size requirements for LPD exists in the literature. Thus, one can assume that the area and design required for LPD implementation are site-specific. As previously presented, live fascines and pole drain might be applied in a herringbone pattern, depending on the drainage needs, topography and landscape restoration goals. Based on live fascines and pole drain potential to reduce flow velocity and to retain debris, building the LPD following flow paths — when readily observable — is recommended (Campbell *et al.*, 2008). Alternatively, flow and drainage paths can be detected in the landscape using GIS approaches (e.g., Gonzalez-Ollauri and Mickovski (2017b).

Regarding the size (diameter and length), number, disposition of plant cuttings into bundles and/or fascines, and into the drainage trench, the following design considerations are worth considering (Campbell *et al.*, 2008):

(a) Cutting and pruning branches in accordance with British Standard BS 3998:1989.
(b) The use of 12-40mm diameter and 750-1000mm long live cuttings for live staking, with an installation protruding 50-80mm above the final surface level.
(c) The use of 20-80mm diameter branches as live cuttings to build the live fascines and pole drain, arranged in the same direction within the bundle with later tying to facilitate handling of the structure. Moreover, live cuttings should comprise a mixed range of diameters and plant age.
(d) A total diameter of live fascines varying between 150-300mm and pole drains varying between 300-500mm diameter, with a length of 2-10m long, depending on site conditions and restrictions on bundle handling.
(e) Overlapping successive live fascines to maintain a continuity of the system within the trench, placing one bundle between 500-700mm over the other.

Furthermore, Campbell *et al.* (2008) underline additional details as possible practices which might result in a higher survival rate of the LPD. For example, these authors emphasise on the importance of creating a moist ground to avoid desiccation of the live cuttings by removing most of the leaves from the branches and by not tying the bundles too tightly. By following these suggestions, a higher number of macropores between cuttings will promote penetrability through the LPD's bundles & soil matrix, with greater water retention within the bundles, preventing cuttings from drying out.

Even though the above recommendations are based on successful implementations and survival rates of LPDs, no research was found to assess their eco-hydrological performance. This research gap allows assumptions that, for example, (i) the considered size of bundles will guarantee enough resprouts to result in a successful implementation; (ii) the diameter of live cuttings impacts in the soil reinforcement conditions; and (iii) the suggested size of live cuttings provides enough reserves to support an initial development of the structure without desiccation.

2.4.3 Environmental Criteria for LPD Creation

Local environmental conditions need to be considered to find adequate locations to host LPDs and ensure LPDs optimum functioning and sustainability (Rey *et al.*, 2019). Thus, prior to constructing an LPD, identification and selection of the most suitable sites in the urban environment is required. Climate variables, soil properties, topographic conditions, proneness to surface flooding, land cover, proximity to greenspaces and to healthy vegetation are the environmental criteria considered in this research, as they play a crucial role throughout the three stages of LPD development, influencing plant growth and the eco-hydrological performance.

Apart from the selection of the right plant species to build the LPD, plant survival and healthy development are directly related with time of planting, climate variables and soil geological conditions (Schiechtl and Stern, 1997). Time of planting (e.g., dormant season) offers specific and favourable climatic conditions to live cuttings' survival rate. As an external forcing to the vegetation in the SPAC, climate variables — such as daily solar radiation, temperature, wind, rainfall (amount, duration, and frequency), and evapotranspiration (Rodriguez-Iturbe and Porporato, 2005) — should be considered along with soil properties (i.e., type/texture, nutrient content, pH; Rodriguez-Iturbe and Porporato (2005)). Specifically, soil texture can contribute to the plant survival and healthy development, as well define drainage conditions (Schiechtl and Stern, 1997).

Site geological and geomorphological conditions — such as slope gradient, curvature, and aspect — determine soil drainage properties, concentration of stormwater runoff and debris flow from erosive processes, and plant development rate. Traditionally, LPDs have been applied in slopping areas and previous experiences reported their implementation in slope gradients ranging between 35-45º (Stokes *et al.*, 2014) and overall 40º (Campbell *et al.*, 2008). Although soil bioengineering techniques can be installed on sloping areas up to 50º, these high steep conditions result in higher costs and lower progress due to decrease on workers' safety and project supervision (Campbell *et al.*, 2008).

Even though suitable plant species for LPD should be water tolerant to withstand partial flooding and continuous water saturation conditions, areas prone to flooding should be avoided since flood water may lead to a loss of soil resulting in potential failure (Schiechtl and Stern, 1997). However, LPD creation close to these areas might improve environmental conditions during rainfall events by promoting water retention and thus decreasing the volume of surface runoff.

Land cover, proximity to greenspaces and to healthy vegetation stock are socio-economic and ecological criteria that may constrain site suitability for LPD implementation. Firstly, land cover, as a result of urbanisation, not only impacts on land availability, but affects soil drainage conditions and rainfall-runoff relationships (D'Ambrosio *et al.*, 2022). Secondly, implementation of LPDs might mitigate urban issues related to lack of biodiversity (Snep and Clergeau, 2012; Elmqvist *et al.*, 2013) and social deprivation towards green accessibility (Hand *et al.*, 2016; Majekodunmi, Emmanuel and Jafry, 2020; Ugolini *et al.*, 2021) by connecting existing greenspaces. Thirdly, as a soil bioengineering technique, LPDs employ locally harvested plants as a source material, requiring proximity to healthy vegetation stock. This approach might also guarantee a higher survival rate and LPD's overall performance since local native plants are naturally adapted to the same environment (i.e., climate variables and soil conditions) in which LPD is implemented (Schiechtl and Stern, 1997; Campbell *et al.*, 2008).

Ultimately, to identify opportunity sites for LPD creation in urban environments, the presented environmental criteria must be combined. Commonly applied by urban planners and decision-makers (Loc *et al.*, 2017), the Multi-Criteria Analysis (MCA) is an approach for assessing simultaneously heterogeneous criteria and score the relative importance of each. Among the available methods, the Analytical Hierarchy Process (AHP), developed by (Saaty, 1980), is one of the most popular approaches to MCA (Vaidya and Kumar, 2006; Velasquez and Hester, 2013) and aims to translate qualitative criteria into quantitative ones by weighting their importance among the decision criteria (Hill *et al.*, 2005). Previous studies

show that the combination of sustainable urban stormwater management and MCA analysis can be effective as it brings objectivity to decision-making processes (Yang and Zhang, 2021), simplifies the identification of the most suitable areas for SuDS (Ariza *et al.*, 2019), and prioritises strategic areas delivering wider co-benefits (Jessup *et al.*, 2021). Therefore, the environmental criteria considered in this study are combined through an MCA and AHP approach to identify the optimal land suitability and thus the opportunity sites for LPD creation.

3 MATERIALS AND METHODS

3.1 Research Framework

This study combined qualitative and quantitative methods, and it was framed to provide the underlying knowledge to propose live pole drains (LPDs) as an alternative to conventional SuDS for regulating the water budget in the urban environment. Figure 3.1 shows the research framework adopted herein to achieve the overall project aim presented under Chapter 1.

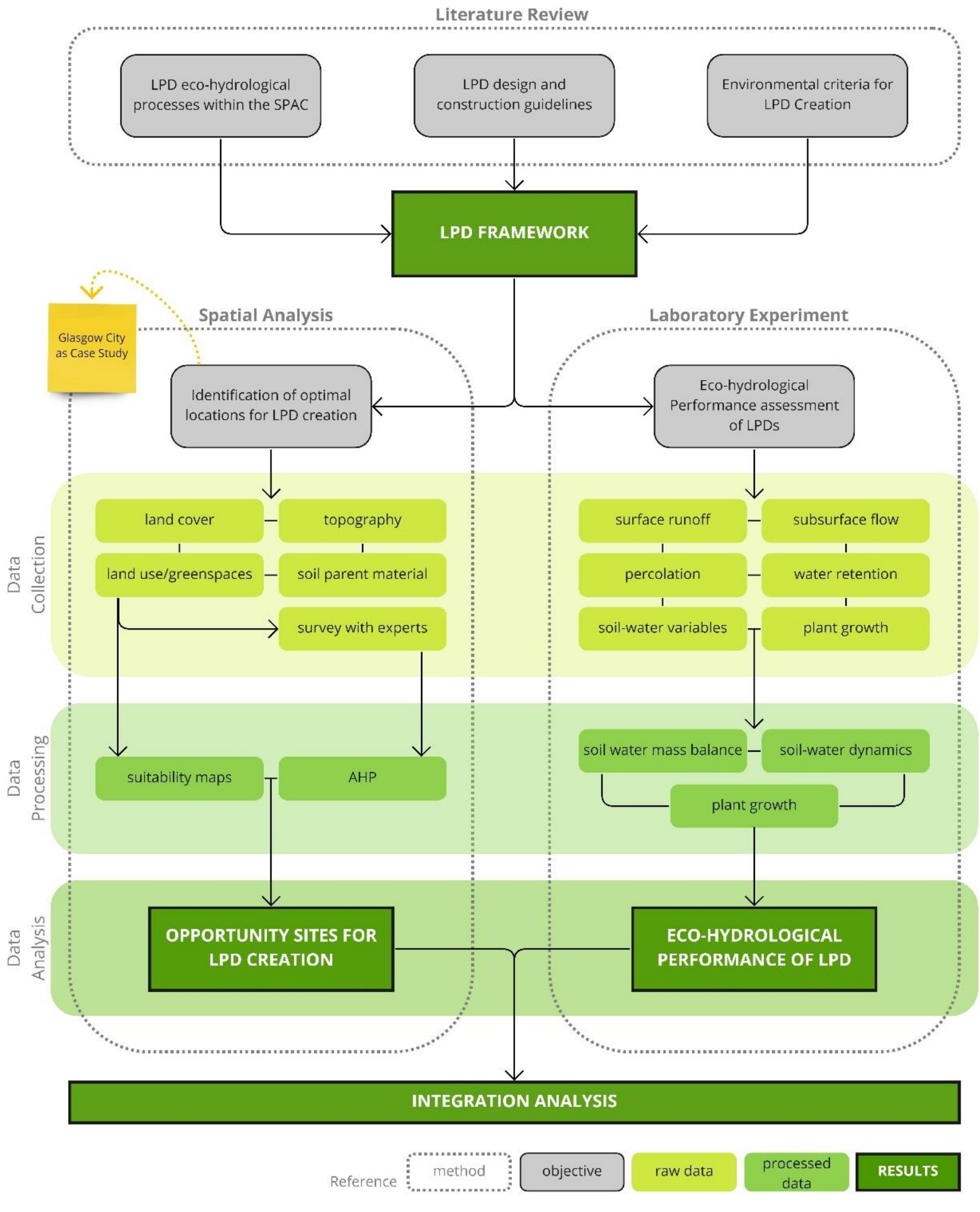


Figure 3.1 Research framework.

The first section of this study — gathered in Chapter 2 — included a comprehensive review of the existing literature on LPDs — i.e., eco-hydrological processes within the soil-plant-atmosphere continuum (SPAC), design and construction guidelines, and environmental criteria for LPD creation — and which was utilised as a basis to build an original LPD framework. Based on this framework, two methods were then applied to illustrate its application: (i) a spatial, multi-criteria analysis to identify urban land suitability and opportunity sites for implementing LPD. Here, Glasgow City area was used as case study; and (ii) a laboratory experiment to assess the performance of the key eco-hydrological processes depicted under the LPD framework. Subsequently, both methods were subdivided into three phases: (i) collection of primary and secondary data; (iii) data processing; and (iii) data analysis. A final section integrating the analysis of both methods was considered to evaluate urban land availability and capability to accommodate LPDs and to provide further strategies and recommendations for future replications and upscaling of this NbS in the urban environment.

3.2 Glasgow City as Case Study

With circa 635,640 inhabitants living within an area of 177.3km², Glasgow is the most populated and largest city in Scotland, UK (GCPH, 2022b). In Glasgow, 55% of the population lives within 500m of vacant and derelict lands (GCPH, 2022a). Vacant and derelict lands account for 9.38km², representing 5.29% of Glasgow's territory (Ordnance Survey, 2021a). The city is positioned 55.85º North longitude and 4.44º West latitude, within the temperate humid climate zone (Cfb: oceanic climate; Köppen (1884)). The mean annual temperature is 9.83ºC with an average annual precipitation of 1,262.83mm (Met Office, 2022). Figure 3.2 presents the location of the city and its administrative boundary, which was considered for the data collection, processing and analysis carried out in this study.

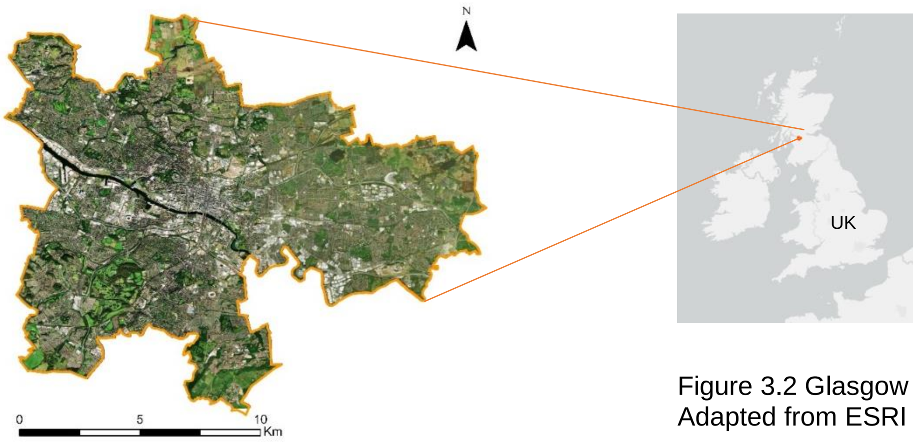


Figure 3.2 Glasgow City.
Adapted from ESRI (2022).

Glasgow City has been historically affected by severe weather hazards and it is identified as being susceptible and potentially vulnerable to different types of flooding (e.g., coastal and surface water flooding; GCC (2021)). According to SEPA (2015), 68% of the city area is at surface water flooding risk, while 32% could be affected by coastal flooding from the river Clyde and its affluents crossing the territory. The challenge to mitigate the impacts of such hydro-meteorological hazards (HMHs) gets deeper when the consequences of climate change (i.e., heavier storms, heat waves, rise of sea levels, etc.) are put into perspective (UKCCRA, 2017). These impacts impose vulnerabilities to human well-being and infrastructure, specially to deprived communities. For example, Majekodunmi, Emmanuel and Jafry (2020) showed that Glasgow's deprived population (44%; Scottish Government (2020)) is most likely to be adversely affected in the occurrence of flooding or heatwave than wealthier communities.

In order to address HMHs, the city of Glasgow has been working in partnership with different stakeholders to promote strategies and deliver initiatives towards a resilient and sustainable city. Regarding urban flooding mitigation, the Metropolitan Glasgow Strategic Drainage Partnership (MGSDP) has been supporting public and private implementations of SuDS. Through an integration of placemaking approach and SuDS into development design and urban planning, the overall aim is to enhance biodiversity, to create open spaces, and to deliver multifunctional green networks (MGSDP, 2016, 2022; UNA, 2022).

3.3 Opportunity Sites for LPD Creation

In order to identify opportunity sites for LPD creation in the urban environment, a land suitability assessment was undertaken for the Glasgow City area. Accordingly, those areas presenting adequate environmental attributes related to the criteria identified in Chapter 2 were scored as more suitable that those that did not. To allocate suitability scores over the study area, a spatial multi-criteria analysis (MCA) was performed using secondary data. The relative importance of the attributes was allocated following the Analytical Hierarchy Process (AHP) method (Saaty, 1980). The AHP was based on experts' opinions, which were obtained through an original survey and gives the relative importance of one attribute over another for subsequent combination through simple additive weighting (SAW; e.g., Gonzalez-Ollauri, Thomson and Mickovski (2020)) analysis. Data processing and analysis to identify the opportunity sites were carried out using the GIS software ESRI ArcGIS Pro 2.9.3.

3.3.1 Environmental Criteria Suitability

Based on the literature review carried out in Chapter 2, the environmental criteria considered to identify the opportunity sites for LPD creation are shown in Table 3.1. Table 3.1 also shows the data source for each environmental criterion, together with its definition and how it is related with LPDs. Additionally, suitability scores were attributed to each class based on the information gathered in Chapter 2.

Suitability scores were applied to determine better or worse conditions among the environmental criteria for creating LPDs at a given spatial location. A suitability scores scale was created, ranging from 1 to 5 (i.e., (1) unsuitable; (2) low suitability; (3) mid-low suitability; (4) moderate suitability; and (5) optimal suitability). Therefore, environmental criteria with optimal suitability condition were scored with a value of 5, while attributes presenting worse conditions were scored accordingly with lower values. An additional “(R) restricted” score was attributed to classify urban land that cannot be transformed into LPDs.

Table 3.1 Environmental criteria and suitability scores.

Environmental Criteria	Definition	Impact on/of LPDs	Class	Score
Soil Texture · Type: Environmental · Subtype: Soil Parent Material · Data Source: BGS (2019) · Raw Data Type: Vector	It refers to the relative distribution of solid particles within the soil (i.e., the percentage of gravel, sand, silt, and clay particles). Soil texture not only determines plant survival and healthy development, but also stormwater infiltration rates and the rates at which water drains through a soil e.g., water moves more freely in sandy soils than in clayey soils.	High suitability scores and priority for LPD creation was given to soils with low infiltration and permeability rates and high runoff potential (USDA, 1986). For example, fine texture soils such as clay would benefit from LPDs drainage properties as they are more prone to flooding and water saturation than coarse soils (e.g., soils with high percentage of gravel and sand particles). Additionally, impervious soils would maintain the water within the LPD matrix, increasing the LPD potential of holding and treating contaminated water and thus avoiding the transfer of pollutants to another environmental compartment.	Clay to Sandy Loam Clayey Loam to Silty Loam Loam to Clayey Loam Clayey Loam to Sandy Loam Loam Loam to Silty Loam Loam to Sandy Loam Sandy Loam to Loam Sandy Loam to Silty Loam Sand to Sandy Loam Peat Varied, Locally Peat No Data Available	4 4 4 3 3 3 3 3 3 2 1 1 1
Slope Gradient · Type: Environmental · Subtype: Topography · Data Source: SRSP (2021) · Raw Data Type: Raster	It refers to the steepness of the land/terrain/topography and it impacts on soil erosion rate and runoff peak flow (Toy, Foster and Renard, 2002; Gardiner and Miller, 2004).	LPD implementation on sloping terrain less than 35º are more cost-effective and safer than on higher slopes gradient (i.e., >35º). However, no information on LPD application on lower slope gradients (i.e., <15º) was found in the literature, so one can assume that this NbS is also suitable for less steep sites. Without movement of water and nutrients down the slope, bundles would develop evenly throughout the structure since optimal conditions for plant growth would be equally distributed (Gonzalez-Ollauri and Mickovski, 2020).	0-1º; Flat 1-5º; Gentle 5-15º; Moderate 15-35º; Steep >35º; Highly steep	5 5 5 3 1

Table 3.1-Cont'd. Environmental criteria and suitability scores.

Environmental Criteria	Definition	Impact on/of LPDs	Class	Score
· Slope Curvature · Type: Environmental · Subtype: Topography · Data Source: SRSP (2021) · Raw Data Type: Raster	It relates to the shape of the land's topography, and it is a determinant factor restricting the use of the land (Gardiner and Miller, 2004). Slope curvature classification considers a convex, planar, or concave shape (Toy, Foster and Renard, 2002). While a convex curvature decelerates the surface water flow, concave surfaces increase the acceleration of the runoff.	In relation to LPDs, the criterion was based on whether the NbS can be deployed or not according to the shape of the slope. Therefore, optimal suitability was given to concave and planar slopes.	Concave Planar Convex	5 5 1
Slope Aspect · Type: Environmental · Subtype: Topography · Data Source: SRSP (2021) · Raw Data Type: Raster	It refers to the positioning of a portion of land in a particular direction in relation to the sun (i.e., north-, east-, south-, west-facing). Differences in slope aspect impacts on air and soil temperature, evapotranspiration, soil moisture content, etc. creating microclimates, which are associated with alterations in vegetation structure and composition (Singh, 2018).	Based on Glasgow's geographical position, optimal suitability was attributed to south-facing slopes, as they have higher incidence of sunlight and thus resulting in better environmental conditions for plant development when compared with north-facing areas.	N; North NE; Northeast E; East SE; Southeast S; South SW; Southwest W; West NW; Northwest N; North	1 2 3 4 5 4 3 2 1

Table 3.1-Cont'd. Environmental criteria and suitability scores.

Environmental Criteria	Definition	Impact on/of LPDs	Class	Score
Proneness to Surface Flooding · Type: Environmental · Subtype: Topography · Data Source: SRSP (2021) · Raw Data Type: Raster	It relates to the land's susceptibility to flooding by surface water. To determine the proneness to surface flooding, the cartographic depth-to-water tool (DTW; White *et al.* (2012) was calculated. The latter can map wet areas in the landscape by providing metrics referring to the distance from a given pixel/point to water bodies or water accumulation zones based on terrain and derived flow accumulation conditions.	LPD deployment close to areas prone to accumulating water is essential to manage and mitigate flood events. In these zones, LPD can help drain the water out downstream from where it is accumulating, also helping upstream by reducing runoff and promoting higher water retention. Optimal suitability was attributed to areas close to ponding areas (i.e., with a distance between 100m and 400m), while low suitability (i.e., score 2) was given to areas considered as ponding areas.	0-100m 100-400m 400-700m 700-1000m >1000m	2 5 4 4 3
Land Cover[1] · Type: Socio-Economic · Subtype: Land Cover · Data Source: Ordnance Survey (2021) · Raw Data Type: Vector	It refers to the physical coverage of the land's surface (e.g., buildings, roads, vegetation, water, bare soil, etc.).	It impacts on the availability of land for LPDs creation and on the degree of exposure and imperviousness of the soil. Moreover, land cover is directly related to rainfall-runoff relationships, which are closely related to the occurrence of flood events and so to the need of SuDS (Barron, Barr and Donn, 2013; Zope, Eldho and Jothiprakash, 2016; Stohmann Aguirre, 2021) or other drainage systems. Moderate or optimal suitability (i.e., scores 4 and 5, respectively) was attributed to areas with an existent vegetation cover (i.e., grassland) or not yet developed. "General surfaces" was considered as unsuitable (i.e., score 1) due to its mixture of man-made surfaces and natural elements.	Amenity Greenspaces Buildings and Structures General Surfaces General Surfaces, Natural Green Corridors Natural/Semi-Natural Greenspaces Open Water Other Functional Greenspaces Parks and gardens Play Spaces and Sports Areas Rails, Roads, Tracks and Paths	5 R 1 5 4 5 R 4 4 3 R

Table 3.1-Cont'd. Environmental criteria and suitability scores.

Environmental Criteria	Definition	Impact on/of LPDs	Class	Score
Proximity to greenspaces · Type: Socio-Economic and Environmental · Subtype: Land Use · Data Source: OS (2021), Scottish Government (2008) · Raw Data Type: Vector	It refers to the distance between LPD and existent greenspaces. "Green corridors", "natural and semi-natural greenspaces", "parks and gardens", "open water" and any "other functional greenspaces" were considered as greenspaces.	LPDs can mitigate issues related to lack of ecosystem connectivity in urban systems by connecting greenspaces, habitats, and promoting biodiversity net gain. LPD deployment can create new accessible greenspace, delivering social benefits (i.e., health improvement, community well-being, etc.; (Hislop and Corbett, 2018)), thus reducing socio-demographic vulnerabilities and inequalities within the territory. Great opportunity sites for LPD creation are those connecting greenspaces as a benefit to biodiversity and human well-being. The "3-30-300 rule" proposed by Konijnendijk (2021) was followed to determine the optimal suitability of urban land for LPD creation. The "3-30-300" strives to guarantee a maximum distance of 300 metres between any household and the nearest greenspace. Thus, optimal suitability was given to areas within a buffer distance of 350m.	<350m >350m	5 4
Proximity to healthy vegetation · Type: Socio-Economic and Environmental · Subtype: Land Use · Data Source: OS (2021), Scottish Government (2008) · Raw Data Type: Vector	It refers to the distance between LPD and healthy vegetation stock as a source of plant materials to build the NbS. It was assumed that every "green corridor", "natural or semi-natural greenspaces", and "parks and gardens" can provide healthy vegetation for LPDs	Proximity to healthy vegetation can also guarantee higher survival rates and overall performance of local native plants due to their adaptation to local environmental conditions. Thus, areas with a distance up to 50m from healthy vegetation were considered as optimal for LPD deployment.	0-50m 50-100m 100-150m 150-200m >200m	5 4 3 2 1

[1] See APPENDIX I for detailed definition of each land cover class.

3.3.2 Relative Weight of Environmental Criteria

After attributing the suitability scores for each environmental criterion, the relative importance of each of them was determined by following the Analytic Hierarchy Process (AHP) using experts' opinion as inputs. To this end, an original survey (see APPENDIX II) was designed together with a LPD brochure (in Portuguese; see APPENDIX III) and sent to anonymous experts in NbS (13 by email and 128 by social media). From a total of 141 experts invited to participate, eight responded the survey.

The survey asked the experts to give a relative importance to the eight criteria through pairwise comparisons. Based on the experts' response, criteria comparison matrices were built with values ranging from 1 to 9, and their inverse counterparts (e.g., 1/n). Following the implementation of the AHP, an eigenvector was retrieved, which was employed to allocate specific weights (i.e., relative importance to each environmental criterion). The total sum of the eigenvector components is 1. Consistency of the AHP results was determined by calculating the consistency index (CI) and the consistency ratio (CR). A value below 0.14 for CI and below 0.10 for CR is acceptable, which indicates that the AHP results are consistent (Saaty, 1980).

Once the relative importance of each criterion was established through the AHP, a simple additive weighting (SAW; $\Sigma X_n = 1$; Eq. *1*) was carried out to compute spatial suitability scores for the study area. To this end, each environmental criterion was first converted to a raster format and then summed through the raster calculator tool.

$$\begin{aligned} Spatial\ Suitability\ for\ LPD\ Creation = {} & X_1 \times Soil\ Texture + X_2 \times Slope\ Gradient + X_3 \times Slope\ Curvature \\ & + X_4 \times Slope\ Aspect + X_5 \times Proneness\ to\ Surface\ Flooding \\ & + X_6 \times Land\ Cover + X_7 \times Proximity\ to\ Greenspaces \\ & + X_8 \times Proximity\ to\ Healthy\ Vegetation \end{aligned} \qquad \textit{Eq. 1}$$

Where:

X_1 to X_8 = eigenvector components resulting from the AHP ($\Sigma Xn = 1$)

3.3.3 Opportunity Sites for LPD Creation

Following the implementation of SAW, only raster cells with scores between moderate (i.e., score 4) and optimal (i.e., score 5) suitability were defined as urban areas with acceptable conditions for LPD creation. Lower scores were considered unsuitable to implement LPDs. This reclassification resulted in the opportunity sites for LPD creation map.

3.3.4 Further Analysis

A further qualitative analysis was carried out to prioritise urban land in which LPDs could be firstly implemented, delivering ecosystems services beyond the ones considered while selecting the environmental criteria for the spatial analysis. Within Glasgow City context, only vacant and derelict land under property of the local council authority was considered to this end. As previously shown in Section 3.2, 55% of the Glaswegian population lives within 500m of vacant and derelict lands. By using vacant and derelict land for LPD creation, Glasgow City Council can mitigate urban challenges such as socio-economic and environmental inequalities. Additionally, three zones were delimited and explore in a larger scale to grasp insights on suitable plots for LPD creation at neighbourhood scale. This analysis also allowed to evaluate the method used within this research.

3.4 Eco-hydrological Performance of LPD

In order to collect primary data to assess the performance of LPDs in terms of key eco-hydrological processes — i.e., surface runoff, subsurface flow, percolation, water retention, and plant growth, a pilot laboratory experiment (Figure 3.3) was carried out in a growing chamber under controlled environmental conditions at Glasgow Caledonian University.

Figure 3.3 LPD pilot laboratory experiment.

Three treatments were established with three repeats each — i.e., a willow (*Salix* sp.) LPD (W); a willow (*Salix* sp.) LPD with alfalfa (*M. Sativa* sp.; seeds, 100g/m²; W+A); and fallow soil as control (C), which were deployed in nine columns made of half round plastic gutters (gutter surface area of 0.46m²). Soil and live willow cuttings were collected in Catterline Bay, Aberdeenshire, UK. The soil was silty sand (e.g., Gonzalez-Ollauri and Mickovski (2017a)) and it was sieved under 2 mm, removing all stones and gravels from the bulk soil sample.

Then, the gutters were perforated every 50 mm (hole ∅ 4mm; 29 holes per gutter) to enable vertical percolation (Figure 3.4a). Subsequently, a nylon mesh was applied to avoid the movement of soil fines out of the columns and to enable the collection of data on subsurface flow on the toe of the column (Figure 3.4b). Next, six bundles of 15 live willow cuttings (50mm length) were built to be allocated under the W and W+A treatments (Figure 3.4c-d). Under these treatments, each gutter received a base with soil and one bundle (Figure 3.4e); once each bundle was in place, they were covered with soil material and gently compacted (Figure 3.4f; approx. bulk density of 0.76g/cm³). Columns under the W+A treatment were sawn with 100g of seeds per m² (Figure 3.4g). In the control columns, gutters were filled only with soil and gently compacted (approx. bulk density of 0.77g/cm³). Ultimately, a flexible funnel was applied in the toe of each column, above the bundle and soil, to allow data collection on surface runoff (Figure 3.4h).

(a)

(b)

Figure 3.4 Steps to build the experiment. (a) Perforated gutter to enable vertical percolation; (b) Nylon mesh to collect data on subsurface flow; (c) Willow live cuttings; (d) Built bundles with 15 live cuttings each; (e) Bundle in place; (f) Covering the bundle with soil; (g) Sawing alfalfa seeds on W+A treatment; (h) Funnel to collect data on surface runoff.

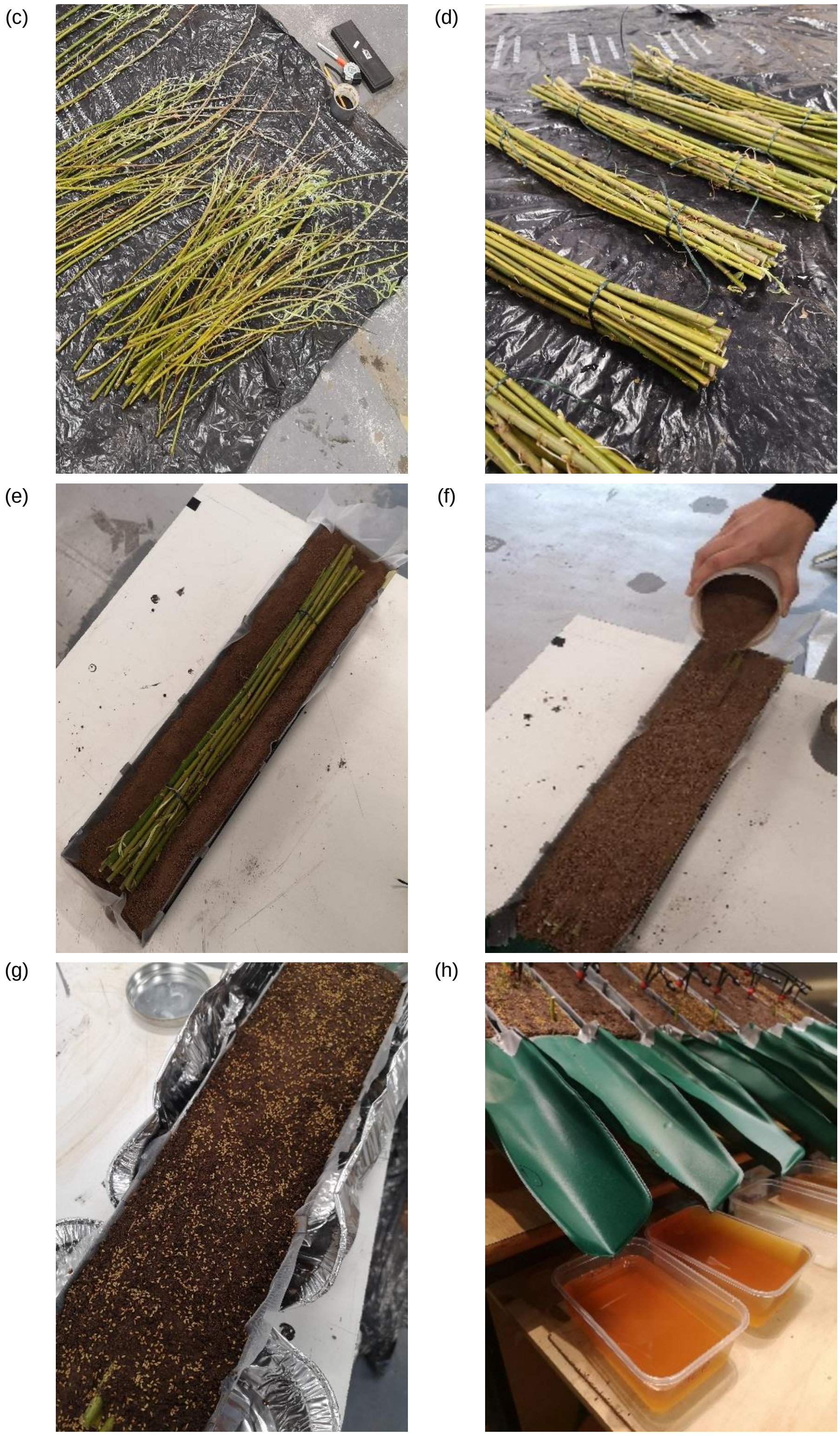


Figure 3.4-Cont'd. Steps to build the experiment. (a) Perforated gutter to enable vertical percolation; (b) Nylon mesh to collect data on subsurface flow; (c) Willow live cuttings; (d) Built bundles with 15 live cuttings each; (e) Bundle in place; (f) Covering the bundle with soil; (g) Sawing alfalfa seeds on W+A treatment; (h) Funnel to collect data on surface runoff.

Once columns were built, they were placed within the growing chamber, which was programmed with a mean air temperature of 22°C. Each gutter was tilted at 30º and placed under artificial daily sunlight (16 hours/day; irradiance 165W/m²; Spider Farmer SF2000). To collect the water outputs from the hydrological processes – i.e., surface runoff, subsurface flow, and percolation, four plastic containers per column were placed below and at the end of the gutter (Figure 3.5).

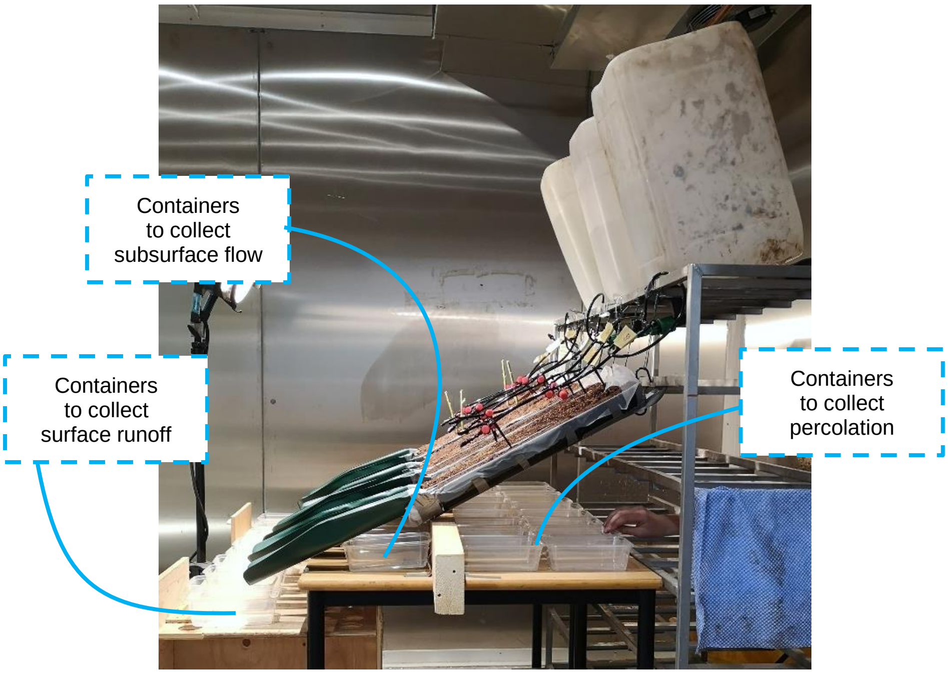


Figure 3.5 Final setup of the experiment.

During the experiment, constant irrigation and ten rainfall simulations were performed to foster LPD development and to understand the overall eco-hydrological performance of LPDs under wetting and drying soil conditions. An irrigation system was built and later connected to three 25L water tanks set as water supply (Figure 3.5). To each column, water was provided through two nozzles equidistant placed throughout the column and fixed throughout the experiment. The irrigation system was also calibrated to provide a constant dripping with an average of 3.56mm/hr of water per column. For the rainfall simulations, a portable rainfall simulator with three nozzles was built and calibrated. Water supply for the rainfall simulations was done through water tap. Each nozzle delivered rainfall for one column, at the crest zone. Thus, each rainfall simulation was performed three times to cover all the nine columns.

The experiment lasted over 50 days in total. Further assessments to determine the potential of LPDs eco-hydrological performance considered the analysis of the soil water mass

balance (SWMB; Section 3.4.1), soil-water dynamics (Section 3.4.2), and plant growth (Section 3.4.3). More details on these analyses are provided below.

3.4.1 Soil Water Mass Balance (SWMB)

A soil water mass balance (SWMB = 0) was performed to evaluate the potential of LPDs to regulate the soil water budget. Throughout the laboratory experiment, rainfall simulations (Table 3.2) were conducted as a water input to the LPDs under different rainfall depths resulting in distinctives cumulative water volumes (i.e., the total of water applied; CWVs). More specifically, RF3 (i.e., rainfall depth of 93.18mm/hr) was determine in accordance with the rainfall depth measured during the 2002 Glasgow's surface flooding (i.e., rainfall depth of 94.5mm/hr, estimated as a 1 in 100-year return period rainfall; SAIFF (2018)). Additional rainfall simulations provided higher rainfall depth variability, which contributed to further assessment of the LPD as regulator of water budget in the soil.

Table 3.2 Rainfall simulations performed during the laboratory experiment.

Rainfall Simulation	Total Duration (min)	Type of Rainfall	Rainfall Depth (mm/hr)	Cumulative Water Volume (CWV; L)
RF 1	1	1min non-stop	372.72	314.33
RF 2	14	1min on + 1min off	186.36	2200.31
RF 3	10	0.5min on + 0.5min off	93.18	1571.65
RF 4	15	1min on + 4min off	74.54	942.99
RF 5	14	2min on + 5min off	106.49	1257.32

Thirty minutes after the end of each rainfall simulation, the water fluxes derived from surface runoff, subsurface flow, and percolation processes were measured. These measurements were done by measuring the volume of water (in litres) collected in the plastic containers placed below and at the end of each column.

Water retention (i.e., the volume of water retained within the soil) was also measured. Water retention was calculated as the difference in water content in soil before and after the rainfall simulation. To this end, the volumetric soil moisture content (θ; %) was measured with six soil moisture sensors (two sensors per treatment; SEN0193 – DF Robot) before and after each rainfall simulation. Then, θ (%) values were transformed to litres based on total soil bulk density, soil porosity and total pore-water volumes.

With the collected data (see APPENDIX IV for raw data), a soil water mass balance (SWMB = 0; Eq. *2*) was performed. SWMB was assumed to have an equal balance between the

water inputs (i.e., the sum of the rainfall cumulative water volume and water content in soil prior rainfall) and the water outputs (i.e., sum of water volumes derived from surface runoff, subsurface flow, percolation, and water content in soil post rainfall). If the SWMB was not balanced (i.e., SWMB ≠ 0), the remained water volume was assumed as water loss. Output values for each SWMB component were plotted through boxplots for visual comparison of the variations between treatments (i.e., W, W+A, and C) and scenarios (i.e., scenario A, soil at water saturation; and scenario B, soil at field capacity).

$$SWMB = [CWV + WC_b] - [R + SF + P + WC_a] - [W_\ell] \qquad \textit{Eq. 2}$$

Where:

CWV = Cumulative water volume, in litres
WC_b = Water content in soil – before rainfall, in litres
SR = Surface runoff, in litres
SF = Subsurface flow, in litres
P = Percolation, in litres
WC_a = Water content in soil – after rainfall, in litres
W_ℓ = Water loss, in litres

3.4.2 Soil-Water Dynamics

Volumetric soil moisture content (*θ*), soil matric suction (*φ*), and soil temperature (*t*) are soil-water variables assumed to have a close relationship with LPD's eco-hydrological performance — i.e., subsurface flow, percolation, water retention, plant uptake and growth, and mechanical reinforcement — within the SPAC. Therefore, these soil-water variables were considered as indicators for the eco-hydrological processes.

During 30 days of the laboratory experiment, these variables were measured with calibrated sensors, which were vertically inserted in the middle of the column, at maximum proximity to the LPD bundle. Volumetric soil moisture content (*θ*) was measured with six soil moisture sensors (two sensors per treatment; SEN0193 – DF Robot). Soil matric suction (*φ*) was measured with three tensiometers (one sensor per treatment; T5 – UMS). Soil temperature (*t*) was measured with nine temperature probes (three sensors per treatment; 107 – Campbell Scientific). Soil moisture sensors were first wired to a 5-volt voltage regulator and then to one electric-powered data logger (CR1000X – Campbell Scientific). Tensiometers and temperature probes were directly wired to a second electric-powered data logger (CR1000X – Campbell Scientific).

Records of *θ*, *φ* and *t* were logged at a resolution of 5 minutes. The retrieved 5-min time series data was aggregated into mean hourly time series and plotted together with the water input during the experiment (i.e., irrigation and rainfall simulations) to visually assess the differences between the treatments (i.e., W, W+A, and C) during wetting and drying soil conditions.

3.4.3 Plant Growth

In order to assess the ecological performance of LPDs in terms of landscape restoration and habitat creation, a plant growth analysis was performed. This analysis was based on daily monitoring of the willow aboveground vegetation (Sections 3.4.3.1 and 3.4.3.2) and a destructive analysis performed after 52 days of the laboratory experiment (Section 3.4.3.3). More details on these analyses are provided below.

3.4.3.1 Plant cover establishment

The plant cover establishment was determined by the total number of resprouting willow stems during the monitored period. A posterior assessment compared the observed numbers between the different LPD treatments (i.e., W and W+A) and between the three zones per treatment (i.e., crest, middle, and toe).

3.4.3.2 Plant growth rate (PGR)

For each new aboveground willow individual, a daily height was measured by placing a ruler against the stem (see APPENDIX V for raw data). Then, a plant growth rate (PGR; Eq. *3*) was estimated. A posterior analysis compared the obtained PGRs between the different LPD treatments (i.e., W and W+A) and between the three zones per treatment (i.e., crest, middle, and toe).

$$PGR = \frac{lnSH_2 - lnSH_1}{t_2 - t_1} \qquad \textit{Eq. 3}$$

Where:

t_1 = time of first measurement, in days
t_2 = time of last measurement, in days
SH_1 = Stem height at t_1, in centimetres
SH_2 = Stem height at t_2, in centimetres

3.4.3.3 Above- and belowground vegetation

On day 52 of the laboratory experiment, a destructive analysis was performed (Figure 3.6a) to collect data on willow above- and belowground vegetation (i.e., dry biomass). To this end, columns were destroyed by removing the bundle from the gutters. Each bundle was washed to remove the bound soil (Figure 3.6b-c). Then, aboveground vegetation (i.e., willow stems)

and belowground vegetation (i.e., roots) were measured and clipped out of the live cutting (Figure 3.6d-f).

Each willow stem had its diameter at middle height measured and then stem was separated from its leaves. Separately, stem and leaves were wet weighted, oven dried for 24h at 60ºC, and dry weighted to calculate the aboveground dry biomass. Later, a biometric relationship between the aboveground (i.e., sum of stem and leaves) dry biomass and stem diameter was established through a second-order polynomial regression. Further analysis applied the regression to estimate aboveground dry biomass of 18 randomly selected willow individuals at day 18, 32, and 46 of the experiment.

Clipped roots of each column were wet weighted, oven dried for 24h at 60ºC, and then dry weighted to calculate the belowground dry biomass. Collected data on aboveground dry biomass and belowground dry biomass were transformed to its tangent, which was used to establish an allometric relationship through a second-order polynomial regression. Further assessment applied the regression to estimate belowground dry biomass of 18 randomly selected willow individuals at day 18, 32, and 46 of the experiment.

(a)

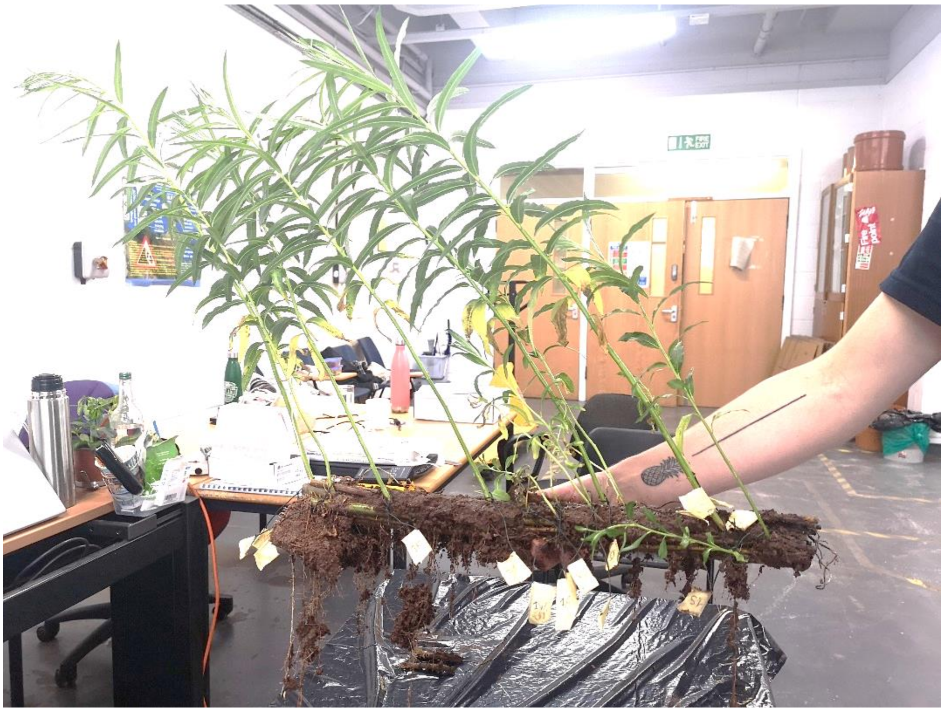


Figure 3.6 Destructive analysis. (a) Bundle removed from gutter; (b) Removing bound soil from bundle and roots; (c) Above- and belowground vegetation; (d-f) Data collection on above- and belowground vegetation.

Figure 3.6 Destructive analysis. (a) Bundle removed from gutter; (b) Removing bound soil from bundle and roots; (c) Above- and belowground vegetation; (d-f) Data collection on above- and belowground vegetation.

3.5 Data Statistical Analysis

For soil water mass balance (SWMB), plant cover establishment analysis, and plant growth rate (PGR), a Kruskal-Wallis test (H) was used to identify whether the differences found between treatments, scenarios, and zones were statistically significant at the 95% confidence level. The H test is a nonparametric statistical test that determines the differences among independently sampled groups on a non-normally distributed continuous variable (Kruskal and Wallis, 1952). Further statistical analysis was performed by plotting the cumulative distribution functions (CDF). Statistically significant differences were evaluated with the Kolmogorov-Smirnov test (K-S; Pratt and Gibbons (1981)) at the 95% confidence level. The K-S test resulted in a K-S index (D), which quantifies the distance

between two CDFs and whether it is statistically significant. For soil-water variables analyses, CDFs were plotted to compare the differences between treatments with posterior K-S tests to indicate whether and how different the time series were. All statistical analyses were performed in the statistical computing software R v4.1.1.

3.6 Integration Analysis

The integration analysis was carried out to combine the results found under Section 3.3.4 Further Analysis and Section 3.4.1 Soil Water Mass Balance (SWMB). One plot with optimal conditions for LPD creation within the zones detailed under Section 3.3.4 was selected to depict its capability to accommodate LPDs. In order to select one plot, a visual assessment was undertaken to compare plot location and the existent and mapped greenspaces in Glasgow within the PAN65 (Scottish Government, 2008). Once the plot was defined, the analysis provided information on LPD design and the potential LPD eco-hydrological performance within the selected area.

4 RESULTS AND ANALYSES

This chapter presents the results obtained and analyses conducted in this study. It is structured into four main sub-sections: LPD4C Framework, Opportunity Sites for LPD Creation, Eco-hydrological Performance of LPD, and Integration Analysis.

4.1 LPD4C Framework

A comprehensive framework (Figure 4.1; see detailed version of the LPD4C framework in APPENDIX VI) to set the basis of Live Pole Drain (LPD) in the urban environment was defined. The Live Pole Drains for Cities (LPD4C) framework assembled the environmental compartments, the driving eco-hydrological processes and respective required variables delineating the information needed to design and assess the performance of LPDs. By building upon the understudied field on LPDs performance, the LPD4C framework supports the adoption of LPDs as a viable type of SuDS for cities. Five main environmental compartments were considered within the framework — i.e., atmosphere, urban surfaces, plant bundles & soil matrix, aboveground and belowground vegetation, connected through an array of eco-hydrological processes (arrows). These processes can be measured through quantifiable variables (dotted boxes; see detailed version of the LPD4C framework in APPENDIX VI). Table 4.1 provides the list of the eco-hydrological processes established in the LPD4C framework together with their respective definitions according to their impact on the soil-plant-atmosphere continuum (SPAC).

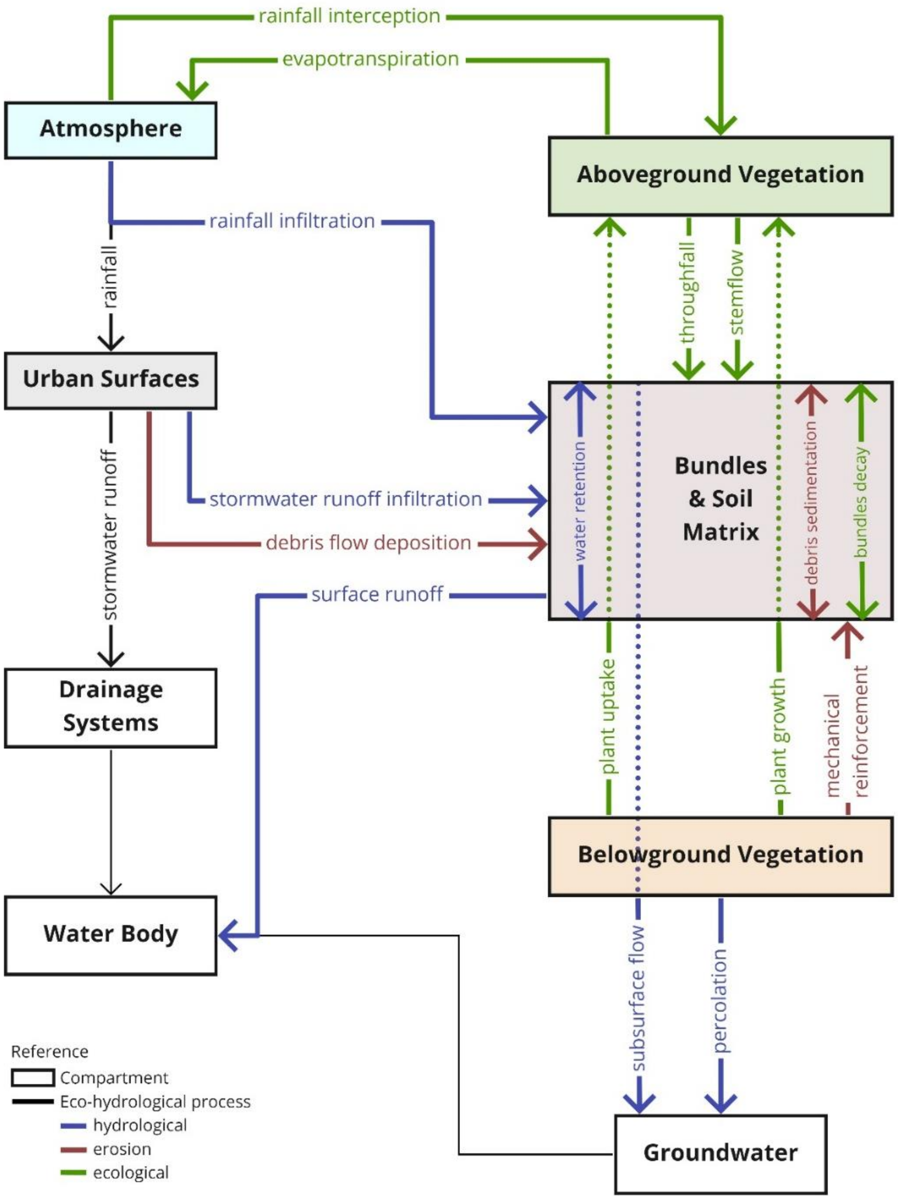


Figure 4.1 LPD4C framework. The framework illustrates the eco-hydrological processes (arrows) across the environmental compartments. See APPENDIX VI for detailed version.

Table 4.1 Eco-hydrological processes of LPD4C framework within the soil-plant-atmosphere continuum (SPAC).

Eco-hydrological Process	Definition	Source
Rainfall interception	Part of the rainfall that is intercepted by tree canopy. While foliage intercepts rainfall, a decrease on volume of water reaching the soil occurs, as well as a reduction of raindrop impact on the soil.	Rodriguez-Iturbe and Porporat (2005); Campbell *et al.* (2008)

Table 4.1-Cont'd. Eco-hydrological processes of LPD4C framework within the soil-plant-atmosphere continuum (SPAC).

Eco-hydrological Process	**Definition**	**Source**
Evapotranspiration	It refers to plant transpiration and evaporation from the soil by tree canopy. Roots uptake water from the soil, which is subsequently transpired by the leaves into the atmosphere.	Rodriguez-Iturbe and Porporat (2005); Campbell *et al.* (2008)
Throughfall	Part of the rainfall that passes through tree canopy, subsequently reaching the ground with less raindrop impact on the soil.	Rodriguez-Iturbe and Porporat (2005); Campbell *et al.* (2008)
Stemflow	Part of the rainfall that is intercepted by tree canopy and subsequently flows downs the branches and stem until reaching the ground.	Levia and Frost (2003); Gonzalez-Ollauri, Stokes and Mickovski (2020)
Rainfall infiltration	It refers to the volume of rainfall infiltrating the soil. It is directly related to rainfall depth and soil-water storage availability, which is also related to the volumetric soil moisture content.	Rodriguez-Iturbe and Porporat (2005)
Stormwater runoff infiltration	Stormwater runoff is a product of the rainfall depth and the degree of permeability of urban surfaces. It refers to the volume of stormwater runoff infiltrating the soil.	Rodriguez-Iturbe and Porporat (2005); Loughlin, Huber and Chocat (2010)
Debris flow deposition	Debris flow is a mixture of soil particles and water moving down the slope by gravity. Deposition of debris flow happens when debris is allocated in any surface acting as a barrier.	Berzi, Jenkins and Larcher (2010)
Surface runoff	When the rainfall depth exceeds the soil-water storage availability, the excess is converted into surface runoff.	Rodriguez-Iturbe and Porporat (2005)
Water retention	It is related to the capacity of the soil in retaining water, which is mainly governed by soil properties.	Rodriguez-Iturbe and Porporat (2005)
Debris sedimentation	Once debris is deposited, the sedimentation process starts. Debris starts settling, resulting in new layers of soil covering the previous surface.	Berzi, Jenkins and Larcher (2010)
Bundles decay	It refers to the process of decomposition of the live cuttings within the bundles. While part of the cuttings will survive and generate new above- and belowground vegetation, part will decay enhancing soil organic matter (SOM).	Rodriguez-Iturbe and Porporat (2005); Campbell *et al.* (2008)

Table 4.1-Cont'd. Eco-hydrological processes of LPD4C framework within the soil-plant-atmosphere continuum (SPAC).

Eco-hydrological Process	**Definition**	**Source**
Plant uptake	It affects the water budget by removing water from the soil. Root system uptakes water from the soil, which is subsequently transpired by the leaves into the atmosphere.	Rodriguez-Iturbe and Porporat (2005); Campbell *et al.* (2008)
Plant growth	It refers to the rate of plant growth, which is also determine by plant water and nutrient uptake. To ensure development and survival, plants need to maintain a sufficient volume of water and nutrients in their tissues. Continuous flux of water also affects the performance of processes such as photosynthesis and nutrient uptake.	Rodriguez-Iturbe and Porporat (2005)
Mechanical reinforcement	Roots provide additional mechanical support to the soil, by increasing its shearing resistance. Roots also bind the surface soil particles, reducing their susceptibility to erosion. Roots may penetrate a firmer substrate, thereby anchoring the upper soil layers.	Campbell *et al.* (2008); Gonzalez-Ollauri and Mickovski (2016)
Subsurface flow	It corresponds to the movement of water through the soil, and it is mainly correlated to the preferential flow governed by the presence of macropores. Plant roots and small organisms alter the soil by opening channels, increasing macroporosity. Through macropores, preferential flow occurs more easily by capillarity forces.	Bouma (1981)
Percolation	It refers to the downwards movement of water to the groundwater through the soil, and its layers, by gravity and capillary forces.	Rodriguez-Iturbe and Porporat (2005)

The LPD4C framework holistically depicted the eco-hydrological processes under soil wetting and drying soil conditions throughout the lifecycle of the LPD. However, LPD is a plant-based system that develops over time. Therefore, three stages of development (i.e., establishment, development, and maturity; Figure 4.2a-c) were explored herein as they have a higher number of eco-hydrological processes occurring within the LPD, critically affecting development and effectiveness. Establishment stage (Figure 4.2a) was defined as the phase from right after construction of the LPD until the firsts resprouting. Development stage (Figure 4.2b) considered the juvenile and pole phases. Maturity stage (Figure 4.2c) was defined as the period in which well-developed plants reach their peaks of tree height and leaf area index (LAI).

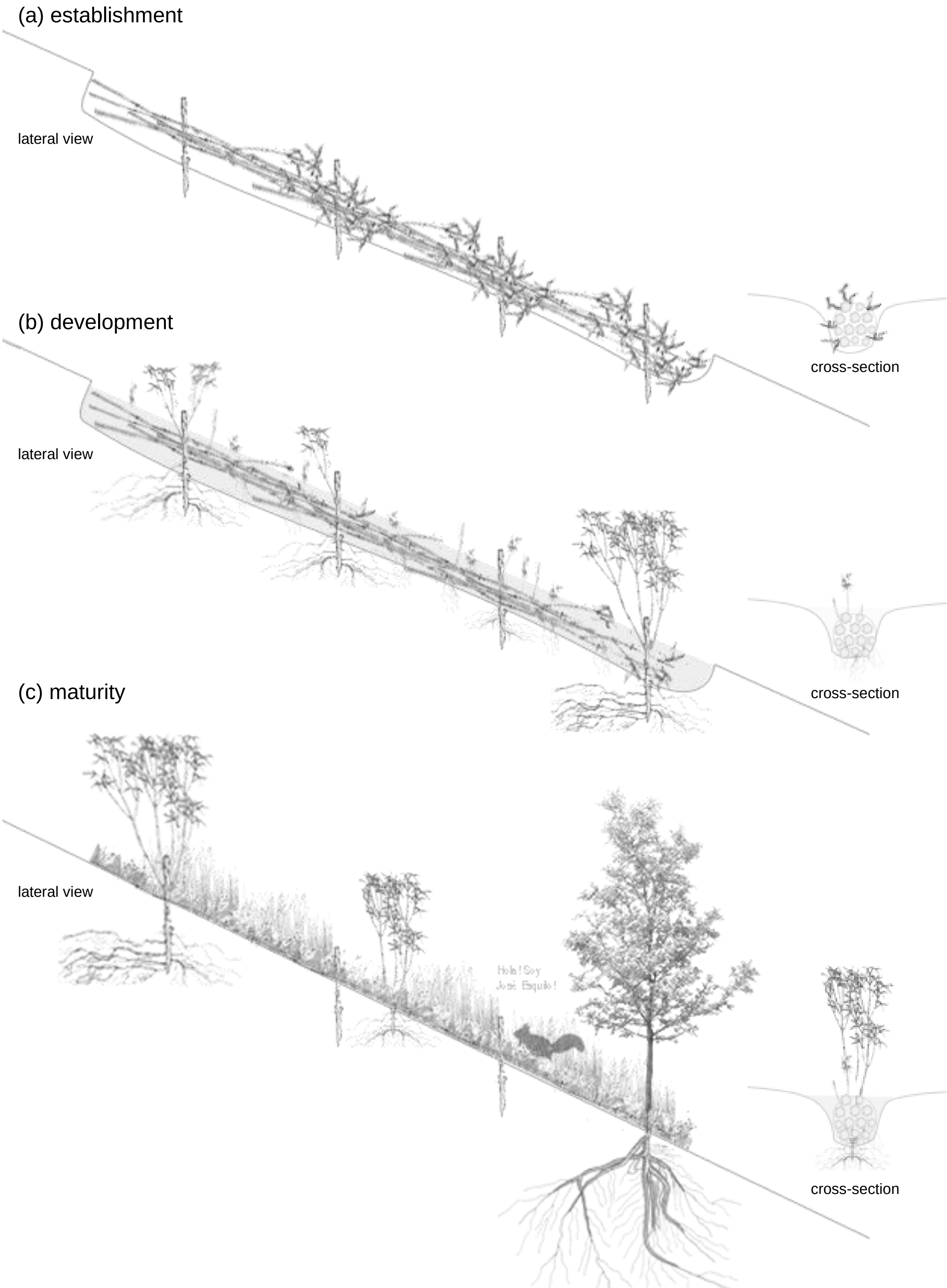
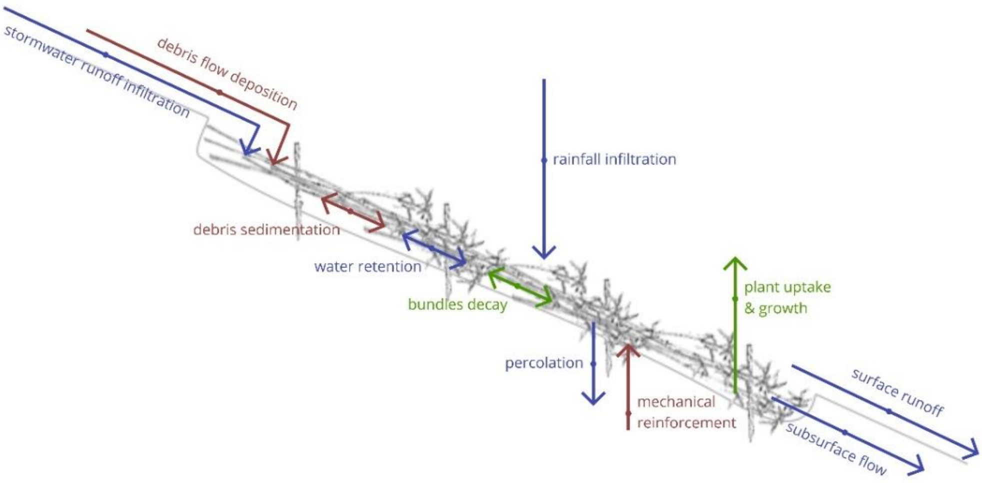


Figure 4.2 The three development stages of an LPD. (a) Establishment stage: the LPD has just been built; live cuttings and stakes are not covered by soil; they start to resprout and form leaves; (b) Development stage: debris flow into the LPD, providing an initial soil cover to the live cuttings; young green shoots start to stabilise and are visible on the LPD's surface; (c) Maturity stage: the LPD is totally covered by soil; live cuttings and stakes are well established; the landscape restoration is completed, mitigating surface runoff and soil erosion, and providing wildlife habitat.

As a result of the changes happening overtime within the LPD, the eco-hydrological processes occurring will likely change following the different development stages of the LPD's vegetation (i.e., establishment, development, and maturity). Figure 4.3a-c illustrates the eco-hydrological processes taking place in the LPD during these phases. On the one hand, a few processes have a delimited occurrence e.g., 'bundles decay' starts during establishment stage and ends during development stage. On the other hand, majority of the eco-hydrological processes happened during the three stages, but with different impact on the LPD performance. For example, 'water retention' during the third stage will have a higher impact on LPD performance than during the first stage due to the soil cover created by 'debris sedimentation' process.

(a) establishment



(b) development

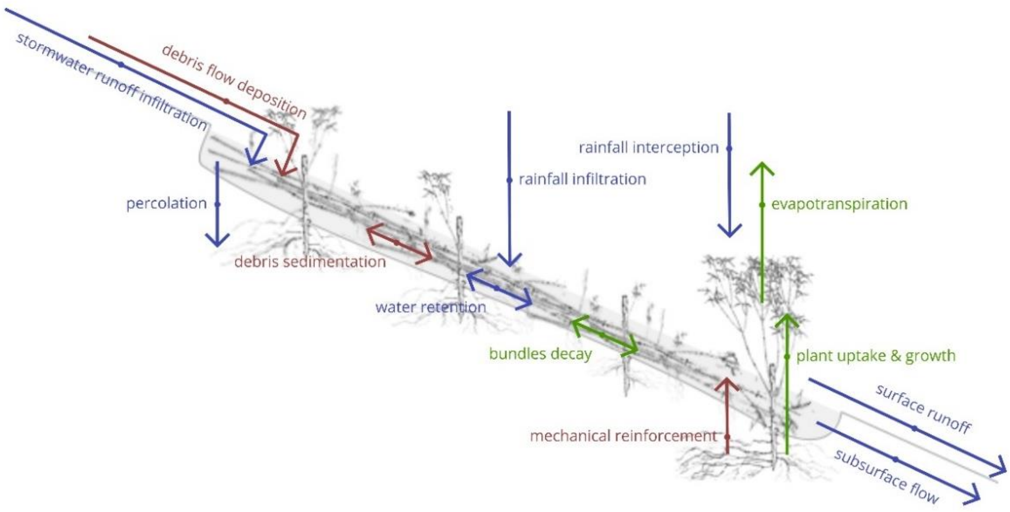


Figure 4.3 Eco-hydrological processes according to LPD development stages. (a) establishment; (b) development; (c) maturity.

(c) maturity

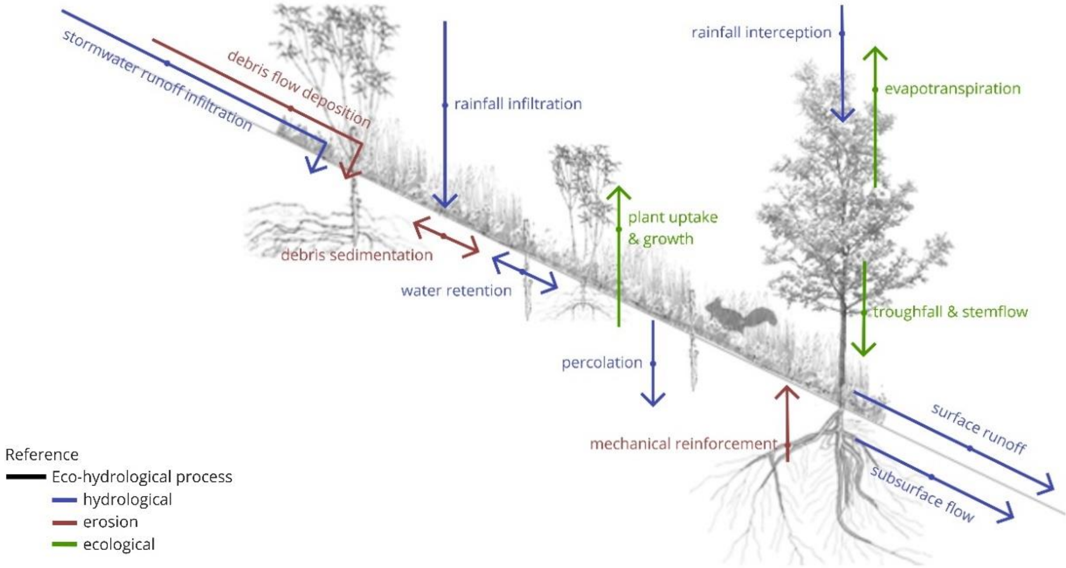


Figure 4.3-Cont'd Eco-hydrological processes according to LPD development stages. (a) establishment; (b) development; (c) maturity.

The LPD design is site-specific, and it should be deployed according to the landscape restoration goals. A simple herringbone pattern (Figure 4.4a) considers the application of the main pole drain and two live fascines on the crest of the slope. This design is recommended to be implemented on slopes with low to moderate surface runoff. In areas with seepage and high surface water flow, additional live fascines should be deployed along the pole drain (Figure 4.4b). This design has a higher eco-hydrological potential than the simple herringbone. The higher the number of live fascines deployed, the higher is the potential in reducing water flow velocity, in retaining debris, and in restoring the landscape.

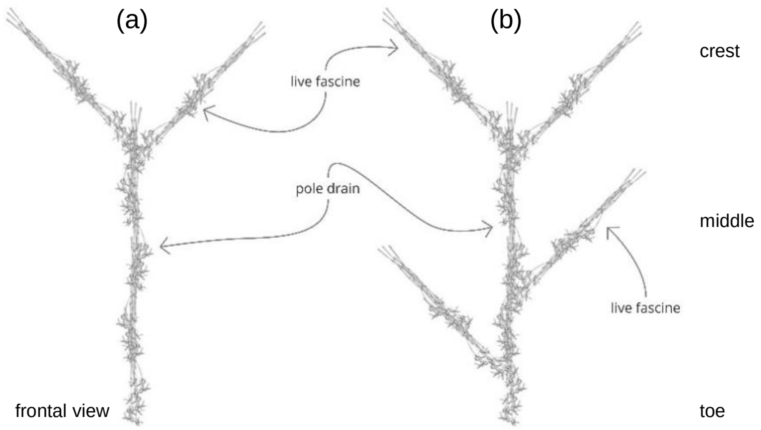


Figure 4.4 LPD design. (a) simple herringbone; (b) herringbone with additional live fascines.

The LPD4C framework helped identify successfully the environmental criteria to find opportunity sites for LPD creation in the urban environment (see Section 4.2), as well the key processes and variables involved in the assessment of the eco-hydrological performance of LPD (see Section 4.3). For the former, eight environmental criteria — i.e., soil texture, slope gradient, slope curvature, slope aspect, proneness to surface flooding, land cover, proximity to greenspaces and proximity to healthy vegetation, were identified and used to find opportunity sites for LPD creation. For the latter, three soil-water variables — i.e., volumetric soil moisture content (θ), soil matric suction (φ), and soil temperature (t), and five key eco-hydrological processes — i.e., surface runoff, subsurface flow, percolation, water retention, and plant growth, were considered to quantify eco-hydrological performance.

4.2 Opportunity Sites for LPD Creation

4.2.1 Environmental Criteria Suitability

The environmental criteria suitability maps for LPD creation within Glasgow City are show in Figure 4.5a-h. Detailed suitability class attributed to each environmental criteria with its resulting Glasgow's surface areas are shown in APPENDIX VII.

In terms of soil texture (Figure 4.5a), Glasgow City area did not present optimal soil conditions for LPD creation. Only 10.18% of the surface had a moderate suitability for LPD creation. Soils classified with mid-low (70.63%), low suitability (2.96%), and not suitable (16.23%) scores accounted for 89.81% of the study area.

Optimal suitability for LPD creation was found for 93.23% of Glasgow's surface in terms of slope gradient (Figure 4.5b). The mid-low suitability attributed to steep slopes (i.e., between 15º and 35º) accounted for 6.12% of the study area, while unsuitable land (i.e., highly steep areas with gradient over 35°) summed only 0.64%.

In relation to slope curvature, optimal suitability for LPD creation was found for 90.14% of the study area (Figure 4.5c). Within this proportion, 140.71km² of the urban land is planar representing almost 80% of the total area. Unsuitable areas with a convex curvature were found for 9.86% of Glasgow's surface.

The slope aspect (Figure 4.5d) was south facing (i.e., SE: 11.73%; SW: 13.31%; and S: 15.38%) for 40.41% of Glasgow's area, presenting a moderate to optimal suitability for LPD

creation. Mid-low and low suitability accounted for 22.31% and 23.24%, respectively, whilst the north facing aspect area, which was considered as unsuitable, was 14.04%.

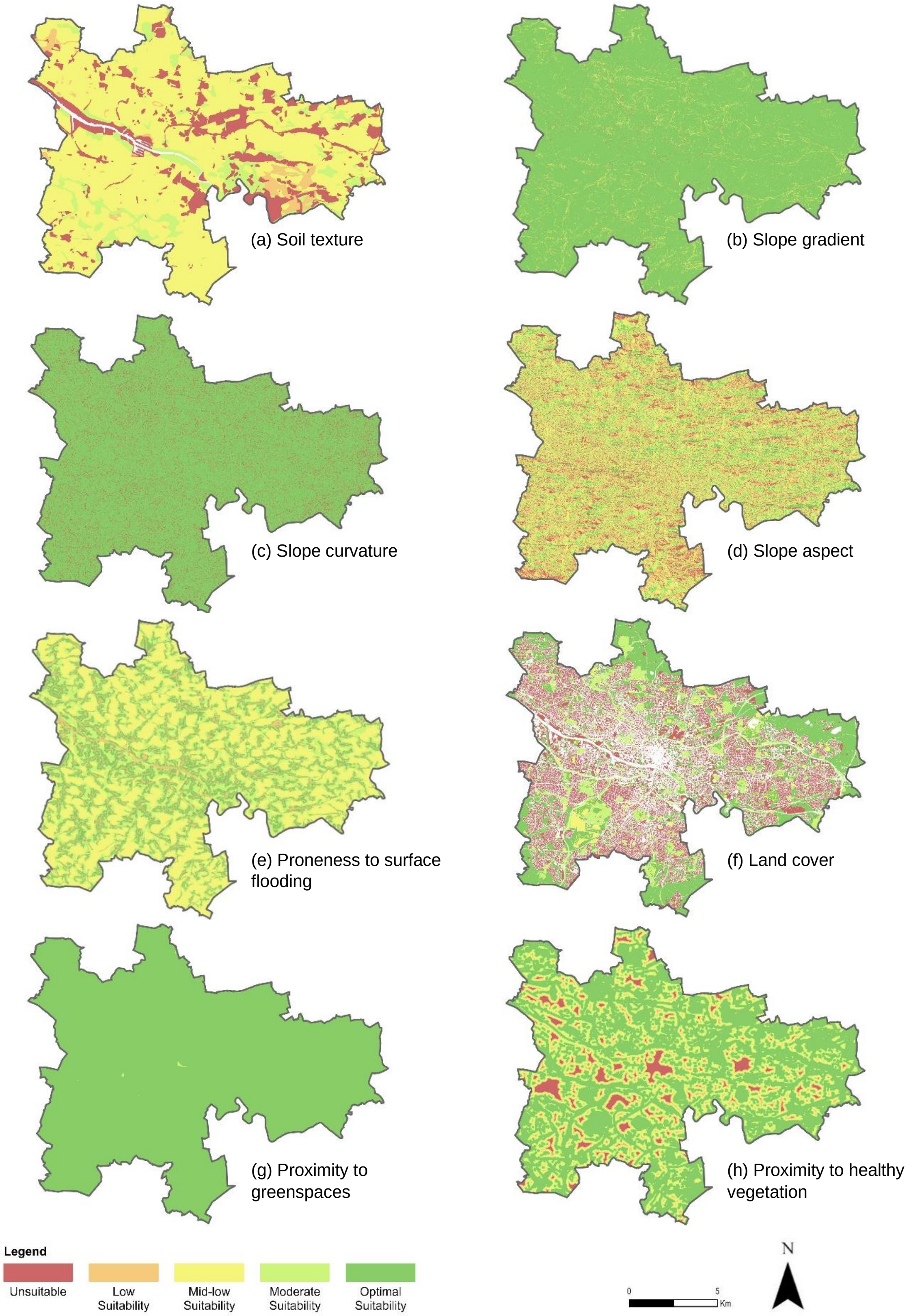


Figure 4.5 Environmental criteria suitability maps for LPD creation within Glasgow City.

Overall, 51.41% of Glasgow's land had moderate to optimal suitability for LPD creation in terms of 'proneness to surface flooding' (Figure 4.5e). A small proportion of 10.09% of the area had lower suitability scores and 38.50% mid-low suitability.

In terms of land cover (Figure 4.5f), 33.48% of the urban land was restricted for LPD creation due to the built environment. Unsuitable areas for LPD creation (i.e., general surfaces) accounted for 25.96%, whereas 2.52% of Glasgow's land cover was scored with mid-low suitability. Moderate to optimal suitability zones for LPD creation covered 38.04% of the study area.

Regarding proximity to greenspaces, optimal suitability for LPD creation was found for 99.93% of the study area (Figure 4.5g). Moderate conditions accounted for 0.07% comprising an area smaller than 1km².

Optimal suitability for LPD creation in terms of the proximity to healthy vegetation was found for 47.50% of the study area (Figure 4.5h). Moderate and mi-low suitability was found for 26.22% and 14.26% of Glasgow's area, respectively. Areas with lower suitability or unsuitable (i.e., distances over 150m) covered 12.02% of the study area.

4.2.2 Relative Weight of Environmental Criteria

The results of the Analytic Hierarchy Process (AHP) are shown in Table 4.2. Proneness to surface flooding was defined as the most important environmental criterion (RW = 0.22) while the least important criterion was proximity to greenspaces (RW = 0.05). The results of the AHP were consistent since the consistency index (CI) and consistency ratio (CR) were below 0.14 and 0.10, respectively (Saaty, 1980).

Table 4.2 Relative Weight of Environmental Criteria.

Environmental Criteria	Relative Weight (RW)
Soil texture	0.17
Slope gradient	0.19
Slope curvature	0.16
Slope aspect	0.07
Proneness to surface flooding	0.22
Land cover	0.08
Proximity to greenspaces	0.05
Proximity to healthy vegetation	0.06
CI	**0.08**
CR	**0.05**

The overall spatial suitability for LPD creation was computed through simple additive weighting (SAW; Equation 1) using the relative weights resulting from the AHP (Table 4.2):

$$Spatial\ Suitability\ for\ LPD\ Creation = 0.17 \times Soil\ Texture + 0.19 \times Slope\ Gradient + 0.16 \times Slope\ Curvature + 0.07 \times Slope\ Aspect + 0.22 \times Proneness\ to\ Surface\ Flooding + 0.08 \times Land\ Cover + 0.05 \times Proximity\ to\ Greenspaces + 0.06 \times Proximity\ to\ Healthy\ Vegetation \quad \text{Eq. 1}$$

4.2.3 Opportunity Sites for LPD Creation

The combination of the considered environmental criteria through SAW resulted in the opportunity sites for LPD creation in Glasgow (Figure 4.6). Optimal suitability for LPD creation was found for 27.94% of the study area (Table 4.3). Additionally, 33.48% of the city accounted for restricted areas due to built-up environment (i.e., buildings, structures, roads, rails, tracks, and paths) and open water environments, while 38.58% showed unsuitability for LPD creation.

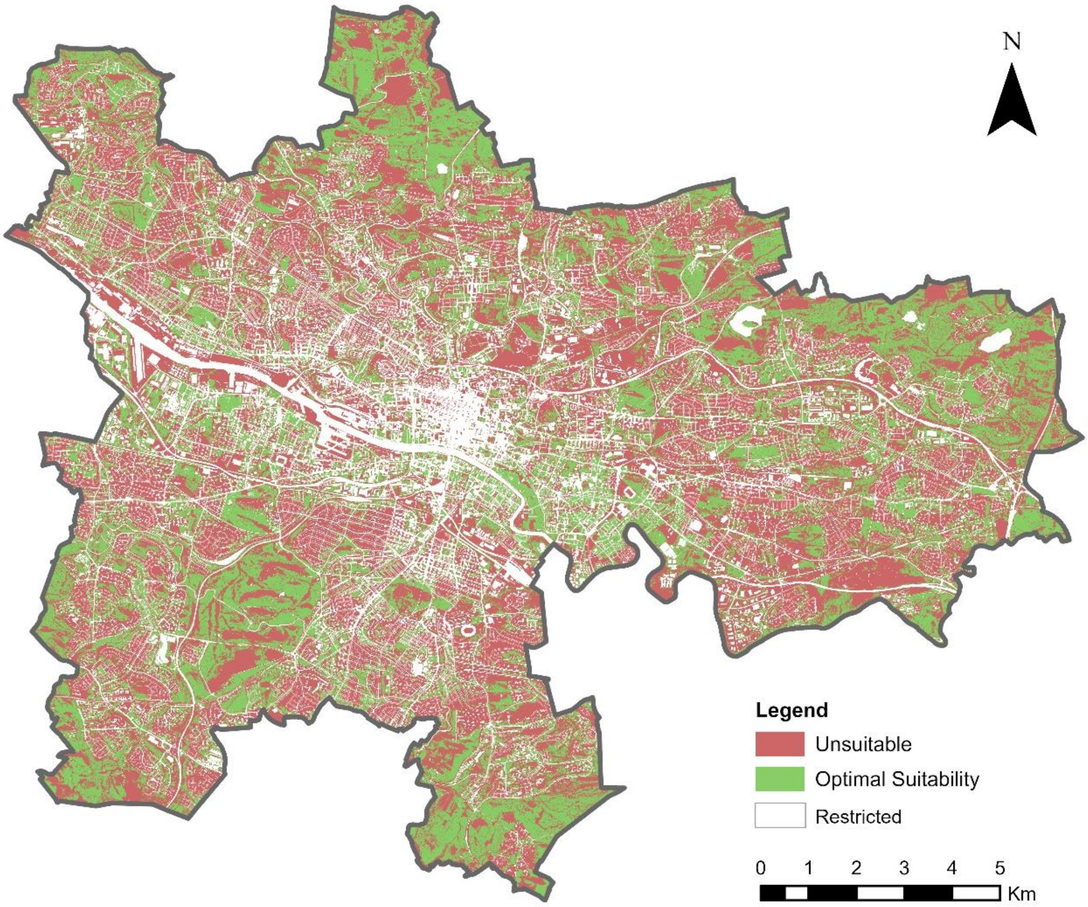


Figure 4.6 Opportunity sites for LPD creation within Glasgow City.

Table 4.3 Land suitability for LPD creation within Glasgow City.

Suitability Class	Total Surface Area (km²)	Proportion (%)
Restricted	59.40	33.48
Unsuitable	68.43	38.58
Optimal	49.57	27.94

Areas close to ponding zones (i.e., with a distance between 100m and 400m; Figure 4.5e) with a slope gradient below 15º (Figure 4.5b) were the most favourable criteria for LPD creation. While 22.71% of Glasgow's area had an optimal condition within the former (APPENDIX VII), over 90% of the surface land presented optimal suitability for the latter (APPENDIX VII). Additionally, soil texture (Figure 4.5a) had significant impact on the final suitability map (Figure 4.6). Not only this environmental criterion was considered the third most important criterion (Table 4.2), but it was identified that Glasgow City area did not present optimal conditions for LPD creation (APPENDIX VII).

Urbanisation had a significant impact on the availability of opportunity sites for LPD creation in Glasgow (Figure 4.6). On the one hand, slope curvature (Figure 4.5c) showed an optimal suitability for over 90% of Glasgow City's area. Remarkably, almost 80% of the area with a planar surface, showing that majority of the Glasgow's surface had been already modified by urbanisation. On the other hand, 33.48% of the study area showed a land cover classification as restricted following the rule that buildings, structures, rails, roads, tracks, and paths cannot be transformed into LPDs (Figure 4.5f)

Ultimately, the identification of optimal conditions for LPD creation (Figure 4.6) was also affected by slope aspect (Figure 4.5d), proximity with healthy vegetation (Figure 4.5h) and proximity to greenspaces (Figure 4.5g). However, these environmental criteria were classified as less important criteria (Table 4.2) by expert's opinion through the AHP, resulting in lower impact on the final output map.

4.2.4 Further Analysis

Further analysis prioritised the use of vacant and derelict lands in Glasgow for LPD creation. As previously shown, Glasgow City has a total of 9.38km² of its land classified as vacant or derelict, from which 4.12km² are under property of local council authority (LCA; Ordnance Survey (2021b)). Based on the optimal locations identified within the opportunity sites for LPD creation map (Figure 4.6), 47.82% of the vacant and derelict land owned by LCA

presented optimal suitability to implement LPDs (Figure 4.7). More specifically, over 5% (i.e., 0.23km²) of vacant and derelict land were identified with a great potential (i.e., suitability score between 4.5 and 5.0) for LPD creation.

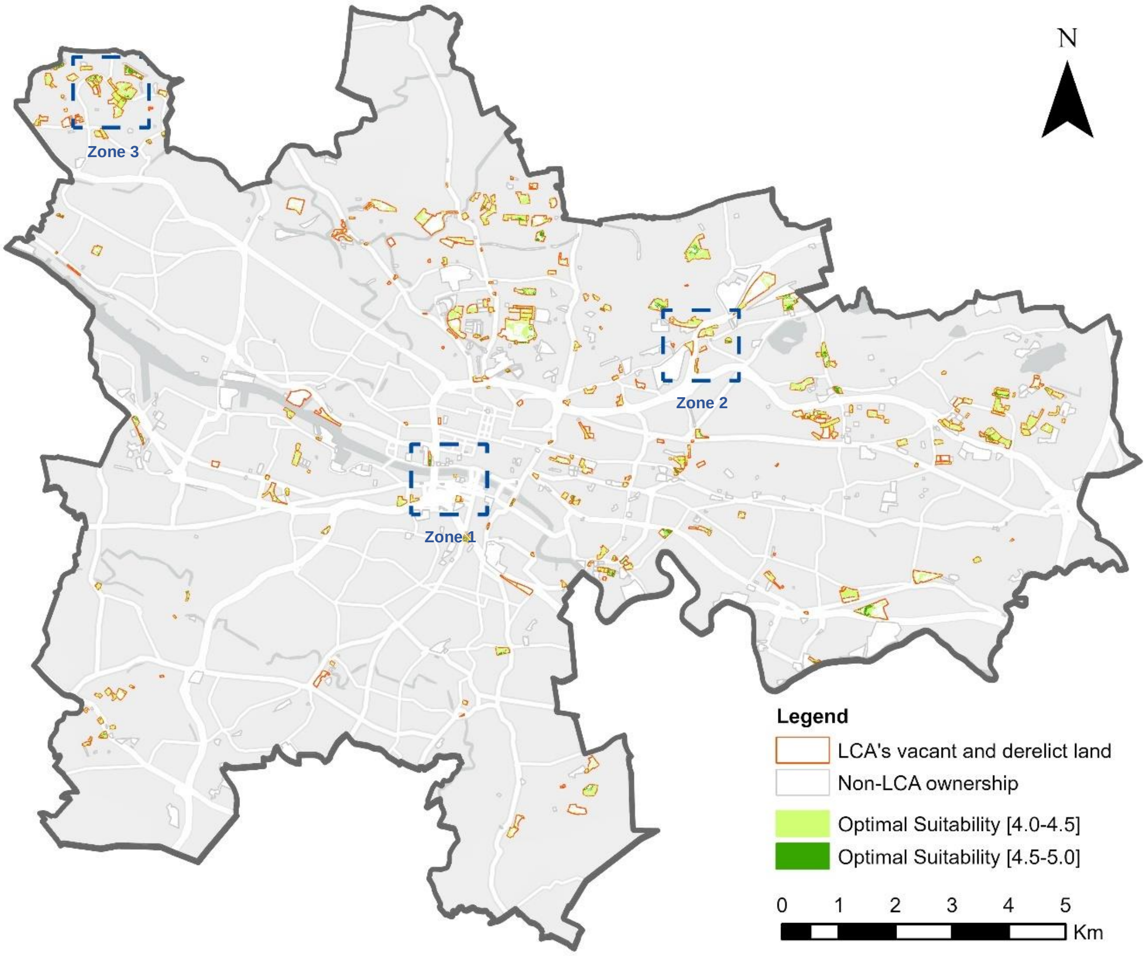


Figure 4.7 LCA’s vacant and derelict land and its suitability score for LPD creation.

Figure 4.7 also shows three delimitated zones, which were expanded in Figure 4.8 to explore in detail the suitability of LCA’s vacant and derelict land for LPD creation. An initial comparison of the spatial analysis’ outputs (Figure 4.8a) against satellite imagery (Figure 4.8b-c) validated the method herein applied, confirming that it was successful in identifying the opportunity sites for LPDs creation within Glasgow. Additionally, detailed assessment of these zones allowed a better understanding of the scale and shape of the opportunity sites for LPD creation within the urban land owned by the local council authority. More importantly, it delivered accurate information on suitability of vacant and derelict land to allocate the first ever seen LPD in a city.

Figure 4.8 Detailed outputs of LCA's vacant and derelict land for LPD creation. (a) Outputs of the spatial analysis and optimal suitability for LPD creation. (b) Satellite imagery and optimal suitability for LPD creation. (c) Satellite imagery of LCA's vacant and derelict land.

4.3 Eco-hydrological Performance of LPD

4.3.1 Soil Water Mass Balance (SWMB)

The results for the different soil water mass balance (SWMB) components — i.e., surface runoff, subsurface flow, percolation, and water retention — gathered through the

experimental assessment of eco-hydrological performance of LPDs are show in Figure 4.9a-d and Table 4.4. The volume of water loss is also show in Figure 4.9e and Table 4.4.

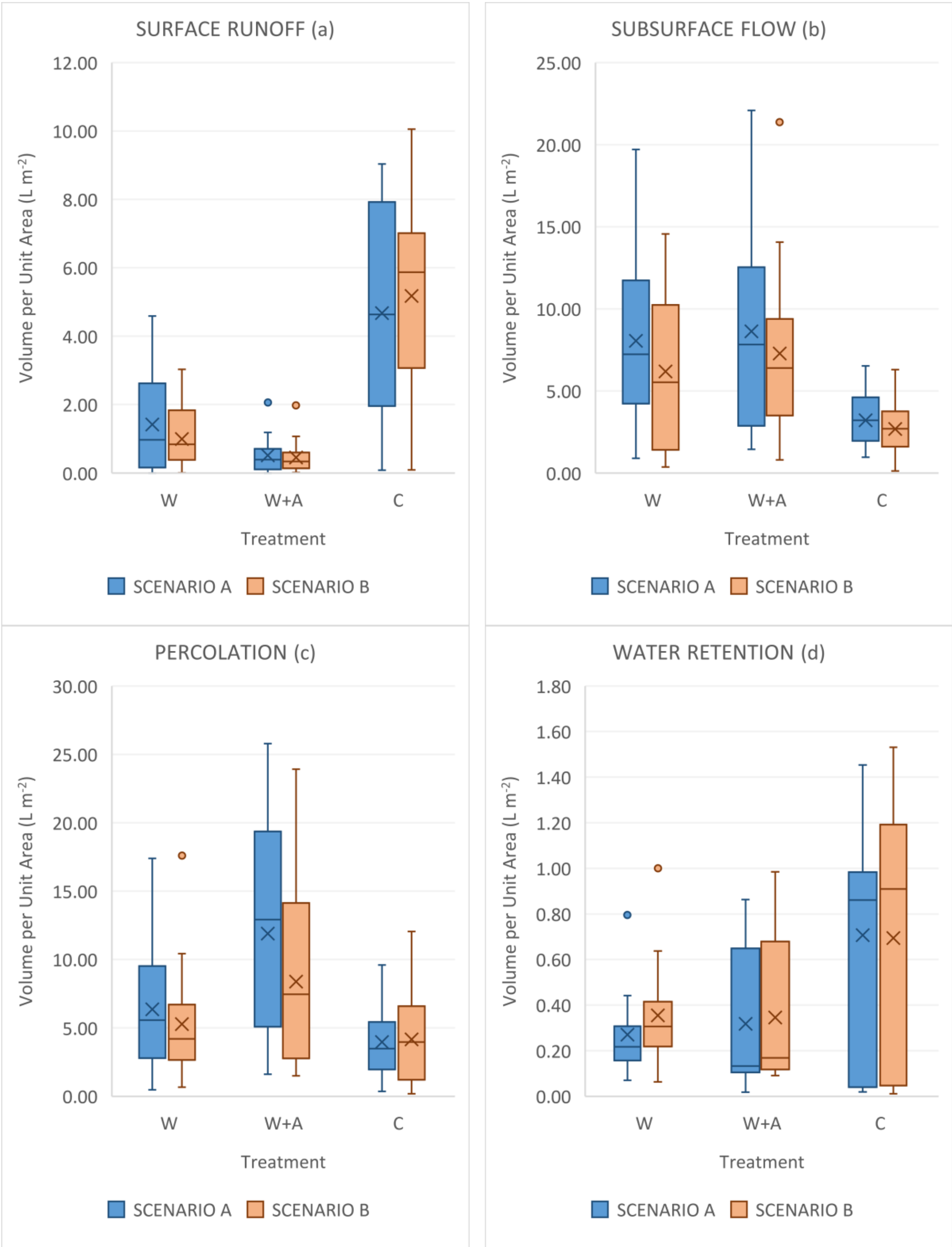


Figure 4.9 Soil water mass balance (SWMB). (a) Surface runoff; (b) Subsurface flow; (c) Percolation; (d) Water retention; (e) Water loss. Water volume per unit area (L m^{-2}) under willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C) treatments, at different scenarios (A: soil at water saturation; B: soil at field capacity).

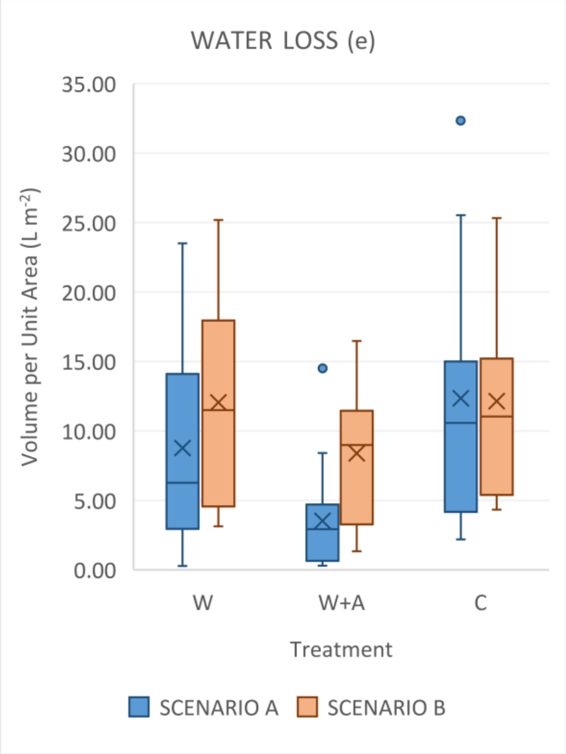


Figure 4.9-Cont'd. Soil water mass balance (SWMB). (a) Surface runoff; (b) Subsurface flow; (c) Percolation; (d) Water retention; (e) Water loss. Water volume per unit area (L m^{-2}) under willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C) treatments, at different scenarios (A: soil at water saturation; B: soil at field capacity).

Table 4.4 Summary of soil water mass balance (SWMB).

		W		W+A		C	
		L m^{-2}	**%**	**L m^{-2}**	**%**	**L m^{-2}**	**%**
Surface Runoff	mean (A)	1.42	6.10	0.51	2.33	4.68	18.96
	range (A)	0.00 - 4.59	0.00 - 18.48	0.00 - 2.06	0.00 - 8.31	0.08 - 9.04	1.32 - 42.77
	mean (B)	0.99	4.41	0.45	1.68	5.18	19.02
	range (B)	0.01 - 3.03	0.07 - 16.28	0.01 - 1.98	0.23 - 7.96	0.09 - 10.05	1.44 - 39.78
Subsurface Flow	mean (A)	8.06	31.24	8.63	32.50	3.22	13.83
	range (A)	0.89 - 19.70	14.36 - 64.67	1.44 - 22.08	11.54 - 50.77	0.96 - 6.52	7.84 - 19.39
	mean (B)	6.18	22.92	7.28	28.62	2.67	10.22
	range (B)	0.36 - 14.56	2.94 - 46.87	0.80 - 21.237	12.83 - 49.15	0.12 - 6.30	1.91 - 17.15
Percolation	mean (A)	6.36	25.39	11.90	44.86	3.96	15.30
	range (A)	0.48 - 17.39	7.70 - 41.76	1.62 - 25.79	21.24 - 62.35	0.37 - 9.60	5.88 - 24.28
	mean (B)	5.29	20.11	8.39	31.22	4.16	14.80
	range (B)	0.67 - 17.59	9.99 - 40.45	1.50 - 23.91	13.20 - 56.87	0.19 - 12.05	3.02 - 27.72
Water Retention	mean (A)	0.25	1.30	0.27	1.74	0.65	3.53
	range (A)	0.00 - 0.80	0.00 - 3.41	0.00 - 0.86	0.00 - 12.08	0.00 - 1.45	0.00 - 13.09
	mean (B)	0.36	2.46	0.35	2.10	0.69	3.26
	range (B)	0.06 - 1.00	0.14 - 16.11	0.09 - 0.98	0.26 - 10.94	0.01 - 1.53	0.10 - 7.05
Water Loss	mean (A)	8.76	35.98	3.53	18.57	12.35	48.38
	range (A)	0.27 - 23.49	1.47 - 57.74	0.28 - 14.50	1.17 - 58.36	2.18 - 32.34	14.38 - 74.37
	mean (B)	12.04	50.10	8.38	36.38	12.14	52.70
	range (B)	3.12 - 25.18	19.43 - 73.30	1.34 - 16.46	10.63 - 63.14	4.31 - 25.31	26.55 - 86.69

Overall, willow LPD with alfalfa (W+A) decreased 90% of surface runoff and 54% of water retention compared to fallow soil (C), while subsurface flow and percolation increased in 170% and 150%, respectively. Under the willow LPD (W) treatment, a reduction of 76% and 55% of surface runoff and water retention, respectively, were observed when compared to fallow soil. An increase of 142% in subsurface flow and 43% in percolation was also noted under the W treatment.

Statistically significant differences were noted between the three treatments (i.e., willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C)). Among the SWMB components, surface runoff (Figure 4.9aFigurea; H = 36.23, df = 2, $p < 0.01$), subsurface flow (Figure 4.9bFigureb; H = 17.88, df = 2, $p < 0.01$), and percolation (Figure 4.9bFigureb; H = 11.60, df = 2, $p < 0.01$) showed substantial differences. Although water retention was different between the three treatments, it was not as substantial as in the other SWMB components (Figure 4.9dFigured; H = 5.22, df = 2, $p = 0.07$). Water loss had significant differences between treatments (Figure 4.9eFiguree; H = 13.00, df = 2, $p < 0.01$).

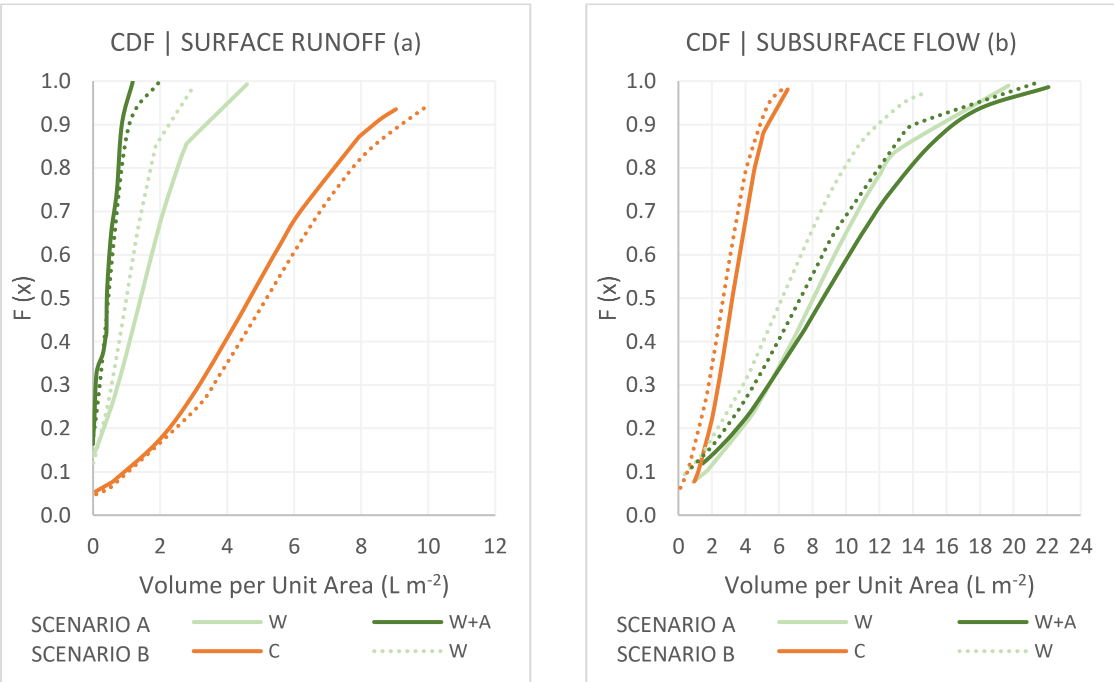
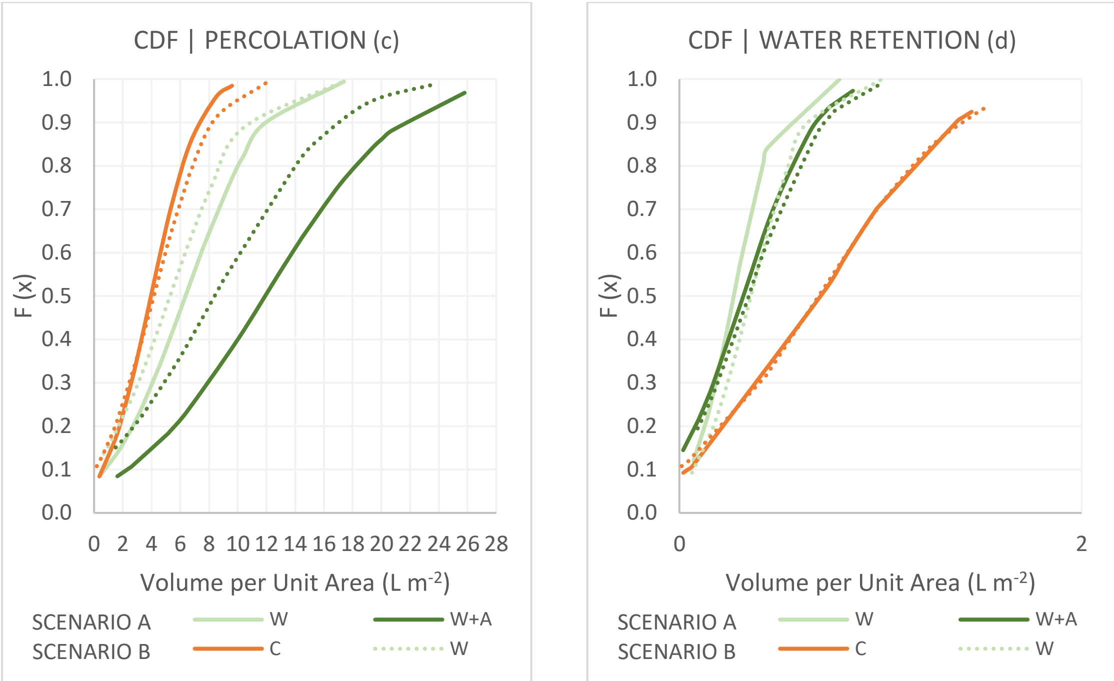


Figure 4.10 Soil water mass balance (SWMB) CDFs. Cumulative distribution functions (CDF) for the Soil Water Mass Balance (SWMB). (a) Surface runoff; (b) Subsurface flow; (c) Percolation; (d) Water retention; (e) Water loss. Water volume per unit area (L m^{-2}) under willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C) treatments, at different scenarios (A: soil at water saturation; B: soil at field capacity).



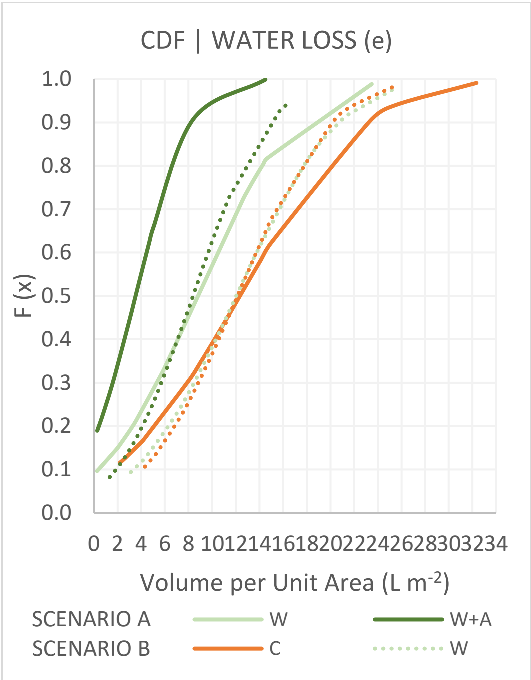


Figure 4.10-Cont'd. Soil water mass balance (SWMB) CDFs. Cumulative distribution functions (CDF) for the Soil Water Mass Balance (SWMB). (a) Surface runoff; (b) Subsurface flow; (c) Percolation; (d) Water retention; (e) Water loss. Water volume per unit area (L m^{-2}) under willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C) treatments, at different scenarios (A: soil at water saturation; B: soil at field capacity).

Surface runoff was substantially higher in fallow soil (C) than in the vegetated treatments at both scenarios (W(A): D = 0.67 $p < 0.01$; W(B): D = 0.80 $p < 0.01$; W+A(A): D = 0.73 $p < 0.01$; W+A(B): D = 0.80 $p < 0.01$). When comparing the two vegetated treatments against each other, the observed surface runoff differences were not statistically significant (A: D = 0.47 $p = 0.08$; B: D = 0.40 $p = 0.18$).

Conversely, significantly higher subsurface flow was observed under the vegetated treatments (W(A): D = 0.60 $p < 0.01$; W(B): D = 0.53 $p < 0.05$; W+A(A): D = 0.60 $p < 0.01$; W+A(B): D = 0.60 $p < 0.01$), being the lowest observed subsurface flow under fallow soil

(C). Between the vegetated treatments, the found differences were not significant (A: D = 0.13 p = 1.00; B: D = 0.20 p = 0.94).

Willow LPD with alfalfa (W+A) showed higher percolation than under willow LPD (W) and fallow soil (C). Statistically, the only significant difference for percolation was found between the willow LPD with alfalfa (W+A) and fallow soil (C) at scenario A (D = 0.60 $p < 0.01$). At scenario A, the observed results were not significantly different between the vegetated treatments (D = 0.47 p = 0.08) and between willow LPD (W) and fallow soil (D = 0.40 p = 0.18). At scenario B, vegetated treatments statistically did not differ from fallow soil (W: D = 0.20 p = 0.94 and W+A: D = 0.40 p = 0.18). Between the two LPDs, the same pattern was found (D = 0.33 p = 0.39).

Regarding water retention, the highest volumes per unit area were observed under fallow soil (C). However, these results were statistically significant only at scenario A (W(A): D = 0.60 $p < 0.01$; W(B): D = 0.47 p = 0.08; W+A(A): D = 0.53 $p < 0.05$; W+A(B): D = 0.47 p = 0.08). Between the vegetated treatments, the found differences were not significant (A: D = 0.47 p = 0.08; B: D = 0.47 p = 0.08).

Water loss was similar across the three treatments and two scenarios, apart from the values observed between the willow LPD with alfalfa (W+A) and fallow soil (C) at scenario A (D = 0.60 $p < 0.01$). At scenario A, the observed differences were not statistically significant between the vegetated treatments (D = 0.47 p = 0.08) and between willow LPD (W) and fallow soil (D = 0.27 p = 0.68). At scenario B, vegetated treatments statistically did not differ from fallow soil (W: D = 0.20 p = 0.94 and W+A: D = 0.33 p = 0.39). The same statistical similarity was identified between the vegetated treatments (D = 0.33 p = 0.39).

4.3.2 Soil-Water Dynamics

4.3.2.1 Volumetric soil moisture content

The time series for the hourly volumetric soil moisture content (θ; Figure 4.11Figure 4.12) showed clear differences between treatments. The highest θ recorded of 44.95% was found at the willow LPD (W) on June 16th. The lowest θ of 27.96% was found at fallow soil (C) on June 13th. A positive response of θ to rainfall simulations was typically observed throughout the experiment.

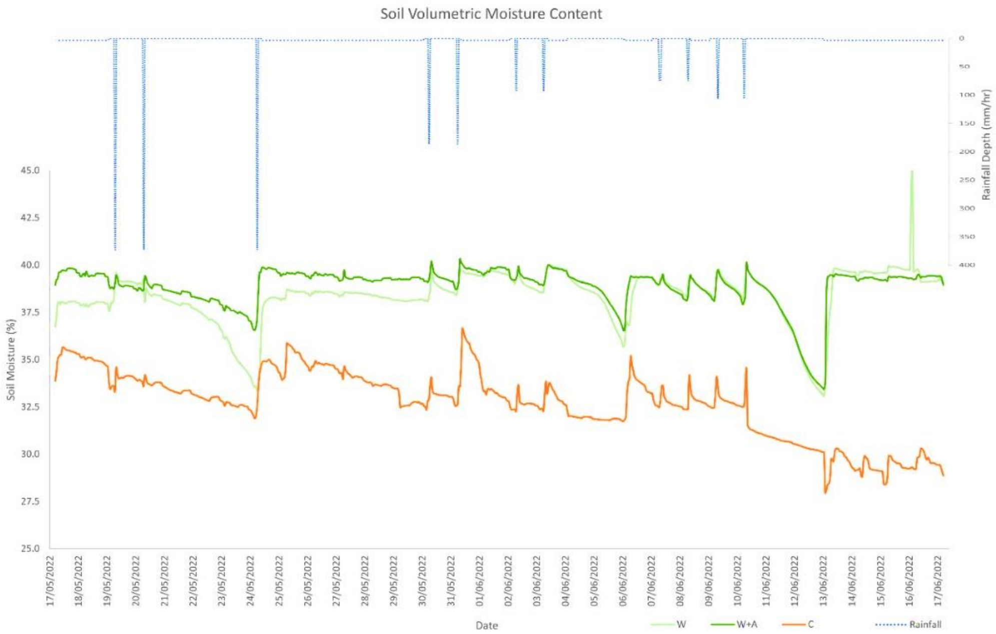


Figure 4.11 Volumetric soil moisture content during experiment. Hourly volumetric soil moisture content (θ; %) time series recorded under the willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C). The time series are plotted together with simulated rainfall events (depth; mm/hr).

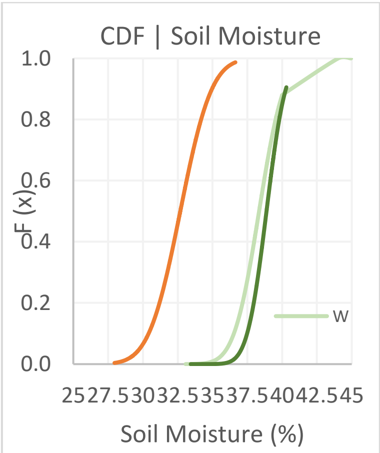


Figure 4.12 Volumetric soil moisture content CDFs. Cumulative distribution functions (CDF) for the hourly volumetric soil moisture content (θ; %) time series recorded under the willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C).

Throughout the observation period, θ under fallow soil (C) was constantly lower than θ under the willow LPD (W) and willow LPD with alfalfa (W+A), showing significant differences between non- and vegetated treatments (W: D = 0.92 $p < 0.01$; W+A: D = 0.96 $p < 0.01$). Between the vegetated treatments, θ under W+A was generally higher than θ under W. This observation shifted after June 14th. Additionally, vegetated treatments showed similar θ values throughout the times series plot, but the differences remained statistically significant (D = 0.32 $p < 0.01$).

The θ differences between the LPD treatments were more noticeable under drying soil conditions (i.e., when nor irrigation was supplied or rainfall was simulated, e.g., θ from May 21st to May 24th, and from June 4th to June 6th) than during wetting soil conditions (i.e., when irrigation was supplied or rainfall was simulated, e.g., θ from June 8th to June 9th). Lastly, an

anomaly was noticed in the time series plot i.e., θ under willow LPD (W) on June 16th, in which the highest θ value of 44.95% was recorded.

4.3.2.2 Soil matric suction

The time series for the hourly soil matric suction (φ; Figure 4.13-Figure 4.14) showed clear differences between the three treatments. The highest φ recorded of -90.22 kPa was found at fallow soil (C) on June 12th. The lowest φ of -0.36 kPa was found at the willow LPD (W) on June 14th. A negative response of φ to rainfall simulations was generally observed throughout the time series plot.

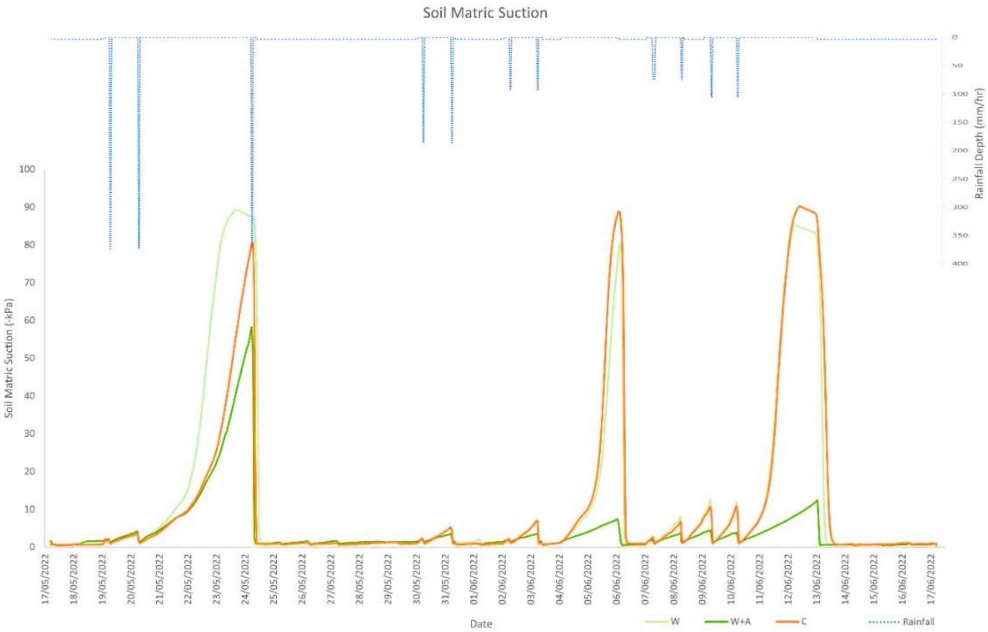


Figure 4.13 Soil matric suction during experiment. Hourly soil matric suction (φ; -kPa) time series recorded under the willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C). The time series are plotted together with simulated rainfall events (depth; mm/hr).

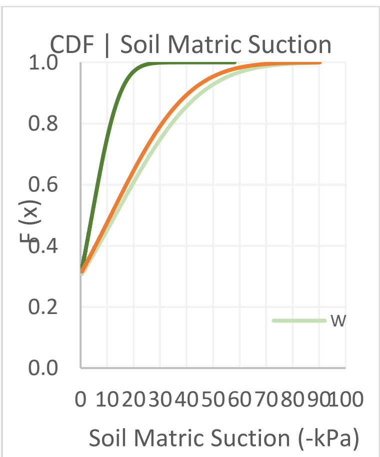


Figure 4.14 Soil matric suction CDFs. Cumulative distribution functions (CDF) for the hourly soil matric suction (φ; -kPa) time series recorded under the willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C).

Statistically, substantial *φ* differences were noted between fallow soil (C) and vegetated treatments (W: D = 0.12 $p < 0.01$; W+A: D = 0.13 $p < 0.01$). Throughout the experiment, *φ* under the willow LPD (W) showed similar *φ* values to fallow soil (C). This behaviour was not observed when comparing fallow soil (C) with the willow LPD with alfalfa (W+A) treatment. Additionally, the *φ* differences between the three treatments were more noticeable under drying soil conditions (i.e., when nor irrigation was supplied or rainfall was simulated, e.g., *φ* from May 21st to May 24th; from June 4th to June 6th; and from June 11th to June 13th) than during wetting soil conditions (i.e., when irrigation was supplied or rainfall was simulated, e.g., *φ* from May 25th to May 31st, and from June 14th to June 17th).

Between the vegetated treatments, *φ* under W+A was generally lower than *φ* under W, showing significant differences throughout the observation period (D = 0.14 $p < 0.01$). Pattern changes on *φ* under the vegetated treatments (W and W+A) were found when comparing the time series plots during the three major drying soil conditions periods (i.e., from May 21st to May 24th; from June 4th to June 6th; and from June 11th to June 13th). During the first drying soil conditions period, W showed the highest *φ,* while W+A reached a *φ* of -60kPa. These observations were not found during the second and third drying soil conditions periods, in which fallow soil (C) showed the highest *φ* values, and W+A reached *φ* values below -15kPa.

4.3.2.3 Soil temperature

The time series for the hourly soil temperature (*t*; Figure 4.15Figure 4.16) generally showed clear differences between treatments. The highest *t* recorded of 23.27ºC was found at the fallow soil (C) on May 24th. The lowest *t* of 17.95ºC was found at the willow LPD (W) on May 18th. A negative response of *t* to rainfall simulations was typically observed throughout the experiment.

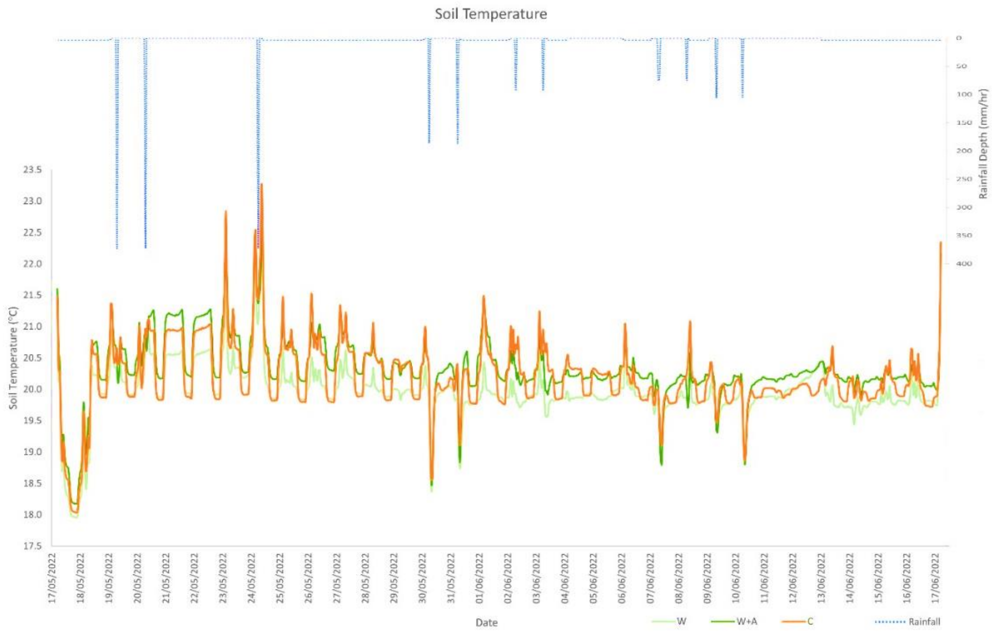


Figure 4.15 Soil temperature during experiment. Hourly soil temperature (*t*; ºC) time series recorded under the willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C). The time series are plotted together with simulated rainfall events (depth; mm/hr).

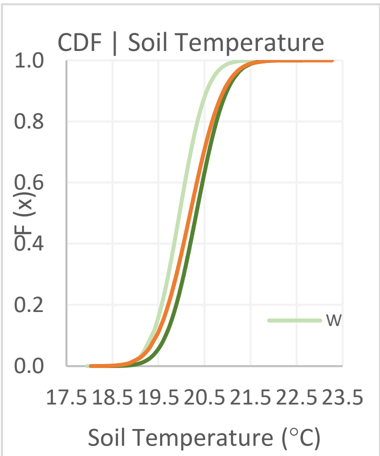


Figure 4.16 Soil temperature CDFs. Cumulative distribution functions (CDF) for the hourly soil temperature (*t*; ºC) time series recorded under the willow LPD (W), willow LPD with alfalfa (W+A), and fallow soil (C).

Statistically, *t* differences were noted between fallow soil (C) and vegetated treatments (W: D = 0.27 $p < 0.01$; W+A: D = 0.36 $p < 0.01$). Between the vegetated treatments, *t* under W+A was generally higher than *t* under W, showing substantial *t* differences throughout the observation period (D = 0.61 $p < 0.01$).

Major fluctuations on *t* were also noted within the three treatments time series plots. These fluctuations derived from the influence of artificial daily sunlight provided to foster plant development. Overall, *t* was usually higher during the day (from 6am to 10pm) and lower throughout the night (from 10pm to 6am).

4.3.3 Plant Growth

4.3.3.1 Plant cover establishment

The plant cover establishment (i.e., the number of resprouting willow stems during the LPD pilot experiment) is shown in Table 4.5. Figure 4.17 shows the plant cover establishment on day 50 of the laboratory experiment. Overall, 136 willow stems grew within a total surface area of $0.30 m^2$ (453.33 individuals per m^2). While 71 new willows grew under the willow LPD (W) treatment, 65 new individuals were observed within the willow LPD with alfalfa (W+A). Additionally, the highest recorded number of new willows per zone was found at the crest (i.e., total of 50 new individuals). New willow aboveground vegetation differences between treatments were not statically significant ($H = 0.43$, $df = 1$, $p = 0.51$), as well as the differences between zones ($H = 2.57$, $df = 2$, $p = 0.28$).

Table 4.5 Plant cover establishment during the LPD pilot experiment.

	W	W+A	Total per zone
Crest	24	26	50
Middle	22	18	40
Toe	25	21	46
Total per treatment	71	65	136

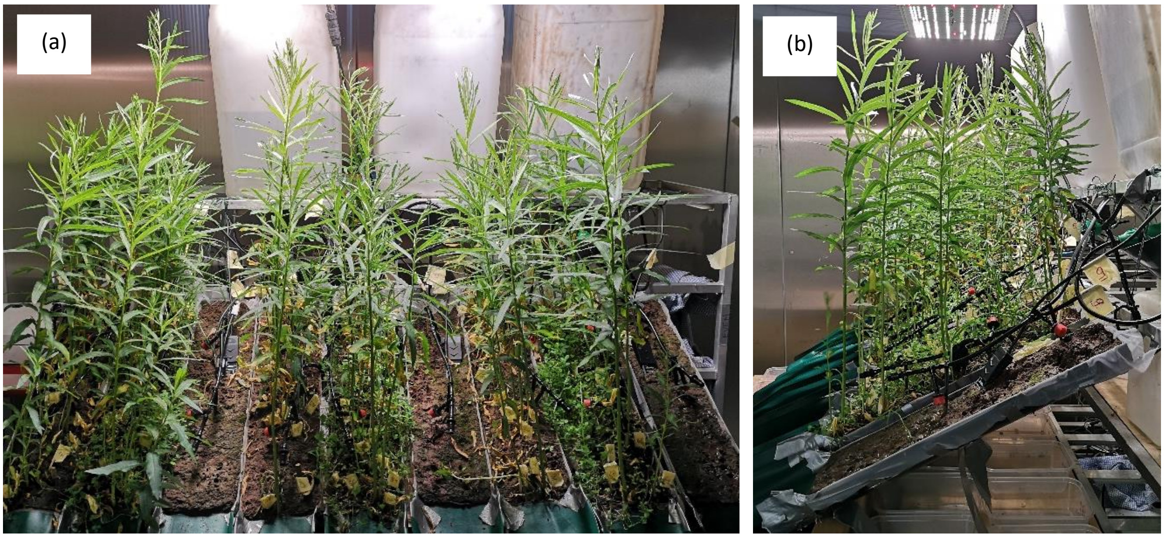


Figure 4.17 Plant cover establishment on day 50 of the experiment. (a) frontal view; (b) lateral view.

4.3.3.2 Plant growth rate (PGR)

The summary of the plant growth rate (i.e., the development of the resprouted willow stems during the LPD pilot experiment; PGR) is shown in Table 4.6. Figure 4.18 shows the development of the willow stems throughout the observation period, at day 3, 11, 20, 27, 32, 36, 46, and 52. Both highest and lowest PGRs were found under the willow LPD (W) treatment at the middle zone. Overall, mean PGR under the W+A treatment was 19% lower than under W treatment.

Table 4.6 Plant growth rate (PGR) during the LPD pilot experiment.

Treatment	Zone	Highest PGR	Lowest PGR	Mean PGR	Std Dev PGR
W	Crest	0.191	0.031	0.084	± 0.033
	Middle	0.309	0.005	0.099	± 0.055
	Toe	0.206	0.022	0.085	± 0.033
W+A	Crest	0.188	0.045	0.076	± 0.028
	Middle	0.101	0.020	0.064	± 0.022
	Toe	0.122	0.049	0.075	± 0.018

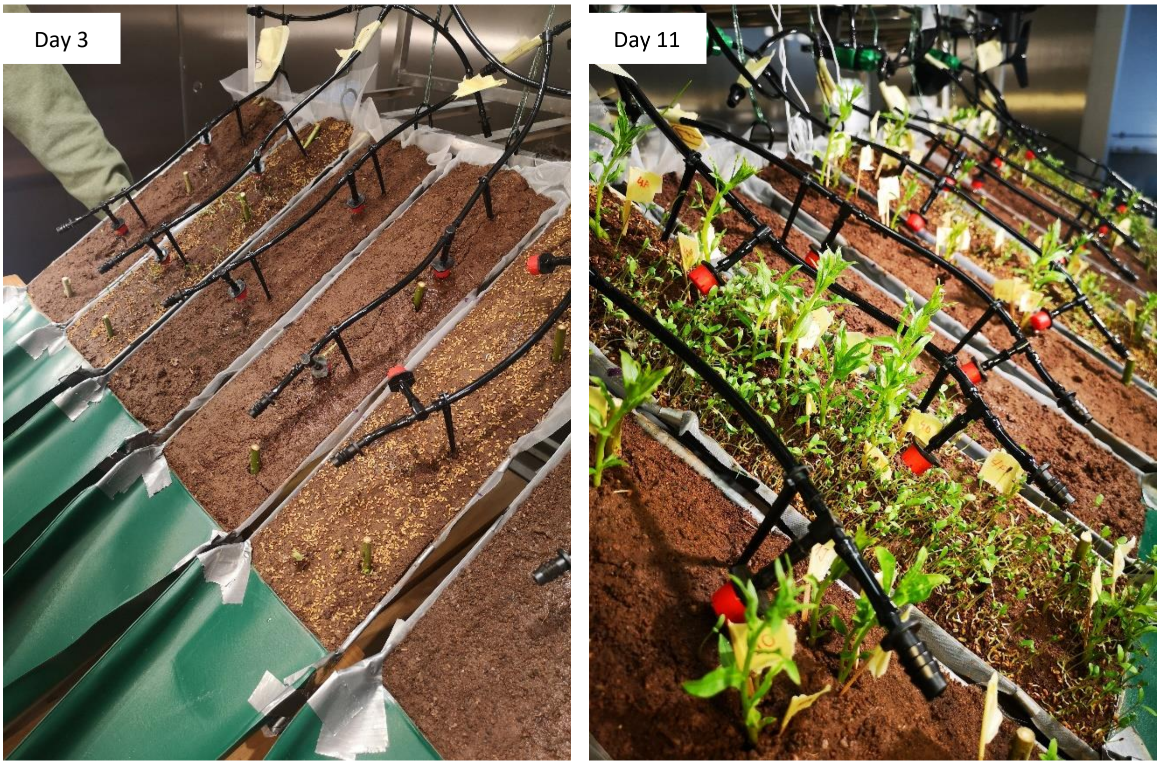


Figure 4.18 Plant growth rate (PGR) during the experiment.

Figure 4.18-Cont'd. Plant growth rate (PGR) during the experiment.

Figure 4.18-Cont'd. Plant growth rate (PGR) during the experiment.

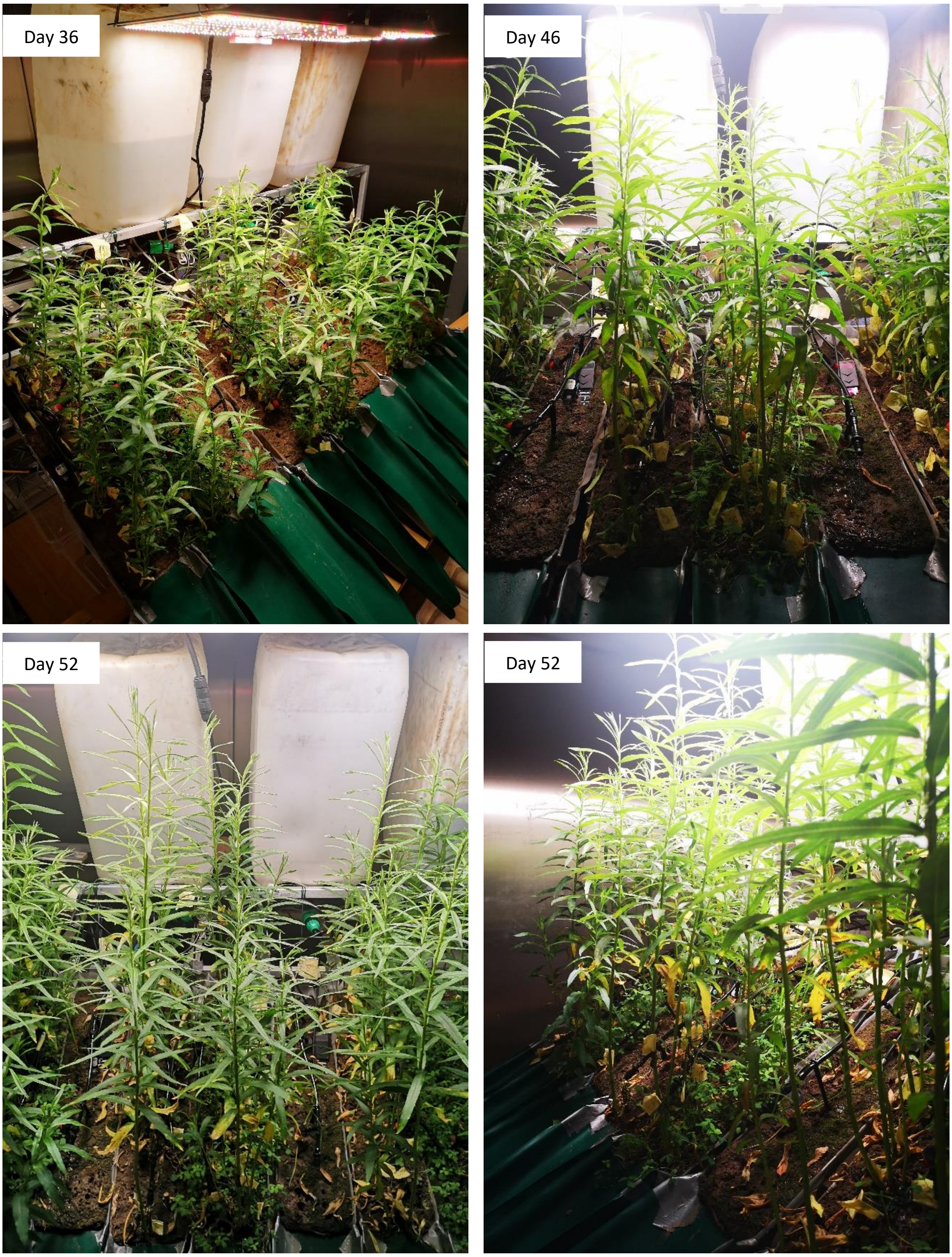


Figure 4.18-Cont'd. Plant growth rate (PGR) during the experiment.

Statistically significant differences were found between treatments (i.e., willow LPD (W), and willow LPD with alfalfa (W+A)) in terms of PGR ($H = 7.69$, $df = 1$, $p < 0.01$). The PGR differences were substantial at the middle zone ($H = 0.49$, $p < 0.05$; Figure 4.19b).

Significant differences between treatments in terms of PGR were not found at the crest and toe zones (H = 0.23, *p* = 0.41, and H = 0.24, *p* = 0.46, respectively; Figure 4.19a and Figure 4.19c). The observed differences in terms of PGR between the three zones (i.e., crest, middle and toe; Figure 4.19d-e) within a given vegetated treatment were not statistically significant (H = 0.07, df = 2, *p* = 0.97).

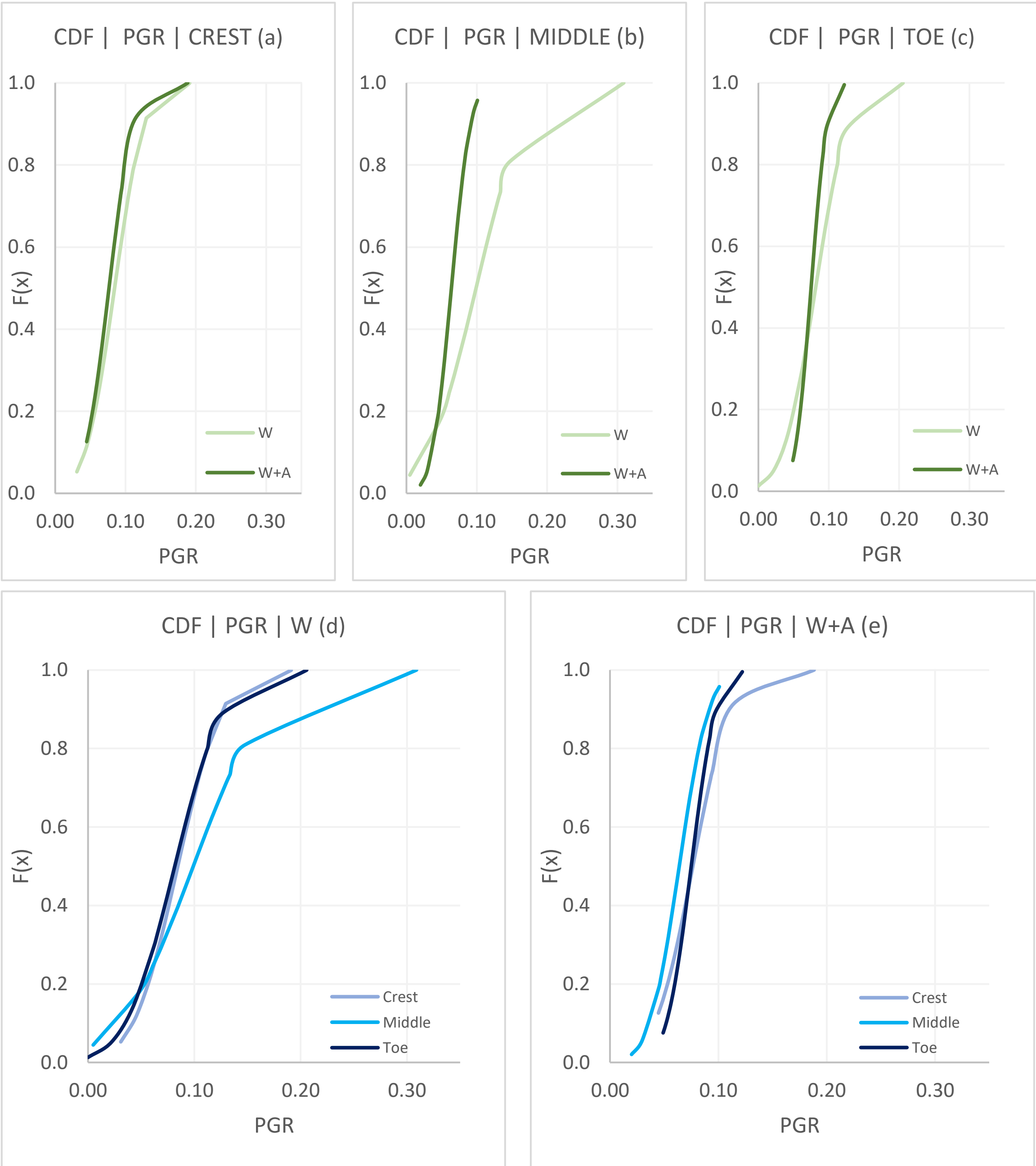


Figure 4.19 Plant growth rate (PGR) CDFs. Cumulative distribution functions (CDF) for the plant growth rate (PGR) at (a) crest, (b) middle, and (c) toe zones under the (d) willow LPD (W) and (e) willow LPD with alfalfa treatments.

4.3.3.3 Above- and belowground biomass

A biometric relationship between willow stem diameter and aboveground willow dry biomass (i.e., sum of leaf dry biomass and stem dry biomass) is shown in Figure 4.20a. A second-order polynomial regression was fitted satisfactorily to the data (R^2: 0.8492). Based on this biometric relationship, it was estimated that the total aboveground dry biomass of 18 randomly selected willow stems (Figure 4.20b) at day 18 (34.54g), day 32 (43.51g), and day 46 (95.97g) of the LPD pilot experiment.

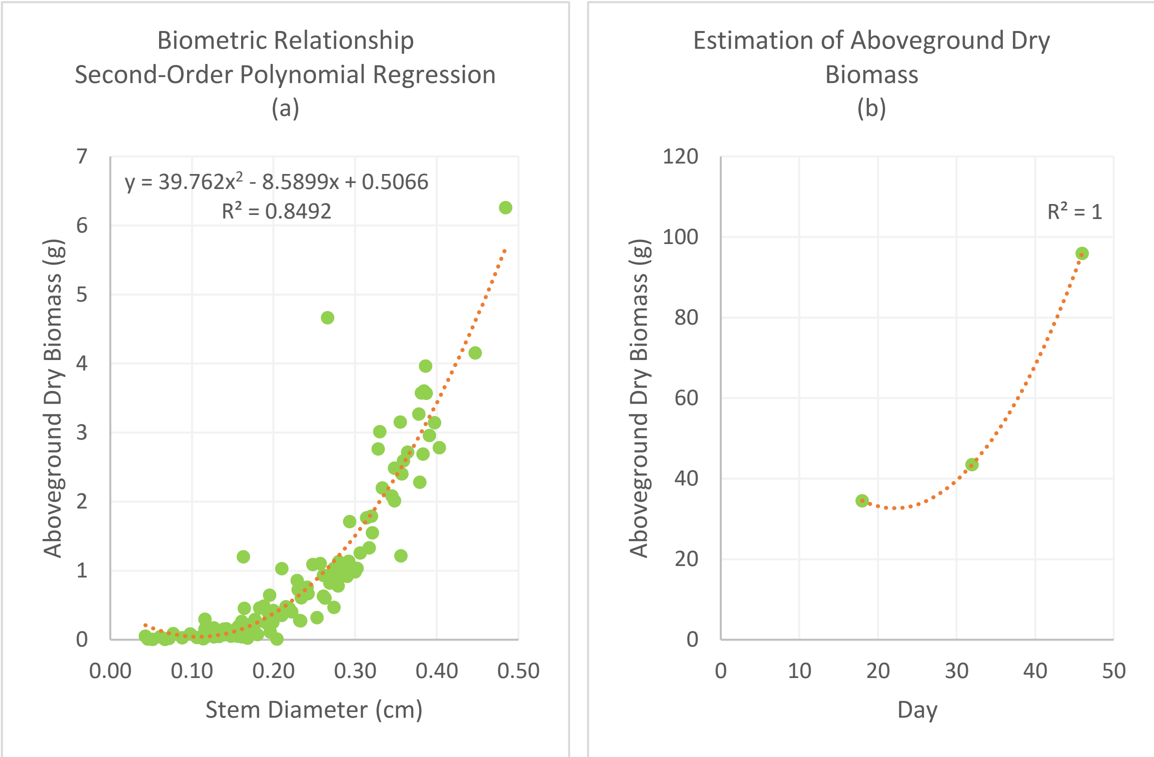


Figure 4.20 Biometric relationship. (a) Biometric relationship between stem diameter and aboveground dry biomass; (b) Estimation of aboveground dry biomass.

The allometric relationship between aboveground willow dry biomass and belowground willow dry biomass is shown in Figure 4.21a. A second-order polynomial regression was fitted satisfactorily to the data (R^2: 0.9332). Based on the allometric relationship, it was estimated that the total belowground dry biomass of 18 randomly selected willow stems (Figure 4.21b) at day 18 (224.38g), day 32 (356.96g), and day 46 (1,745.31g) of the LPD pilot experiment.

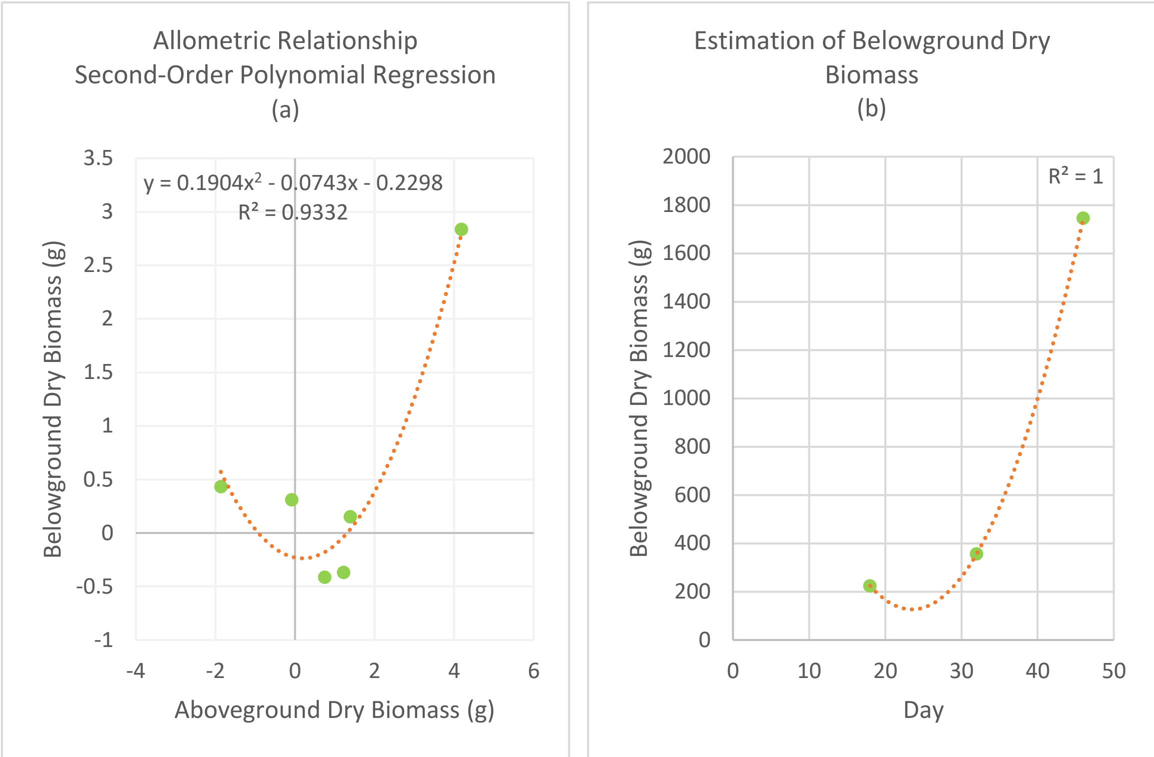


Figure 4.21 Allometric relationship. (a) Allometric relationship between above- and belowground dry biomass; (b) Estimation of belowground dry biomass.

4.4 Integration Analysis

The design of the first Live Pole Drain (LPD) in a city is shown in Figure 4.22. The LPD was designed on a plot within Zone 1 (Figure 4.23a-e; Section 4.2.4), which is close to city centre. This area was chosen since there is a lack of greenspaces at downtown, and implementation of an LPD would deliver the currently inexistent ecosystems services to community and wildlife within this area of Glasgow. The plot is close to areas prone to flooding (Figure 4.23c), with a flat/gentle slope gradient (Figure 4.23d) and with a soil textural classification of clay to sandy loam (Figure 4.23e). To build the LPD, healthy vegetation can be obtained within 100m (Figure 4.23b).

The LPD design followed the surface water flow accumulation of the plot (Figure 4.23b). It has a surface area of 64.5m² (eight live fascines and one pole drain; total length 215m and width 0.3m). By upscaling the results obtained during simulated wetting soil conditions (Section 4.3.1) under the willow LPD with alfalfa (W+A), this design would decrease 286.60 litres of surface runoff and 23.24 litres of water retention in soil. Subsurface flow and percolation would be enhanced within the soil, resulting in an increase of 323.28 litres and 392.52 litres, respectively.

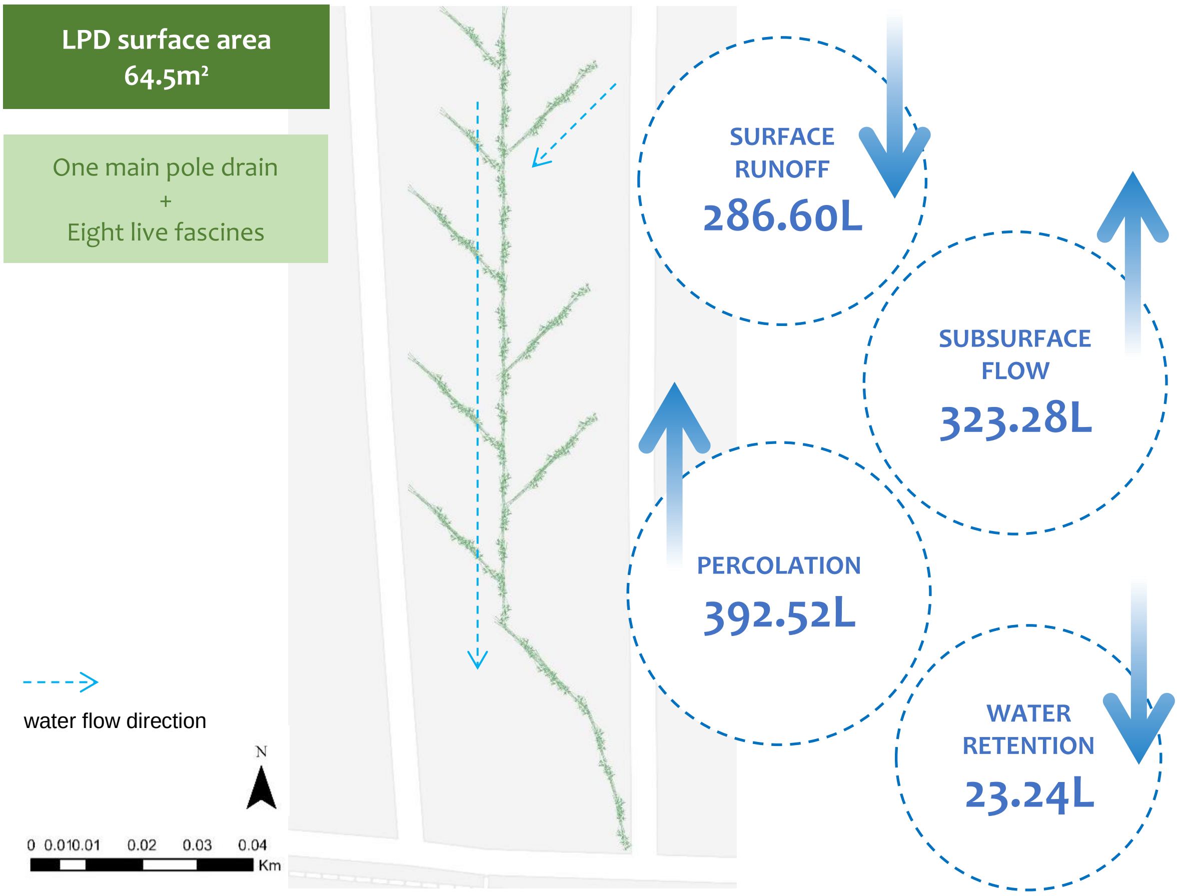


Figure 4.22 Design of the first Live Pole Drain (LPD) in a city.

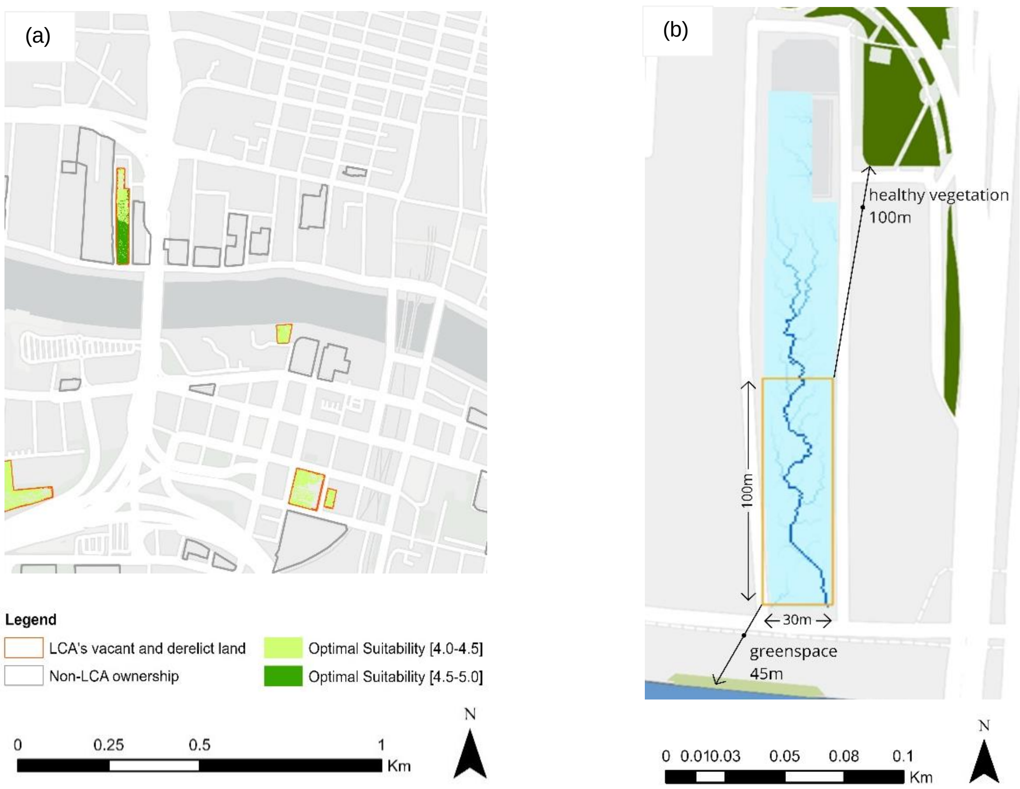


Figure 4.23 LPD plot. (a) Plot location; (b) Plot water flow accumulation; (c) Plot proximity to areas prone to flooding; (d) Plot slope gradient; (e) Plot soil texture.

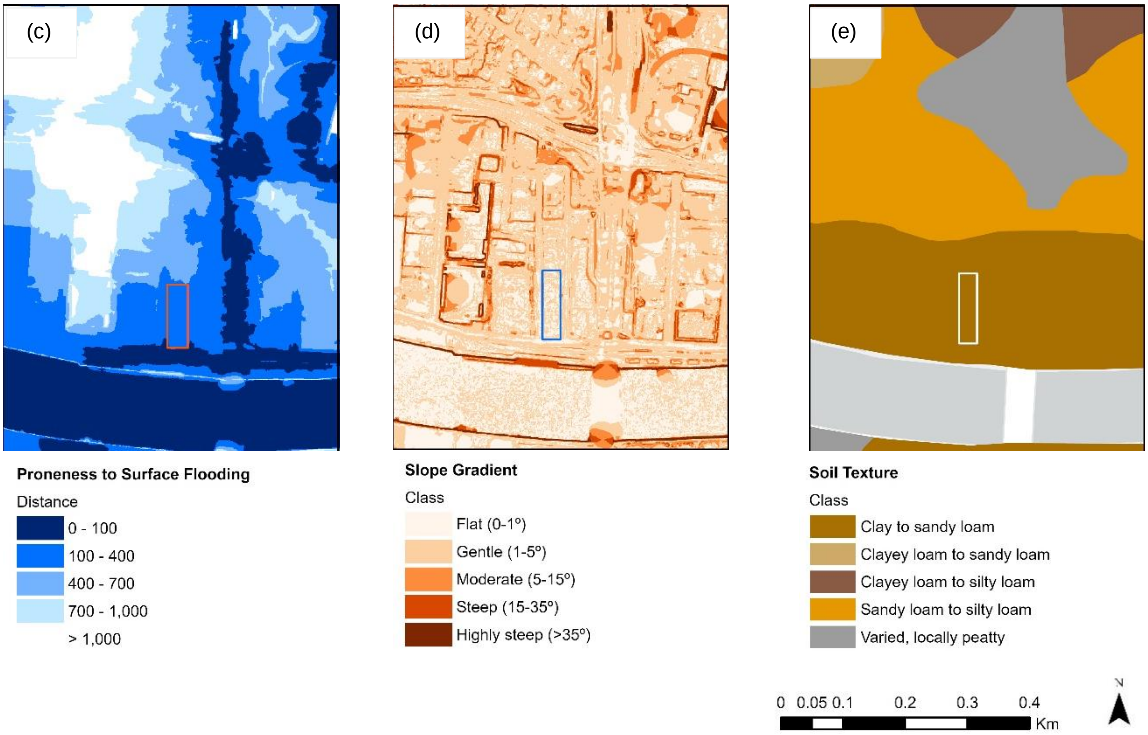


Figure 4.23-Cont'd. LPD plot. (a) Plot location; (b) Plot water flow accumulation; (c) Plot proximity to areas prone to flooding; (d) Plot slope gradient; (e) Plot soil texture.

5 DISCUSSION

This section presents the discussions on the results obtained and analyses undertaken in the previous chapter. The results are compared with research findings of other studies and an overall reflection on the approaches herein taken is presented. Towards the end of the section, the limitations of the study and recommendations to further develop and explore the results found in this research are highlighted.

5.1 LPD4C Framework

The Live Pole Drain for Cities (LPD4C) framework (Figure 4.1; APPENDIX VI) depicts the key components and eco-hydrological processes involved in an LPD. It builds upon the evidence base of LPDs, it delivers ground knowledge on LPD performance, and it supports the reproduction and adoption of LPDs in urban environments.

The LPD4C framework reflects on the limited available information on LPDs (i.e., textbooks, grey literature, and reports of previous successful implementations). Yet, the lack of research on LPDs as a soil-bioengineering technique, as identified in Chapter 2, delineated the scope of this study. To better understand LPD's overall functions and establish the eco-hydrological processes within the SPAC, insights into SuDS and subsurface flow wetlands (e.g., Jones (1996); US-EPA (2000); Maria and Liehr (2001); Malaviya and Singh (2012); Ballard *et al.* (2015)) were drawn and exploited herein to create the framework. Although this is a valid approach considering that LPD, SuDS, and subsurface flow wetlands are plant-based systems with similar features and structure, it is worth noting that different NbS will likely deliver different functions (e.g., Ariza *et al.* (2019); Joshi *et al.* (2021)). Additionally, detailing the eco-hydrological processes within the LPD, setting the boundaries of the framework, the control volume of LPDs, and on where a process starts, or ends, was somewhat challenging when building the framework. LPDs are complex, with a myriad of hydrological and ecological processes occurring within (Table 4.1), and yet changing throughout the lifecycle of LPDs (Figure 4.3).

The lack of detailed information on LPDs standard design and construction guidelines imposed the need for establishing assumptions throughout this study. Undoubtedly, LPD design is conditioned by site-specific conditions. Hence, LPD design is directly affected by the availability of plant species and surface area for LPD creation. More importantly, the design and shape of the LPD is determined by the drainage needs, topography, and

landscape restoration goals e.g., herringbone shape with additional live fascines along the pole drain (Figure 4.4b) delivers higher eco-hydrological performance than the simple herringbone shape (Figure 4.4a). However, how the number and diameter of live cuttings within the bundle, the diameter of the bundles, and the plant species composition may impact on the eco-hydrological performance of LPDs remains unexplored.

LPDs have not yet been explored in urban settings, which also highlights the originality of the LPD4C framework, in general, and of the present study, in particular. Due to LPD4C's novelty, the identification environmental criteria to find opportunity sites for LPD creation in cities was challenging. Factors such as the size of the framework – delimitated by the number of eco-hydrological processes – and data availability determined the number of the environmental criteria, and which of them would be considered throughout this study. Within an extensive list of possible environmental criteria to assess the land suitability for LPD creation, the selected and analysed environmental criteria within this study (i.e., soil texture, slope gradient, curvature, and aspect, proneness to surface flooding, land cover, proximity to greenspaces, and proximity to healthy vegetation) helped to successfully identify sites for LPD creation in Glasgow. However, replication of the LPD4C framework in another urban context will be subjected to data availability, which will require further assessment to determine the sensitivity of the considered environmental criteria for identifying opportunity sites for LPD creation.

The LPD4C framework was built in a context of urban flooding, soil erosion and landslides, yet its dimensions and components are holistic, enabling its reproduction in other environmental contexts facing different challenges. For example, the LPD4C was conceived in line with the current policies and practice on SuDS (Ballard *et al.*, 2015), which mainly focus on SuDS implementation within new urban developments. However, taking into consideration existent urban environments, the impacts of urbanisation and climate change, the LPD4C framework also considers the potential of LPDs while retrofitting SuDS. Still, the upscale and applicability of the framework, as well as the adoption of LPDs in urban environments, would benefit from changes in policies. Local planning authorities (LCAs) must update their policies to require well-designed, integrated SuDS, but also to embrace the 'connecting first to SuDS' principle instead of allowing direct connection of surface water to grey infrastructure.

5.2 Opportunity Sites for LPD Creation

Findings of this study demonstrate that Glasgow City has suitable land with optimal conditions to accommodate LPDs, which are indicated in the opportunity sites map (Figure 4.6). Even though the best locations for LPD creation accounted for the lowest portion of Glasgow's urban land (28%; Table 4.3), the obtained percentage represents a satisfactory result when compared with previous studies on urban land suitability for SuDS. For example, within the public areas of Bogotá, Colombia, Ariza *et al.* (2019) identified suitable land to implement infiltration basins, wetlands, and tree boxes, for 5.3%, 5.4%, and 58% of the study area, respectively; Joshi *et al.* (2021) identified 14% of land suitability for SuDS implementation within the study area in Switzerland; and Dearden, Marchant and Royse (2013) suggested that 34% of the UK is suitable for infiltration SuDS. Restricted areas (33%; Table 4.3) were defined based on the Glasgow's land cover map and on the assumption that the built-up environment and open water environments cannot be transformed into LPDs. Unsuitable areas for LPD creation accounted for the highest portion of Glasgow's territory (39%; Table 4.3), which is directly related to the soil textures found in Glasgow (Table 3.1) – the third most important environmental criterion according to experts' opinions (Table 4.2).

Soil texture defines overall soil infiltration rates and drainage conditions, also impacting on LPD eco-hydrological performance. In terms of LPD creation to mitigate urban flooding by decreasing stormwater volume and peak flow, priority was given to soils with low infiltration rate and permeability. Once water infiltrates an LPD in an impervious soil, it moves more freely than in a non-vegetated soil. This subsurface flow is as result of the presence of belowground vegetation (i.e., bundles and roots) that increases the number of macropores in the soil (Gonzalez-Ollauri, Stokes and Mickovski, 2020). Then, water flow can be properly redirected and connected to other SuDS creating a SuDS train system (Ballard *et al.*, 2015). Depending on the slope gradient in which the LPD was built, water can be retained increasing LPD potential of treating contaminated stormwater and thus avoiding the transfer of pollutants to other environmental compartments (e.g., groundwater; Tedoldi et al., 2016). Within Glasgow City, optimal conditions for LPD creation in terms of soil texture were not found, while a minimal portion of the urban land showed a moderate suitability (10%; Figure 4.5a). This result suggests a challenge towards LPD creation for urban flooding mitigation, a potential impact on LPD eco-hydrological performance and a possible threat to groundwater quality. Majority of soil textural classes in Glasgow has a high percentage of sand particles, resulting in high infiltration rate and permeability, which will likely impact on

the LPD potential of collecting water to be properly drained or even to treat polluted stormwater.

The second most important criterion determined by experts' opinions was slope gradient (Table 4.2). Traditionally and as a soil bioengineering technique, LPDs have been applied in slopes with gradients higher than 30º. No information was found on their application on less steep slopes during review of literature. On the one hand, lack of knowledge surrounding LPDs and their implementation in flat areas allowed the assumption that they can also be applied in slopes with gradients ranging from 0º to 30º. This hypothesis was built based on insights obtained from SuDS and subsurface flow wetlands as they have similar features and structures to LPDs. LPDs in different slope gradients will deliver different eco-hydrological functions and performances. When in moderate slopes (5-15º), LPDs can be deployed to deliver its hydrological and soil erosion functions (i.e., water infiltration, subsurface flow, percolation, debris flow deposition and sedimentation, and soil mechanical reinforcement (e.g., Stokes *et al.*, (2007); Campbell *et al.* (2008;) Mickovski and van Beek (2009)). In flat/gentle sites (0-5º), LPDs provide permeable surfaces with a slow water flow, and can work delivering processes simulating subsurface flow wetlands (i.e., phytoremediation, e.g., Vervaeke *et al.* (2003); Jensen *et al.* (2009); Stefanakis (2019)). On the other hand, LPD is a less known type of NbS, and if known, it is associated with soil engineering techniques on steep slopes. This association is directly translated into the high importance attributed to the slope gradient criterion by the NbS experts. Considering LPDs versatility identified within this research – i.e., they can be deployed in flat, moderate, and steep slopes, further investigation is needed to better understand LPD applicability and overall performance in flat areas. This can potentially dissociate LPD as a solution suitable only for steep slopes, which may result on a review of the given importance of the criterion. Additionally, optimal suitability in terms of slope gradient was found for over 90% of Glasgow City's area (Figure 4.5b). This result suggests that the output for this criterion in cities with a high percentage of flat to moderate topography (i.e., slope gradient between 0º and 15º) needs further analysis. It is recommended that priority for LPD creation should be given to the slope gradient that will potentialize the LPD eco-hydrological function set during planning stage of SuDS implementation.

Proneness to surface flooding had the highest importance score within the Analytic Hierarchy Process (AHP; Table 4.2). Indeed, areas prone to flooding pose as a challenge to cities as they place human life, infrastructure and environment under risks increasing vulnerability against floods. Implementation of LPDs in proximity to ponding areas are key towards surface water management and mitigation of flooding events. LPDs provide a

permeable surface which allows water to infiltrate, decreasing stormwater volume and peak flow reaching ponding areas. In the case of Glasgow, the output obtained with the depth-to-water (DTW) tool and hence on the proneness to surface flooding suitability map (Figure 4.5e) were in accordance with the high percentage of surface water flooding risk reported by SEPA (2015). Careful consideration is required at planning stage for LPD creation in Glasgow. For example, deploying an LPD close to a ponding area with a flat impervious soil delivers a higher LPD potential in retaining water for a longer period before it gets transfer to the next environmental compartment (i.e., ponding area or open water). Unfortunately, this is not the case for Glasgow. With high infiltration rate and permeability soils, caution while planning for LPD creation is required to increase the chances of successful implementation and performance. Overall, a general awareness that LPD eco-hydrologically performs based on plot environmental conditions is needed to optimise LPD functions and performance.

Urbanisation had a significant impact on the availability of opportunity sites for LPD creation in Glasgow (Figure 4.6). Specifically, slope curvature and land cover are the most affected environmental criteria by man-made interventions. Slope curvature is a determinant factor for LPD creation since slope shape is highly related to LPD structure's design. For example, LPDs can be deployed only in planar and concave surfaces. Remarkably, the results herein found show that Glasgow has almost 80% if its area with a planar surface (Figure 4.5c), suggesting that majority of the territory had been already modified by urbanisation. This finding implies that slope curvature is not a determinant factor when identifying land suitability for LPD creation within urban contexts with high percentage of built-up area. Conversely, slope curvature in cities with lower influence of man-made interventions will have a higher impact on the final suitability map.

Land cover (Figure 4.5f), even though the fifth most important criterion (Table 4.2), had a direct impact on the opportunity sites map (Figure 4.6) based on urban elements – i.e., buildings, structures, rails, roads, tracks, and paths – classified as restricted since they cannot be transformed into LPDs. Further investigation is required to locate the existent grey drainage systems within built environment that have potential to be converted into LPDs, following policies and guidelines on retrofitting SuDS (Ballard *et al.*, 2015). Additionally, land cover priority for LPD creation was given to undeveloped areas, to surfaces with no dominant vegetation cover, and to open spaces previously developed. This decision was made based on three criteria. First, it followed recommendations given by the SuDS manual (Ballard *et al.*, 2015) for implementation of SuDS within new urban developments. Second, it reflected on LPDs delivery of new greenspaces providing habitat

for wildlife. Third, it was based on the assumption that LPDs deliver higher eco-hydrological performance when compared with established grassland found in developed open spaces. Therefore, optimal conditions for LPD creation were found, in its majority, close to city's boundaries and less built-up areas. This result follows the same pattern seen in any other European city, where open and available areas are bound to city's greenbelts and boundaries (Hennig *et al.*, 2015; Pourtaherian and Jaeger, 2022). Further investigation is needed to better understand the impact of LPDs on socio-economic and environmental inequalities, especially if LPDs are created in less built-up areas.

Slope aspect, proximity to healthy vegetation and proximity to greenspaces were the less relevant criteria according to experts' opinion. Slope aspect directly impacts on plot environmental conditions (i.e., soil and air temperature, soil moisture content, evapotranspiration, etc.) creating a specific microclimate, which affects LPD eco-hydrological performance. A minimal area of Glasgow had adequate slope aspect conditions to implement LPDs (Figure 4.5d) following Glasgow's geographical position and the priority given to south-facing slopes. This result exposes a risk on LPD survival and overall performance because the amount of solar irradiance hours in Glasgow is low (i.e., 1,282 hours; Singh (2018); Met Office (2022)). It impacts on the amount of sunlight available for the LPD, which is related to plant growth, plant water uptake and evapotranspiration. These eco-hydrological processes are directly associated with LPD functions (i.e., regulation of soil water budget, removal of soil moisture, and landscape restoration). Therefore, careful consideration during planning stage of LPD creation in terms of slope aspect is needed.

Nonetheless, LPD resilience and survival rates are directly related to design guidelines such as time of planting (i.e., dormant season) and deployed plant species to build the LPD (e.g., willows (*Salix* sp.). Willows have great resilience in different environmental conditions and easily adapted to water logging and polluted soils (Jensen *et al.*, 2009; Wani, Khan and Bodha, 2011; Zárubová *et al.*, 2015; Frédette *et al.*, 2019). Building LPDs with suitable plant species is crucial. Besides willows (*Salix* sp.), suitable candidates are poplar (*Populus* sp.) and ash (*Fraxinus* sp.) as they easily propagate from live cuttings. Hence, proximity to healthy vegetation was one of the criteria selected for this study. Creating LPDs close to existing healthy vegetation increases survival rates as local native plants adapt more efficiently to local environmental conditions than plants brought from external sources, which also decreases LPD implementation costs. Once a new LPD is established and developed – i.e., reaching its maturity stage, the NbS starts working as a healthy vegetation for further replication of LPDs. Although a substantial area of Glasgow provides healthy

vegetation (Figure 4.5h), supplementary and detailed research is required to identify whether the greenspaces defined as areas with healthy vegetation indeed have the suitable plant species candidates to build LPDs.

Glasgow has a good network of greenspaces that translates into a good ecosystem connectivity (Figure 4.5g). LPD creation within an urban context like Glasgow would improve the existent connectivity, delivering habitat for wildlife and potentially mitigating socio-economic and environmental inequalities. However, most of over 3,500 ha of greenspaces within the city (Glasgow City Council, 2018) are located close to city's outskirts and less built-up areas, as previously discussed. Therefore, during planning stage for LPD creation, further qualitative analysis is required to prioritise areas which would deliver a higher number of ecosystem services.

Findings from this study also show that Glasgow has vacant and derelict land by property of LCA with optimal conditions for LPD creation (Figure 4.7-Figure 4.8). The use of vacant and derelict lands is a great opportunity for implementation of new green areas within a dense, built-up environment. In the case of Glasgow, prioritising these lands for LPD creation supports previous findings connecting these vacant and derelict lands with the potential of mitigation of socio-economic and environmental inequalities (e.g., Zala (2020)).

It is worth noting that the identification of opportunity sites for LPD creation were directly affected by the environmental criteria defined in Chapter 2 (Table 3.1), the weights assigned to each criterion in the light of experts' opinion (Table 4.2), and the quality and reliability of the input datasets and experts' responses. On the one hand, selection and delimitation of the environmental criteria, as well the attributed suitability scores, were defined based on literature review. On the other hand, the relative importance of each environmental criterion against each other was based on experts' opinion. Although these approaches have been applied in previous studies (e.g., Gonzalez-Ollauri, Thomson and Mickovski (2020)), the AHP was based on the opinion of eight out of 141 invited experts, suggesting that the relative importance between environmental criteria shown herein should be taken with caution and thus further consultation is recommended.

Regarding the input datasets, the use of LiDAR data with a high-resolution (SRSP, 2021) to build the Digital Elevation Model (DEM) had a great impact on spatial suitability resulting in detailed outputs. For example, data processing of the high-resolution DEM at Glasgow's built environment delivered noise derived from the slope curvature tool, which required careful attention when interpreting and communicating the results. However, the high-resolution DEM allowed mapping in detail zones prone to surface flooding (i.e., DTW index;

Figure 4.5e), which were very relevant for identifying opportunity sites for LPD creation and helped circumvent flood data licensing issues (i.e., SEPA's data are not freely available). Although a few limitations were found while identifying opportunity sites for LPD creation in an urban context, it should be noted that the data used herein is freely and readily available for urban planners and decision-makers in Glasgow, and relatively easy to collect for other cities, which makes the method easy to replicate in other contexts.

5.3 Eco-hydrological Performance of LPDs

Key findings of the eco-hydrological performance of LPDs showed that this NbS is effective in draining the excess of surface water, regulating the water budget in the soil and promoting landscape restoration. Particularly to LPDs hydrological performance, this research identified that LPDs, at certain design and environmental conditions, can decrease surface runoff up to 90% and water retention up to 54% when compared to fallow soil, while subsurface flow and percolation are increased up to 170% and 150%, respectively.

Greater surface runoff was observed under fallow soil when compared to vegetated treatments (Figure 4.9-Figure 4.10), which is in agreement with the findings reported in El-Hassanin, Labib and Gaber (1993) and Komatsu *et al.* (2018). Following the same pattern observed in surface runoff, fallow soil also tended to accumulate higher volume of water within the soil during wetting soil conditions. This suggests a challenge to cities with high rainfall rate striving to mitigate urban flooding (e.g., Glasgow). Fallow soil under a series of rainfall events with short periods of time between one event and another will retain more water, thus increasing its water saturation level, without enough time to dry out via evapotranspiration. Once fallow soil reaches its maximum water saturation level, stormwater is incapable to infiltrate into soil increasing the volume of surface runoff.

As anticipated, subsurface flow and percolation under fallow soil was substantially lower than under vegetated treatments due to the absence of belowground vegetation (Figure 4.9-Figure 4.10). Conversely, both vegetated treatments presented considerable subsurface flow and percolation due to the higher number of macropores created by the living cuttings in the bundles and the growing roots. These results were in line with the findings from Gonzalez-Ollauri and Mickovski (2020), which demonstrated that vegetation (e.g., willows) can contribute to effectively drain the excess water from the soil. These findings are useful in a context of decision-making process towards strategies to urban flooding mitigation.

LPDs not only decrease surface runoff but also quickly drains water surplus, making of this NbS a great opportunity to be applied as SuDS.

Differences between the two vegetated treatments were also found under the hydrological processes (Figure 4.9-Figure 4.10). W+A treatment had on average lower surface runoff, while subsurface flow, percolation and water retention were substantially higher when comparing to W treatment. These outputs can be attributed to the presence of the herbaceous, non-competitive species (i.e., alfalfa). While aboveground vegetation of alfalfa increases soil cover and roughness thus decreasing surface runoff, belowground vegetation of alfalfa contributes to opening the soil creating channels enhancing preferential flow. In terms of water retention, denser root systems enlarge rhizosphere and amount of micropores, increasing the number of points where water can be hold within the soil matrix.

When upscaling these findings to the wider urban scale, a few lessons can be drawn. First, presence of a non-competitive herbaceous species covering the soil is beneficial to improve LPDs hydrological functions and performance. Second, there are two options to establish a ground cover with herbaceous species (i.e., natural ecological succession or intervention) and both are related to the overall aim for LPD creation. LPDs deployed with focus on soil erosion processes (i.e., debris flow deposition and sedimentation) require a design that does not cover the bundles with soil. With time, bundles will be covered, and a natural ecological succession of secondary species will be established. LPDs focused on hydrological processes (i.e., surface runoff, subsurface flow, percolation, and water retention) could have bundles covered with soil and posterior seedling to optimise ground cover ecological succession and potentialize LPD performance. Third, herbaceous species tend to grow faster than new resprouts of willows, integrally covering the soil shadowing new willow individuals that reach surface and thus impacting on willow growth and LPD overall performance. Therefore, monitoring and maintenance of LPD might be required at establishment phase. Evidently, results herein found are based on the tested combination of willow and alfalfa, which require additional replication of the laboratory experiment to validate these findings. Also, the composition of other woody plant species for the LPD and other herbaceous species for ground cover would have different interactions and thus different performances. Further investigation and trials are needed to explore LPDs performance in combination with other ground cover species.

Soil at different water saturation conditions (i.e., soil at water saturation (scenario A) and soil at field capacity (scenario B)) impacted on the results obtained (Figure 4.9-Figure 4.10). This observation is likely related to the higher relative infiltration capacity of the saturated soil resulting from its hydraulic conductivity being close to saturation (i.e., water can only

travel in the soil as a continuous film; Rodriguez-Iturbe and Porporato (2005)). While surface runoff was higher at soil at field capacity than at saturated conditions under fallow treatment thus following the abovementioned hypothesis on hydraulic conductivity, the same was not observed under vegetated treatments. This suggests that surface roughness and availability of channels for preferential flow and water infiltration delivered by vegetation still have an impact at drier soil conditions. Different hydraulic conductivity similarly impacted on subsurface flow, percolation, and water retention under vegetated and non-vegetated treatments. Both subsurface flow and percolation decreased following the decrease of the hydraulic conductivity as the soil dries out. With lower hydraulic conductivity, water does not travel within the soil, which explains the obtained results for water retention – i.e., water retention was higher within soil at field capacity than at water saturation. Although the identified differences between scenarios were not significant, these results highlight few findings on water budget regulation by LPDs under drying soil conditions, which is essential when considering LPD creation within drier urban environments or even during long periods of drought. Therefore, additional studies are required to better understand LPD hydrological performance under drying soil conditions reaching soil at wilting point – i.e., when soil water reaches its minimum level, also impacting on availability of soil water for plants.

Willow-vegetated treatments retained moisture more effectively than fallow soil (Figure 4.11Figure 4.12), which is conversely related with soil matric suction (i.e., the higher the soil moisture in the soil, the lower the pore-water pressure, or soil matric suction, will be; Figure 4.13-Figure 4.14). Observed high soil moisture under vegetated treatments can be explained by the soil structure features related to the presence of a dense belowground vegetation (i.e., live cuttings and roots). These results are in line with previous findings reported by Gonzalez-Ollauri and Mickovski (2020). However, special attention must be given to the volumetric soil moisture content and soil matric suction observed during the time-series plots (Figure 4.11;Figure 4.13) and the water retention component obtained under the SWMB (Figure 4.9) since the results found are contradictory. On the one hand, fallow soil had the lowest moisture content throughout the observation period (i.e., at wetting and drying soil conditions). On the other hand, the highest water retention capacity under wetting soil conditions was under fallow soil treatment. LPDs provide a greater number of macropores when compared with fallow soil. In the event of a rainfall, water drains and percolates out of the soil, resulting in a lower water retention by the LPD. All these observations are related to the key eco-hydrological functions of LPDs: drainage of the soil while keeping it relatively drier when compared to fallow soil. Under drying soil conditions, absence of plant cover under fallow treatment results in higher and direct incidence of sunlight at soil surface, which increases soil evapotranspiration rates resulting in lower soil

moisture content. The latter is also observed on soil temperature times-series plots (Figure 4.15), in which fallow soil quickly absorbs heat once sunlight is provided while vegetation acts as a thermal insulator maintaining a more balanced soil temperature. These results are in accordance with previous studies e.g., Jiménez, Tejedor and Rodríguez (2007).

The establishment (Table 4.5;Figure 4.17) and development of a dense plant cover observed herein (Table 4.6; Figure 4.18-Figure 4.19) confirmed that LPDs are able to quickly restore landscape and support ecological succession and habitat provision. Over 450 new stems per square metre resprouted during the observation period with a mean plant growth rate of 0.08, which can be considered as a great and quick performance on landscape restoration when compared with development stages of willows (*Salix* sp.) reported by Saska and Kuzovkina (2010). Evidently, the performance herein obtained is directly related to the optimal conditions provided to the LPDs during the experiment (i.e., constant irrigation, warm temperature of 22ºC and 16h of artificial sunlight). Plant growth is directly influenced by water availability in soil and warmth and sunlight (Lower and Orians, 2003). While water and nutrient uptake depends on water availability, environmental conditions such as warmth and sunlight enhance evapotranspiration thus requiring further water uptake from the soil.

As for the differences found between treatments, the total number of resprouting stems was lower under W+A than under the W, which could be attributed to plant competition issues with alfalfa (Grace and Tilman, 1990). The same influence was observed in terms of plant relative growth (PGR). Mean PGR under the W+A treatment was, overall, 19% lower than under W treatment. Ecologically, the presence of an herbaceous species (i.e., alfalfa) covering the soil negatively impacted on willow development but as previously discussed, alfalfa had a great and positive impact on overall hydrological LPD performance. Even though plant growth was affected, the results obtained from the combination of woody and herbaceous species for LPD creation were not significant to disqualify this approach. Indeed, at an urban plot-scale, ground cover will naturally grow if not previously planted during construction stage of LPD. Thus, maintenance during the establishment phase to enhance willow growth is recommended so ground cover is contained to avoid shadowing on the resprouting willows. Further investigation and trials are needed to test willow with different herbaceous species to identify a combination that will positively impact ecologically and hydrologically on LPD performance. Additionally, studies with longer monitoring periods are required to understand the impact of secondary species on ecological performance throughout the different development stages of LPDs.

The highest number of new willow stems and highest PGR were found at the crest and middle zone, respectively. These findings are somewhat contradictory with general eco-hydrological knowledge. It is widely accepted that plant establishment and development at sloping areas is usually better at the toe zone since water and nutrients tend to move downwards concentrating at the toe and thus delivering better conditions for plant growth (Gonzalez-Ollauri and Mickovski, 2020). During the observation period, this pattern was not found, which can be attributed to the scale of the experiment and the absence of ecosystem dynamics within a growing chamber. Therefore, further replications are required to better understand the results herein found. Specifically, studies on LPD at plot-scale within the soil-plant-atmosphere continuum (SPAC) would deliver greater information on eco-hydrological performance of LPDs.

Based on stem diameter measurements, strong relationships were determined for above- and belowground dry biomass, allowing a better understanding of overall plant development throughout the experiment (Figure 4.20-Figure 4.21). Although a good fit for the data was found, these results need to be supported by further replications of the experiment since the obtained data was limited and does not allow the determination of biometric and allometric relationships through linear regressions.

The evidence gathered within this research needs to be validated through replication of the laboratory experiment to ensure a high degree of reliability. It is also worth noting that the results found and explored herein are determined by the defined and applied LPD design. Different design and conditions (i.e., plant species, overall size of the bundles, soil type, slope gradient, etc.) could deliver different outputs. Lastly, it is acknowledged that errors and inconsistencies derived from the deployed equipment affected the performance of the laboratory experiment. For example, (i) dysfunctional behaviour on temperature of the environmental chamber impacted on plant development as well as on the soil temperature sensors; (ii) daily watering was affected by lack of consistency of the dripping system, resulting in periods varying between over-watering or no-water provision; and (iii) the rainfall simulator, even though calibrated, impacted on the final 'water loss' output within the WMB, especially under the W+A treatment. Even though the method applied to assess the performance of the key eco-hydrological processes was restricted by timeframe, it allowed the determination of the overall effectiveness of LPDs.

5.4 Integration Analysis

The design for the first LPD within a city showed that the system has a great hydrological potential under wetting soil conditions at an urban plot-scale (Figure 4.22-Figure 4.23). However, caution must be taken when upscaling the results of the LPD hydrological performance. It is worth noting that the excellent LPD hydrological performance – obtained through surface runoff, subsurface flow, percolation and water retention processes – was observed under controlled environmental conditions (i.e., warm temperature, extended hours of sunlight and constant irrigation throughout the entire observation period). Evidently, these conditions are not necessarily found at plot scale. This will have a direct impact on LPD's survival, development, and eco-hydrological performance.

Differences in soil texture and slope gradient between LPDs under experimental condition and the designed LPD at urban plot scale will likely impact on overall LPD eco-hydrological performance. While silty sand soil and a slope gradient of 30º were applied at indoor LPDs, clay to sandy loam and a slope gradient ranging between 0º and 5º were identified within the plot analysed. As discussed under Section 5.2, soil texture defines overall soil infiltration rates and drainage conditions, and slope gradient affects soil erosion rate and surface runoff peak flow. Within the environmental conditions found at the analysed plot, surface water will likely move slowly; infiltration of water in the clay soil will be enhanced through preferential flow due to presence of vegetation; subsurface water within bundles will also move in a lower flow rate, which may also increase percolation and water retention within the system. Therefore, the result and interpretation of the integration analysis suggests that the designed LPD could be implemented to reduce the volume of surface runoff, while acting with functions observed in subsurface flow wetlands (i.e., phytoremediation).

The integration analysis has its limitations, which are somewhat related to the method applied to assess the eco-hydrological performance of LPDs. To design and to build an LPD experiment allows, to a certain point, to have control over plant species, soil texture, slope gradient, and environmental conditions within the growing chamber. Based on these, data was collected and analysed. When upscaling it to an urban context, it is then observed that optimal conditions created within a controlled environment cannot be found outdoors. Therefore, the obtained results for LPD eco-hydrological performance cannot be directly extrapolated until new replications of the experiment are made or further studies on LPDs in situ are undertaken. Additionally, each plot should be individually analysed when upscaling the LPD hydrological performance since plot specific environmental conditions directly affects LPD eco-hydrological performance. Nevertheless, the findings of this research provided substantial information to adopt LPDs as a viable SuDS in cities.

5.5 Limitations

Considering the comprehensive methodological approach applied herein, limitations related to methods and data are listed below:

- Overall lack of knowledge and research on LPDs, available timeframe to build a framework and showcase its applicability were constrains that limited the scope of the research.
- Within an extensive list of environmental criteria that could be considered for the spatial, multi-criteria analysis, the ones selected were based on (i) the size of the survey applied to collect expert's opinion; (ii) the availability of open-source data; and (iii) the available timeframe to run the spatial analysis.
- Designing, building and daily monitoring a pilot laboratory experiment, even though in a small scale due to source of materials and limited space within the environmental chamber, was time consuming. As a pioneer project, the experiment had its trials and errors until reaching the best possible setup to allow the collection of primary data on LPDs.
- A few constrains affected the overall performance of the experiment, as well as impacted on the quality of the collected primary data. First, the number of the available sensors was limited. From the nine columns built, the data collected for the soil matric suction is representative of only three of them (i.e., one per treatment). Second, the dripping system for the daily water provision and the system to simulate the rainfalls – even though calibrated – were somewhat dysfunctional, resulting in a few inconsistencies on the input volume of water throughout the experiment. Third, unforeseen temperature variations and dysfunctional behaviour of the environmental chamber during the final days provoked malfunctioning of the temperature sensors as well impacted on willow health.

5.6 Future Work: Roadmap to Develop LPD4C

The research herein has delivered a detailed framework on LPDs with regards to their eco-hydrological processes, design and construction guidelines, and environmental criteria for implementation at urban scale. Thus, a solid foundation on LPDs has been set, which delivers substantial knowledge now allowing further studies to investigate the topic in more detail. Towards this end, the following recommendations are given:

- LPDs are an easy-to-build NbS but relatively unknown. The NbS and the LPD4C framework developed need further dissemination in order to achieve their potential.

Reproduction and expansion of the gathered knowledge herein could be achieved by integrating the stakeholders into the framework.

- LPDs are also a great solution for phytoremediation purposes and can have a great potential when applied to mitigate issues related to agricultural or industrial waste. Therefore, the LPD4C could expand by integrating the eco-hydrological processes involving the treatment of wastewater and/or soil nutrients cycle.
- While this research adopted the assumption that specific greenspaces would provide healthy vegetation to build LPDs, further research and supplementary data on available woody species throughout the city would result in a more detailed map of available material as a source to LPDs.
- To enhance green accessibility, research and data collection are needed to update the PAN 65 Glasgow's greenspaces map issued in 2008. In addition, a more detailed interpretation of the data under the 'proximity to greenspaces' environmental criterion should consider green areas classified as 'private gardens' as non-accessible.
- The land cover open-sourced available data by OS is somewhat generalist in its classification of 'general surfaces', which requires further and detailed interpretation. As a result, a detailed map would extent the number of optimal locations for LPD creation, specially at plot scale.
- Further studies would benefit from adding socio-demographic data into the spatial analysis to identify the opportunity sites for LPD creation. For example, by assessing land suitability and availability together with socio-demographic data, priority areas would be determined by the potential of LPDs to address further urban challenges such as socio-economic and environmental inequalities.
- The overall LPD design, and hence its performance, would benefit from connecting this NbS together with other SuDS, working within a SuDS train. However, data collection is required to map all the SuDS at urban scale as, to this date, no information/data on the existent SuDS in Glasgow was found.
- Further and detailed investigation is needed to understand the plot-street scale impacts of LPDs on the existent built-up environment e.g., how the root system would affect existent infrastructure. Additionally, further consideration is needed to assess the influence of existing buildings shadowing LPDs, which would impact plant growth, and thus LPD performance.
- Further studies would require the gathering of information to deliver a numerical modelling to assess the LPD performance through simulations.

- Repetition of the pilot laboratory experiment are required to validate the output data collected herein. In addition, the overall knowledge on LPDs performance would benefit from designing, building and constant monitoring LPDs at outdoor plot-scale.

6 CONCLUSIONS

The aim of this research was to propose LPDs as an original NbS alternative to conventional SuDS, following the hypothesis that LPDs are a suitable for cities and an effective solution towards urban flooding mitigation. Based on the objectives set to determine whether the hypothesis is confirmed, this study gathered information upon the unstudied field of LPDs and built the first LPD framework. Based on the framework, opportunity sites for LPD creation were identified through a spatial, multi-criteria analysis, and the eco-hydrological performance of LPDs was assessed with primary data collected during a pilot laboratory experiment. As a result, the findings identified herein support LPDs as a viable type of SuDS for cities.

The Live Pole Drain for Cities (LPD4C) framework is unique in its nature and the first one developed for LPD. The framework – developed to complete Objective 1 – provides information on the main environmental criteria for LPD creation. It sets the basis for informing LPD design and construction. It delineates the steps to assess the eco-hydrological performance of LPD at the soil-plant-atmosphere-continuum (SPAC). The LPD4C framework was conceived to support climate change adaptation (CCA) in urban environments, especially to address natural hazards such as soil erosion, shallow landslides, and floods. In addition, the framework can support effective SuDS decision-making process, increasing the chances for successful LPD implementation effectively delivering of ecosystem services to human communities.

Opportunity sites for LPD creation were satisfactorily identified for Glasgow City, accomplishing Objective 2. Understanding the impact of environmental conditions on LPDs and then identifying the most suitable sites to implement them is crucial to ensure LPDs optimal performance and sustainability. Accordingly, the selected eight environmental criteria herein were chosen as these play a critical role throughout the LPD development stages, impacting on plant growth and hence overall eco-hydrological performance.

As per Objective 3, understanding LPD eco-hydrological processes within the soil-plat-atmosphere continuum (SPAC) and its overall performance is vital to optimise LPD eco-hydrological potentials, which are directly impacted by deployed LPD design and local environmental conditions in which the LPD was built. This research not only confirmed the scarce information on LPD effectiveness, but also quantified its performance through the selected key eco-hydrological processes. When compared with fallow soil, LPDs have, at certain design and environmental conditions, the potential to decrease surface runoff up to

90%, with a reduction of water retention up to 54%, and an increase of subsurface flow and percolation up to 170% and 150%, respectively.

The integration analysis was undertaken to evaluate urban land suitability and capacity to accommodate LPDs (Objective 4). This analysis also showcases the applicability of the results obtained within this research. Together, the results provide insights on LPD design and LPD hydrological performance at plot-scale in Glasgow City. The design for the first LPD within a city showed that the system has a great hydrological potential under wetting soil conditions at an urban plot-scale. Particularly to the environmental conditions found at the analysed plot, the integration analysis suggests that the designed LPD could be implemented to reduce the volume of surface runoff, while acting with functions observed in subsurface flow wetlands (i.e., phytoremediation). However, caution must be taken when upscaling the results of the LPD hydrological performance obtained thought the laboratory experiment. The results cannot be directly extrapolated since the differences on LPD design and environmental conditions between indoor LPD and designed LPD at plot-scale will likely impact on LPD eco-hydrological performance.

This research also provided strategies and recommendations to support the adoption of LPDs as an effective SuDS within cities, achieving Objective 5. Specifically, the reflections made on the research findings were elaborated so the user is able to interpret the results beyond the conditions set within this research. In general, recommendations were given based on the multiple interactions between LPD design, LPD environmental conditions in which it would be implemented, and LPD eco-hydrological function and performance. Understanding that all these factors are directly related, impacting on each other, is crucial for successful LPD deployment, survival, development and performance.

This research is not without limitations. Limited available information on LPDs resulting in a substantial knowledge gap; quality and reliability of the collected secondary data; lack of engagement from NbS experts during the Analytic Hierarchy Process (AHP) survey; timeframe to design, to build and to monitor a pilot laboratory experiment were few of the constrains found. To enhance reliability of the findings obtained during this study, further replications of the undertaken approaches are needed. By repeating the methods and by putting the LPD4C framework into practice, further evidence on LPDs performance and effectiveness within the urban environment can be gathered. Based on the solid foundation and evidence of LPDs created within this research, next steps were listed in order to explore LPDs, and the LPD4C framework, in a deeper detail. Further studies and application of the LPD4C will further validate the results obtained in this study.

Nonetheless, this research successfully built pioneering evidence on LPDs eco-hydrological performance, which now supports LPDs as a suitable solution to mitigate urban flooding in cities. Within the LPD4C scope, the findings of this research can be useful for urban planners, environmental managers, policy makers, decision-makers, and contractors during the planning phase of projects seeking to manage flood hazards whilst enhancing the natural value of the urban environment. Specifically, this study delivered information for implementation of the first ever seen LPD in a city.

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APPENDIX I

Land cover classification and suitability scores

Land Cover Classification	Reasoning	Score
Amenity Greenspaces	Landscaped areas usually separating buildings or land use for environmental, visual or safety reasons and utilised for informal social activities	5
Buildings and Structures	Includes substantial and permanent construction with a roof and walls to shelter the different uses; any built structure without a roof (i.e., water tower, telecommunications mast, etc.); and minor constructions which may be roofed but not intended for habitation e.g., kiosk and covered walkways	Restricted
General Surfaces	Any man-made surface and/or any composite surface comprising a mixture of artificial and natural elements e.g., a garden or landscaped area adjacent to a building	1
General Surfaces, Natural	Areas with no dominant vegetation cover	5
Green Corridors	Routes such as canals, rivers corridors, and old railway lines linking different areas within a city or surrounding country sides and parks and mostly used for walking, cycling or horse riding	4
Natural and Semi-Natural Greenspaces	Areas that are undeveloped or previously developed with natural or introduced habitats or colonized by vegetation and wildlife including woodland and wetland areas	5
Open Water	Areas of still open water e.g., lakes, canals, ponds, mere, water filled gravel pits and reservoirs. It includes silted-up areas with associated vegetation of reeds, rushes and willow (as long as the area of open water is >40% of the total).	Restricted
Other Functional Greenspaces	Includes allotments, community gardens, and burial grounds	4
Parks and gardens	Public and private areas of enclosed land, designed, constructed managed and maintained as public/private park or garden or garden	4
Play Spaces and Sports Areas	Safe and accessible areas for children to play and mostly associated with houses. It also includes large flat areas of grassland or synthetic surface used generally for various sporting activities	3
Rails, Roads, Tracks and Paths	It refers to permanent metalled (i.e., artificial surface including asphalt, concrete/brick paviours, granite sets and gravel) way for cars, buses, lorries, and other road vehicles. It also considers railways, paved surfaces for use by pedestrians and/or cyclists.	Restricted

Source: Adapted from Harrison (2006) and Scottish Government (2008).

APPENDIX II

Live Pole Drain Survey template for Analytic Hierarchy Process (AHP)

Questionnaire

Environmental Criteria for finding locations for Live Pole Drains (LPDs) as a Sustainable Drainage System (SuDS) in the urban environment.

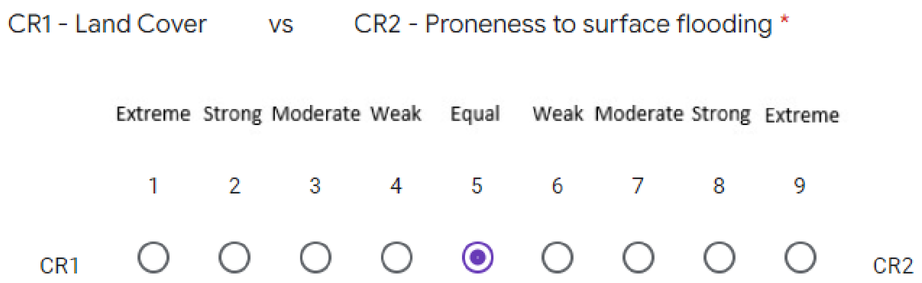
This questionnaire is part of an MSc Research at the School of Computing, Engineering & Built Environment at Glasgow Caledonian University. Due to your expertise in the field, you are kindly invited to take part in this questionnaire. This should take 5-10 minutes of your time and you may withdraw at any stage. Please take time to decide whether you wish to voluntarily participate or not. Should you need more information, please contact Fernanda Berlitz | fberli200@caledonian.ac.uk.

Background: Live Pole Drains (LPDs) are a plant-based drainage system aiming to drain the excess of surface water whilst regulating the soil's water budget and fostering landscape restoration. LPDs are a type of SuDS that have not received much attention yet; their application in the urban environment is not documented.

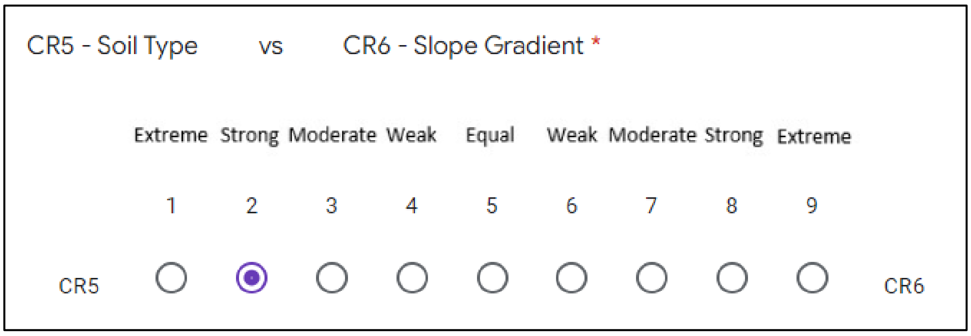
Questionnaire Aim: To collect expert input on the relative importance of different environmental criteria related to site selection for LPDs in the urban environment.

Procedure: You are requested **to score the relative importance of 28 pairs of criteria (CR). Each criterion is explained below.** For each pair of criteria, please, indicate which, in your opinion, is more important for selecting sites for LPDs. To this end, the following examples are provided:

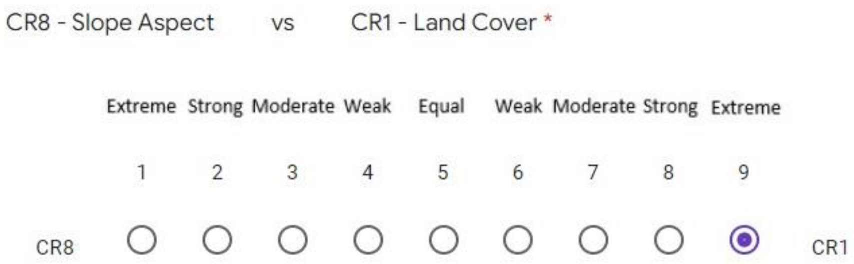
Example 1: CR1 – Land Cover vs CR2 – Proneness to surface flooding. Score: "Equal (5)". Interpretation: CR1 is equally important as CR2.



Example 2: CR5 – Soil Type vs CR6 – Slope Gradient. Score: "Strong (2)". Interpretation: CR5 is strongly more important than CR6.



Example 3: CR8 – Slope Aspect vs CR1 – Land Cover. Score: "Extreme (9)". Interpretation: CR1 is extremely more important than CR8.



Criteria	Definition	Impact
CR1 – Land Cover	Surface cover on the ground	Degree of imperviousness; exposure and availability of soil; construction costs
CR2 – Proneness to surface flooding	Land areas susceptible to flooding by surface water	Improve drainage conditions, reducing surface water runoff
CR3 – Proximity to healthy vegetation	Distance to healthy vegetation stock	Source to build LPDs; use of local native plants guarantees a higher survival rate of LPDs
CR4 – Proximity to green areas/infrastructures	Distance to existent green areas (e.g., parks) and/or green infrastructures (e.g., NbS (Nature Based Solutions))	Ecosystem connectivity in urban systems
CR5 – Soil Type	Texture of the soil (e.g., sand, clay, loam, etc.)	Plant survival and healthy development; drainage properties
CR6 – Slope Gradient	Steepness of the slope	Soil erosion rate; runoff peak flow; cost-effectiveness; workers' safety
CR7 – Slope Curvature	Shape of the slope (e.g., concave, or convex curvature)	Suitability of land for LPD (Live Pole Drain) implementation (e.g., LPD cannot be deployed in a convex curvature)
CR8 – Slope Aspect	Orientation of the slope in relation to the sun	Creation of microclimates affecting plant development
* From the extensive Environmental Criteria for LPD implementation, herein it is the shortlisted criteria based on data availability.		

APPENDIX III

Live Pole Drain Brochure (in Portuguese)

APPENDIX IV

Primary data collected during laboratory experiment for soil water mass balance (SWMB)

Treatment	Event	Scenario	Cumulative Water Volume (L)	Water Content Prior (L)	Surface Runoff (L)	Subsurface Flow (L)	Percolation (L)	Water Content Post (L)	Water Loss (L)
W	RF 1	A	0.31433	0.269	0.008	0.090	0.024	0.280	0.181
W	RF 1	A	0.31433	0.277	0.000	0.045	0.109	0.286	0.151
W	RF 1	A	0.31433	0.266	0.002	0.074	0.082	0.274	0.149
W	RF 2	A	2.20031	0.271	0.071	0.997	0.482	0.283	0.639
W	RF 2	A	2.20031	0.283	0.039	0.570	0.392	0.294	1.188
W	RF 2	A	2.20031	0.240	0.001	0.554	0.880	0.281	0.725
W	RF 3	A	1.57165	0.281	0.092	0.661	0.141	0.281	0.678
W	RF 3	A	1.57165	0.281	0.049	0.473	0.302	0.288	0.741
W	RF 3	A	1.57165	0.258	0.034	0.593	0.605	0.281	0.317
W	RF 4	A	0.94299	0.268	0.108	0.253	0.282	0.279	0.289
W	RF 4	A	0.94299	0.282	0.139	0.610	0.173	0.289	0.014
W	RF 4	A	0.94299	0.272	0.133	0.347	0.367	0.272	0.096
W	RF 5	A	1.25732	0.263	0.027	0.270	0.231	0.278	0.713
W	RF 5	A	1.25732	0.275	0.142	0.214	0.235	0.289	0.652
W	RF 5	A	1.25732	0.257	0.232	0.366	0.525	0.278	0.113
W+A	RF 1	A	0.31433	0.240	0.000	0.080	0.082	0.244	0.148
W+A	RF 1	A	0.31433	0.271	0.020	0.073	0.126	0.277	0.090
W+A	RF 1	A	0.31433	0.268	0.000	0.109	0.134	0.306	0.033
W+A	RF 2	A	2.20031	0.239	0.060	0.766	1.305	0.246	0.063
W+A	RF 2	A	2.20031	0.270	0.002	0.905	1.050	0.276	0.237
W+A	RF 2	A	2.20031	0.275	0.005	1.117	1.015	0.312	0.026
W+A	RF 3	A	1.57165	0.245	0.020	0.564	0.735	0.245	0.253

Treatment	Event	Scenario	Cumulative Water Volume (L)	Water Content Prior (L)	Surface Runoff (L)	Subsurface Flow (L)	Percolation (L)	Water Content Post (L)	Water Loss (L)
W+A	RF 3	A	1.57165	0.266	0.021	0.540	0.980	0.275	0.022
W+A	RF 3	A	1.57165	0.282	0.017	0.634	0.865	0.306	0.032
W+A	RF 4	A	0.94299	0.239	0.014	0.171	0.328	0.243	0.425
W+A	RF 4	A	0.94299	0.265	0.043	0.375	0.505	0.270	0.014
W+A	RF 4	A	0.94299	0.310	0.036	0.451	0.257	0.310	0.199
W+A	RF 5	A	1.25732	0.237	0.104	0.145	0.267	0.244	0.734
W+A	RF 5	A	1.25732	0.257	0.019	0.396	0.654	0.273	0.172
W+A	RF 5	A	1.25732	0.266	0.027	0.228	0.729	0.309	0.230
C	RF 1	A	0.31433	0.267	0.030	0.055	0.019	0.267	0.211
C	RF 1	A	0.31433	0.221	0.029	0.061	0.073	0.262	0.110
C	RF 1	A	0.31433	0.195	0.004	0.048	0.019	0.231	0.206
C	RF 2	A	2.20031	0.267	0.099	0.330	0.135	0.267	1.636
C	RF 2	A	2.20031	0.217	0.262	0.228	0.486	0.262	1.180
C	RF 2	A	2.20031	0.181	0.155	0.251	0.430	0.255	1.291
C	RF 3	A	1.57165	0.266	0.434	0.260	0.341	0.268	0.534
C	RF 3	A	1.57165	0.213	0.457	0.164	0.187	0.262	0.715
C	RF 3	A	1.57165	0.179	0.235	0.233	0.275	0.249	0.759
C	RF 4	A	0.94299	0.265	0.221	0.163	0.151	0.267	0.406
C	RF 4	A	0.94299	0.215	0.403	0.127	0.229	0.262	0.136
C	RF 4	A	0.94299	0.224	0.224	0.163	0.099	0.226	0.455
C	RF 5	A	1.25732	0.267	0.313	0.117	0.172	0.267	0.656
C	RF 5	A	1.25732	0.213	0.401	0.099	0.214	0.262	0.494
C	RF 5	A	1.25732	0.180	0.283	0.143	0.176	0.251	0.584
W	RF 1	B	0.314	0.269	0.020	0.072	0.034	0.280	0.178
W	RF 1	B	0.314	0.277	0.000	0.018	0.057	0.285	0.230
W	RF 1	B	0.314	0.207	0.002	0.048	0.056	0.258	0.158
W	RF 2	B	2.200	0.270	0.019	0.675	0.414	0.283	1.079

Treatment	Event	Scenario	Cumulative Water Volume (L)	Water Content Prior (L)	Surface Runoff (L)	Subsurface Flow (L)	Percolation (L)	Water Content Post (L)	Water Loss (L)
W	RF 2	B	2.200	0.289	0.095	0.518	0.310	0.292	1.274
W	RF 2	B	2.200	0.247	0.025	0.575	0.890	0.279	0.678
W	RF 3	B	1.572	0.267	0.094	0.737	0.157	0.280	0.570
W	RF 3	B	1.572	0.279	0.027	0.290	0.178	0.288	1.067
W	RF 3	B	1.572	0.253	0.002	0.433	0.528	0.280	0.582
W	RF 4	B	0.943	0.262	0.154	0.280	0.311	0.278	0.183
W	RF 4	B	0.943	0.277	0.093	0.297	0.165	0.291	0.374
W	RF 4	B	0.943	0.256	0.043	0.233	0.134	0.274	0.516
W	RF 5	B	1.257	0.260	0.059	0.279	0.212	0.278	0.690
W	RF 5	B	1.257	0.273	0.069	0.037	0.228	0.289	0.907
W	RF 5	B	1.257	0.257	0.054	0.197	0.339	0.278	0.647
W+A	RF 1	B	0.314	0.240	0.002	0.089	0.089	0.245	0.130
W+A	RF 1	B	0.314	0.268	0.001	0.040	0.076	0.277	0.188
W+A	RF 1	B	0.314	0.270	0.001	0.116	0.096	0.304	0.068
W+A	RF 2	B	2.200	0.239	0.030	0.361	0.970	0.245	0.833
W+A	RF 2	B	2.200	0.271	0.023	0.475	1.210	0.276	0.487
W+A	RF 2	B	2.200	0.275	0.031	1.081	0.785	0.313	0.265
W+A	RF 3	B	1.572	0.239	0.054	0.324	0.377	0.245	0.811
W+A	RF 3	B	1.572	0.266	0.011	0.712	0.459	0.274	0.381
W+A	RF 3	B	1.572	0.280	0.014	0.672	0.288	0.303	0.576
W+A	RF 4	B	0.943	0.238	0.007	0.212	0.140	0.242	0.579
W+A	RF 4	B	0.943	0.256	0.021	0.424	0.381	0.273	0.100
W+A	RF 4	B	0.943	0.267	0.012	0.264	0.173	0.307	0.455
W+A	RF 5	B	1.257	0.237	0.100	0.177	0.445	0.244	0.528
W+A	RF 5	B	1.257	0.264	0.021	0.347	0.715	0.273	0.165
W+A	RF 5	B	1.257	0.259	0.017	0.231	0.166	0.309	0.794
C	RF 1	B	0.314	0.272	0.014	0.031	0.029	0.272	0.241

Treatment	Event	Scenario	Cumulative Water Volume (L)	Water Content Prior (L)	Surface Runoff (L)	Subsurface Flow (L)	Percolation (L)	Water Content Post (L)	Water Loss (L)
C	RF 1	B	0.314	0.213	0.026	0.022	0.026	0.235	0.218
C	RF 1	B	0.314	0.196	0.005	0.006	0.010	0.218	0.272
C	RF 2	B	2.200	0.265	0.355	0.319	0.429	0.267	1.095
C	RF 2	B	2.200	0.214	0.415	0.106	0.610	0.262	1.020
C	RF 2	B	2.200	0.185	0.297	0.211	0.334	0.262	1.281
C	RF 3	B	1.572	0.264	0.313	0.270	0.219	0.266	0.769
C	RF 3	B	1.572	0.211	0.509	0.153	0.154	0.262	0.704
C	RF 3	B	1.572	0.185	0.303	0.190	0.272	0.260	0.731
C	RF 4	B	0.943	0.266	0.155	0.098	0.167	0.268	0.521
C	RF 4	B	0.943	0.210	0.279	0.139	0.229	0.256	0.250
C	RF 4	B	0.943	0.181	0.191	0.115	0.082	0.241	0.495
C	RF 5	B	1.257	0.266	0.500	0.136	0.061	0.268	0.558
C	RF 5	B	1.257	0.214	0.250	0.081	0.201	0.262	0.678
C	RF 5	B	1.257	0.178	0.317	0.152	0.337	0.245	0.385

APPENDIX V

Summary of primary data collected during laboratory experiment for plant relative growth (PGR)

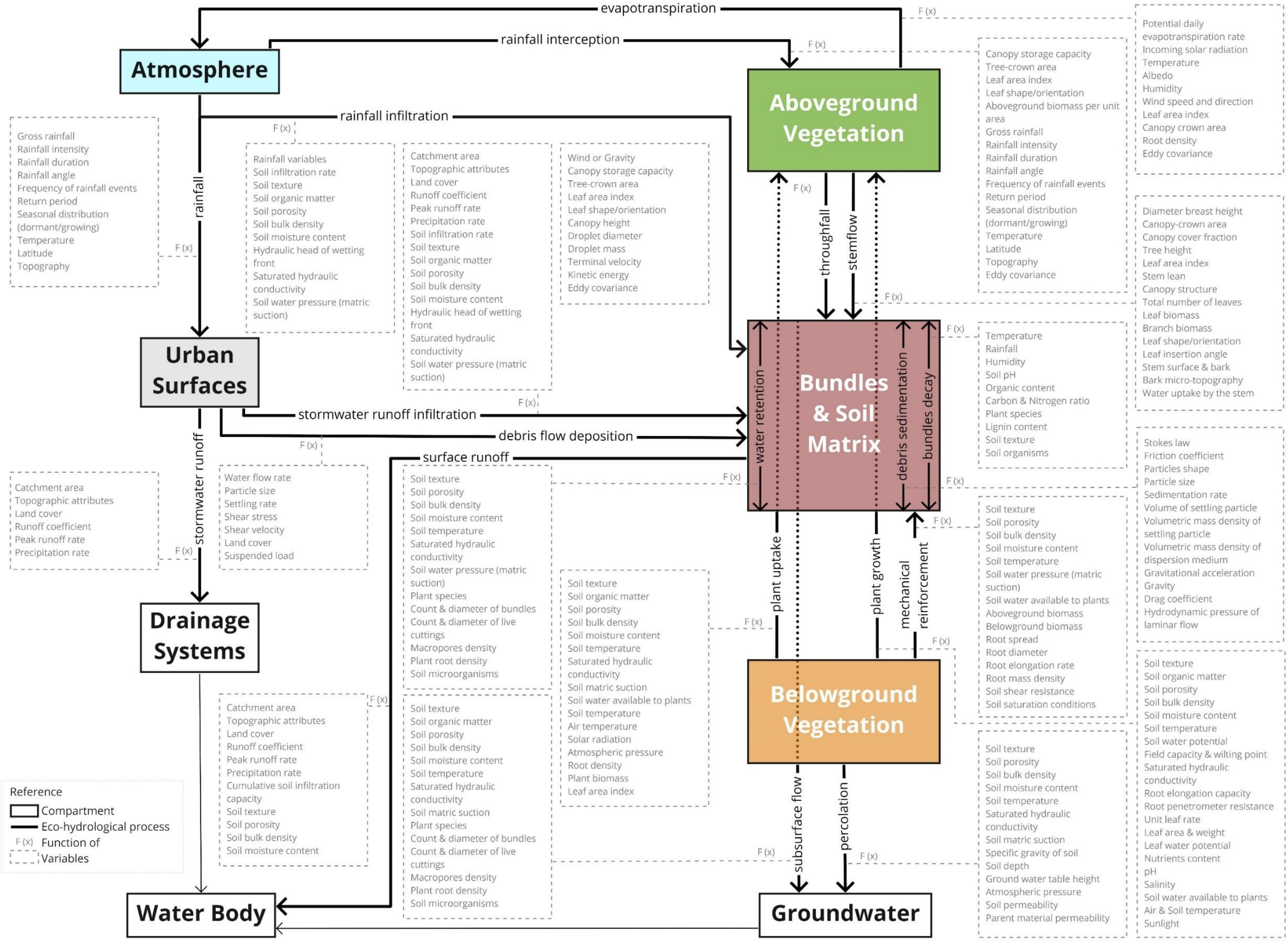
ID	Treatment	Zone	t1	t2	S1_mm	S1_cm	S2_mm	S2_cm	lnS1	lnS2	RGR
1A	W	toe	3	52	2	0.20	170	17.00	-1.609	2.833	0.091
1B	W	toe	3	52	12	1.20	296	29.60	0.182	3.388	0.065
1C	W	crest	5	42	6	0.60	29	2.90	-0.511	1.065	0.043
1D	W	crest	5	49	7	0.70	61	6.10	-0.357	1.808	0.049
1E	W	crest	5	31	6	0.60	173	17.30	-0.511	2.851	0.129
1F	W	crest	5	52	7	0.70	468	46.80	-0.357	3.846	0.089
1G	W	middle	5	52	2	0.20	484	48.40	-1.609	3.879	0.117
1H	W	toe	5	52	7	0.70	288	28.80	-0.357	3.360	0.079
1I	W	toe	5	52	2	0.20	159	15.90	-1.609	2.766	0.093
1J	W	toe	6	52	14	1.40	506	50.60	0.336	3.924	0.078
1K	W	middle	6	52	8	0.80	415	41.50	-0.223	3.726	0.086
1L	W	crest	7	52	4	0.40	610	61.00	-0.916	4.111	0.112
1M	W	toe	7	52	6	0.60	134	13.40	-0.511	2.595	0.069
1N	W	toe	8	42	5	0.50	220	22.00	-0.693	3.091	0.111
1O	W	toe	9	52	15	1.50	211	21.10	0.405	3.049	0.061
1P	W	toe	9	49	29	2.90	155	15.50	1.065	2.741	0.042
1Q	W	crest	11	52	12	1.20	143	14.30	0.182	2.660	0.060
1R	W	crest	11	52	10	1.00	405	40.50	0.000	3.701	0.090
1S	W	toe	11	52	26	2.60	580	58.00	0.956	4.060	0.076
1T	W	crest	12	30	6	0.60	187	18.70	-0.511	2.929	0.191
1U	W	middle	13	49	12	1.20	133	13.30	0.182	2.588	0.067
1V	W	toe	13	38	28	2.80	181	18.10	1.030	2.896	0.075
1W	W	middle	14	49	11	1.10	121	12.10	0.095	2.493	0.069
1X	W	middle	24	49	31	3.10	35	3.50	1.131	1.253	0.005
1Y	W	crest	31	48	16	1.60	27	2.70	0.470	0.993	0.031
2A	W	crest	4	52	5	0.50	397	39.70	-0.693	3.681	0.091
2B	W	middle	3	52	13	1.30	342	34.20	0.262	3.532	0.067
2C	W	middle	4	48	2	0.20	40	4.00	-1.609	1.386	0.068
2D	W	crest	5	49	4	0.40	182	18.20	-0.916	2.901	0.087
2E	W	crest	5	52	6	0.60	305	30.50	-0.511	3.418	0.084
2F	W	toe	5	49	2	0.20	517	51.70	-1.609	3.945	0.126
2G	W	crest	6	52	8	0.80	233	23.30	-0.223	3.148	0.073
2H	W	middle	6	52	4	0.40	630	63.00	-0.916	4.143	0.110
2I	W	middle	6	31	5	0.50	25	2.50	-0.693	0.916	0.064
2J	W	middle	8	52	6	0.60	602	60.20	-0.511	4.098	0.105
2K	W	middle	8	45	2	0.20	226	22.60	-1.609	3.118	0.128
2L	W	crest	10	52	16	1.60	501	50.10	0.470	3.914	0.082
2M	W	crest	12	52	10	1.00	132	13.20	0.000	2.580	0.065
2N	W	middle	15	30	16	1.60	33	3.30	0.470	1.194	0.048
2O	W	toe	16	49	5	0.50	57	5.70	-0.693	1.740	0.074
2P	W	middle	16	52	5	0.50	266	26.60	-0.693	3.281	0.110
2Q	W	toe	17	52	8	0.80	320	32.00	-0.223	3.466	0.105
2R	W	toe	19	38	4	0.40	199	19.90	-0.916	2.991	0.206
2S	W	toe	19	29	7	0.70	15	1.50	-0.357	0.405	0.076
2T	W	toe	24	25	18	1.80	18	1.80	0.588	0.588	0.000

2U	W	middle	25	52	21	2.10	111	11.10	0.742	2.407	0.062
2V	W	middle	49	52	19	1.90	48	4.80	0.642	1.569	0.309
3A	W	crest	4	52	2	0.20	371	37.10	-1.609	3.614	0.109
3B	W	toe	4	52	2	0.20	436	43.60	-1.609	3.775	0.112
3C	W	toe	3	52	24	2.40	605	60.50	0.875	4.103	0.066
3D	W	crest	5	52	6	0.60	204	20.40	-0.511	3.016	0.075
3E	W	middle	5	52	4	0.40	541	54.10	-0.916	3.991	0.104
3F	W	middle	5	52	2	0.20	203	20.30	-1.609	3.011	0.098
3G	W	toe	5	52	15	1.50	492	49.20	0.405	3.896	0.074
3H	W	toe	5	52	4	0.40	394	39.40	-0.916	3.674	0.098
3I	W	crest	6	52	5	0.50	126	12.60	-0.693	2.534	0.070
3J	W	toe	7	52	16	1.60	474	47.40	0.470	3.859	0.075
3K	W	crest	9	20	6	0.60	25	2.50	-0.511	0.916	0.130
3L	W	crest	10	52	16	1.60	171	17.10	0.470	2.839	0.056
3M	W	crest	11	52	9	0.90	115	11.50	-0.105	2.442	0.062
3N	W	crest	11	52	13	1.30	375	37.50	0.262	3.624	0.082
3O	W	middle	11	52	15	1.50	461	46.10	0.405	3.831	0.084
3P	W	toe	11	52	14	1.40	338	33.80	0.336	3.520	0.078
3Q	W	toe	13	32	23	2.30	35	3.50	0.833	1.253	0.022
3R	W	crest	14	48	3	0.30	25	2.50	-1.204	0.916	0.062
3S	W	middle	14	31	12	1.20	147	14.70	0.182	2.688	0.147
3T	W	toe	17	49	12	1.20	190	19.00	0.182	2.944	0.086
3U	W	middle	17	38	20	2.00	169	16.90	0.693	2.827	0.102
3V	W	middle	33	52	21	2.10	265	26.50	0.742	3.277	0.133
3W	W	middle	36	45	25	2.50	59	5.90	0.916	1.775	0.095
3X	W	crest	39	42	11	1.10	15	1.50	0.095	0.405	0.103
4A	W+A	crest	3	52	7.5	0.75	373	37.30	-0.288	3.619	0.080
4B	W+A	middle	4	52	13	1.30	450	45.00	0.262	3.807	0.074
4C	W+A	middle	4	52	13	1.30	174	17.40	0.262	2.856	0.054
4D	W+A	middle	3	52	25	2.50	351	35.10	0.916	3.558	0.054
4E	W+A	middle	5	49	14	1.40	505	50.50	0.336	3.922	0.081
4F	W+A	toe	5	26	5	0.50	65	6.50	-0.693	1.872	0.122
4G	W+A	toe	5	52	12	1.20	530	53.00	0.182	3.970	0.081
4H	W+A	middle	5	52	13	1.30	401	40.10	0.262	3.691	0.073
4I	W+A	crest	6	52	22	2.20	395	39.50	0.788	3.676	0.063
4J	W+A	middle	6	52	26	2.60	456	45.60	0.956	3.820	0.062
4K	W+A	crest	7	52	15	1.50	296	29.60	0.405	3.388	0.066
4L	W+A	crest	7	45	10	1.00	242	24.20	0.000	3.186	0.084
4M	W+A	toe	7	52	6	0.60	376	37.60	-0.511	3.627	0.092
4N	W+A	toe	9	21	24	2.40	45	4.50	0.875	1.504	0.052
4O	W+A	middle	9	38	28	2.80	283	28.30	1.030	3.343	0.080
4P	W+A	toe	9	52	23	2.30	308	30.80	0.833	3.428	0.060
4Q	W+A	middle	10	42	7	0.70	108	10.80	-0.357	2.380	0.086
4R	W+A	toe	12	52	29	2.90	209	20.90	1.065	3.040	0.049
4S	W+A	toe	11	52	36	3.60	362	36.20	1.281	3.589	0.056
4T	W+A	crest	11	52	45	4.50	335	33.50	1.504	3.512	0.049
4U	W+A	middle	13	17	24	2.40	29	2.90	0.875	1.065	0.047
4V	W+A	crest	18	31	26	2.60	72	7.20	0.956	1.974	0.078
4W	W+A	toe	18	52	18	1.80	183	18.30	0.588	2.907	0.068
4X	W+A	middle	24	33	21	2.10	32	3.20	0.742	1.163	0.047
5A	W+A	crest	4	52	15	1.50	310	31.00	0.405	3.434	0.063
5B	W+A	toe	3	52	4	0.40	321	32.10	-0.916	3.469	0.089

5C	W+A	toe	3	52	20	2.00	221	22.10	0.693	3.096	0.049
5D	W+A	middle	5	42	11	1.10	23	2.30	0.095	0.833	0.020
5E	W+A	toe	5	52	9	0.90	544	54.40	-0.105	3.996	0.087
5F	W+A	toe	5	52	6	0.60	129	12.90	-0.511	2.557	0.065
5G	W+A	middle	5	52	3	0.30	345	34.50	-1.204	3.541	0.101
5H	W+A	crest	6	52	10	1.00	306	30.60	0.000	3.421	0.074
5I	W+A	middle	6	52	9	0.90	92	9.20	-0.105	2.219	0.051
5J	W+A	crest	8	52	28	2.80	391	39.10	1.030	3.666	0.060
5K	W+A	crest	9	52	13	1.30	151	15.10	0.262	2.715	0.057
5L	W+A	toe	9	52	28	2.80	486	48.60	1.030	3.884	0.066
5M	W+A	crest	10	49	12	1.20	471	47.10	0.182	3.852	0.094
5N	W+A	crest	10	52	6	0.60	295	29.50	-0.511	3.384	0.093
5O	W+A	toe	11	52	35	3.50	402	40.20	1.253	3.694	0.060
5P	W+A	crest	11	52	16	1.60	481	48.10	0.470	3.873	0.083
5Q	W+A	crest	9	38	15	1.50	61	6.10	0.405	1.808	0.048
5R	W+A	crest	13	33	9	0.90	37	3.70	-0.105	1.308	0.071
5S	W+A	toe	13	42	14	1.40	181	18.10	0.336	2.896	0.088
5T	W+A	toe	13	52	16	1.60	477	47.70	0.470	3.865	0.087
5U	W+A	middle	13	31	34	3.40	150	15.00	1.224	2.708	0.082
5V	W+A	crest	14	49	17	1.70	117	11.70	0.531	2.460	0.055
5W	W+A	middle	15	52	48	4.80	254	25.40	1.569	3.235	0.045
5X	W+A	crest	15	39	13	1.30	53	5.30	0.262	1.668	0.059
6A	W+A	crest	4	52	2	0.20	485	48.50	-1.609	3.882	0.114
6B	W+A	toe	3	52	6	0.60	722	72.20	-0.511	4.279	0.098
6C	W+A	toe	5	52	7	0.70	363	36.30	-0.357	3.592	0.084
6D	W+A	middle	6	52	6	0.60	474	47.40	-0.511	3.859	0.095
6E	W+A	toe	9	52	18	1.80	585	58.50	0.588	4.069	0.081
6F	W+A	crest	10	52	14	1.40	356	35.60	0.336	3.572	0.077
6G	W+A	crest	10	52	11	1.10	72	7.20	0.095	1.974	0.045
6H	W+A	crest	11	52	13	1.30	356	35.60	0.262	3.572	0.081
6I	W+A	toe	13	52	13	1.30	255	25.50	0.262	3.239	0.076
6J	W+A	crest	13	52	14	1.40	489	48.90	0.336	3.890	0.091
6K	W+A	crest	14	52	10	1.00	237	23.70	0.000	3.165	0.083
6L	W+A	crest	18	52	35	3.50	216	21.60	1.253	3.073	0.054
6M	W+A	middle	18	52	49	4.90	515	51.50	1.589	3.942	0.069
6N	W+A	crest	19	45	13	1.30	99	9.90	0.262	2.293	0.078
6O	W+A	crest	21	31	19	1.90	125	12.50	0.642	2.526	0.188
6P	W+A	middle	24	49	10	1.00	21	2.10	0.000	0.742	0.030
6Q	W+A	toe	34	38	35	3.50	45	4.50	1.253	1.504	0.063

APPENDIX VI

LPD4C framework – full version



APPENDIX VII

Glasgow land suitability for LPD creation according to the defined environmental criteria

Soil texture suitability for LPD creation within Glasgow City.

Suitability Class	Soil Textural Classification	Surface Area (km²)	Total Surface Area (km²)	Proportion (%)
Unsuitable	No Data Available	2.05	28.79	16.23
	Peat	1.54		
	Varied, Locally Peat	25.20		
Low	Sand to Sandy Loam	5.25	5.25	2.96
Mid-Low	Sandy Loam to Silty Loam	39.00	125.29	70.63
	Sandy Loam to Loam	0.70		
	Loam to Sandy Loam	1.53		
	Loam to Silty Loam	0.70		
	Loam	3.50		
	Clayey Loam to Sandy Loam	79.86		
Moderate	Loam to Clayey Loam	1.77	18.07	10.18
	Clay to Sandy Loam	8.54		
	Clayey Loam to Silty Loam	7.76		

Slope gradient suitability for LPD creation within Glasgow City.

Suitability Class	Gradient	Surface Area (km²)	Total Surface Area (km²)	Proportion (%)
Unsuitable	>35°	1.14	1.14	0.64
Mid-low	15-35°	10.86	10.86	6.12
Optimal	5-15°	40.12	165.40	93.23
	1-5°	98.22		
	0-1°	27.06		

Slope curvature suitability for LPD creation within Glasgow City.

Suitability Class	Curvature Classification	Surface Area (km²)	Total Surface Area (km²)	Proportion (%)
Unsuitable	Convex	17.49	17.49	9.86
Optimal	Planar	140.71	159.91	90.14
	Concave	19.20		

Slope aspect suitability for LPD creation within Glasgow City.

Suitability Class	Aspect	Surface Area (km²)	Total Surface Area (km²)	Proportion (%)
Unsuitable	N	24.90	24.90	14.04
Low	NE	20.34	41.22	23.24
	NW	20.88		
Mid-Low	E	18.78	39.58	22.31
	W	20.80		
Moderate	SE	20.80	44.42	25.04
	SW	23.62		
Optimal	S	27.28	27.28	15.38

Proneness to surface flooding suitability for LPD creation within Glasgow City.

Suitability Class	DTW Classification	Surface Area (km²)	Total Surface Area (km²)	Proportion (%)
Low	0-100m	17.90	17.90	10.09
Mid-low	>1000m	68.31	68.31	38.50
Moderate	700-1000m	21.51	50.91	28.70
Moderate	400-700m	29.40		
Optimal	100-400m	40.28	40.28	22.71

Land cover suitability for LPD creation within Glasgow City.

Suitability Class	Land Cover	Surface Area (km²)	Total Surface Area (km²)	Proportion (%)
Restricted	Buildings and Structures	21.68	59.40	33.48
	Rails, Roads, Tracks and Paths	34.07		
	Open Water	3.65		
Unsuitable	General Surfaces	46.05	46.05	25.96
Mid-Low	Play Spaces and Sports Areas	4.47	4.47	2.52
Moderate	Green Corridors	5.48	15.68	8.84
	Other Functional Greenspaces	2.31	2.31	1.30
	Parks and gardens	7.89		
Optimal	Amenity Greenspaces	6.42	51.80	29.20
	General Surfaces, Natural	25.24		
	Natural and Semi-Natural Greenspaces	20.14		

Proximity to greenspaces suitability for LPD creation within Glasgow City.

Suitability Class	Buffer distance from green areas/infrastructure	Surface Area (km²)	Total Surface Area (km²)	Proportion (%)
Moderate	>350m	0.09	0.09	0.07
Optimal	<350m	137.24	137.24	99.93

Proximity to healthy vegetation suitability for LPD creation within Glasgow City.

Suitability Class	Buffer distance from healthy vegetation	Surface Area (km²)	Total Surface Area (km²)	Proportion (%)
Unsuitable	>200m	7.31	7.31	5.10
Low	150-200m	9.91	9.91	6.92
Mid-Low	100-150m	20.43	20.43	14.26
Moderate	50-100m	37.56	37.56	26.22
Optimal	0-50m	68.07	68.07	47.50