Open-air Nb-SuDS facility design, construction, and instrumentation

Featuring Live Pole Drains

Design, Construction and Modeling of an Experimental Setup for the long term Eco-hydrological behavior of a Live Pole Drain

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Abstract

Live Pole Drains (LPDs) are a plant-based drainage system used to drain natural slopes and prevent shallow gully erosion. LPDs are a Nature-based Solution built by placing a live fascine in a shallow ditch or gully along the slope direction, allowing moderate fluxes of surface runoff or seepage to infiltrate and high water fluxes to be conveyed along the fascine without further eroding the slope. Despite their practical implementation, the transient and long-term eco-hydrological behavior of LPDs is not well understood. We aim to better understand the LPD's water balance, the seasonal and life-span changes in hydrological behavior, as well as the impact of an LPD on surface runoff water quality. To this end, we built and instrumented an artificial slope with full-scale LPDs in an open-air lab (OAL) at TU Delft. The design of the setup and the monitoring plan of the LPDs were developed in collaboration with Glasgow Caledonian University with insights from the construction and monitoring of three LPDs at different growth stages in their OAL on the east coast of Scotland. Herein, the design and possible research experiments that can be performed over the next 5 years are presented, generating a data set to further develop and validate hydrological modeling of LPDs. We expect this long-term demonstrative setup to generate interest and facilitate a more comprehensive understanding of LPD functions, ultimately leading to the incorporation of LPD design and maintenance standards in engineering toolboxes for slope and gully stabilization.

Keywords: Nature-based Solutions, Live Pole Drain, Open Air Lab, Sustainable Drainage Solutions

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1 Introduction

This thesis project aims to take the first steps in establishing a long-term, experimental, open-air, full-scale setup to research the ecohydrological behavior of Vegetated Swales and Live Pole Drains (LPDs) with a focus on the latter. The project is completed as part of the TU Delft Sponge Campus project on establishing an open-air living lab on campus for research and education on Nature-based Solutions (NbS) and sustainable drainage solutions (SuDS) led by Dr. Thom Bogaard funded through the Climate Action Program. The choice to focus on LPDs comes from collaboration with the Applied Ecology research group at Glasgow Caledonia University whose work with NbS in an open-air lab at Catterline Bay, Aberdeenshire, UK, includes LPDs.

1.1 Theoretical Background

What are NbS and SuDS and what general gaps exist?
Nature-based solutions (NbS) is a broad term referring to strategies involving managed ecosystems to address problems. In civil engineering, NbS often incorporates grey and green infrastructure to reduce the cost and carbon footprint of a project, while providing ecosystem services beyond the scope of the project. NbS for drainage and slope stabilization are gaining popularity in discussions around resilience to flooding and landslides. NbS applied specifically to managing surface water are referred to as Sustainable Drainage Solutions or SuDS. While the hydrological behavior of some SuDS has been widely studied and is common in practitioners' toolkits, other more innovative approaches lack a clear enough description of their hydrological function to incorporate them into engineering design for drainage and slope stability planning. Even on established NbS, gaps remain in understanding the ecological behavior and the effect of the NbS on water quality (Seddon et al., 2020). There are two gaps: (1) While many NbS/SuDS are designed to solve a specific problem, there isn't much research on their long-term behavior, and (2) NbS have many positive externalities, by understanding these NbS can be specifically designed and proposed to solve the problems that these externalities address.

What is an LPD? and What do we know so far about LPDs?
Live Pole Drains (LPDs) are a plant-soil system, nature-based drainage solution that is used to mitigate or prevent shallow gully erosion (Polster, 2003) (Figure 1). They consist of a live fascine (a long bundle of woody vegetation such as small branches and twigs) typically 30 cm in diameter; the fascine is placed on a trench on a hill slope, typically where a gully has started forming, or where a shallow landslide has disturbed the surface and poses a risk of further erosion. The Live Pole Drain functions by allowing surface runoff from up-slope to be conveyed along its length without further eroding the gully, over time, the LPD twigs sprout and grow, forming a vegetated area that further stabilizes the slope against gullies and shallow landslides.
Willow LPDs fulfill two functions in soil reinforcement on slopes per classification by Gray and Sotir (1996): capturing and restraining due to its structure and quick propagation in the first growth phases, and reinforcing and supporting due to its deep roots, high root/shoot biomass ratio, and high transpiration potential (Kuzovkina and Volk, 2009).
If an LPD is well established, its function includes typical functions of vegetation on slope stability (canopy interception reducing rainfall reaching soil, transpiration depleting soil moisture, foliage cover and leaf litter maintaining infiltration capacity, rooting system and leaf litter encourage soil biological activity and formation of meso- and macropores (Stokes et al., 2008)).
LPDs are used in practice in roadworks (Polster, 2003) and watershed restoration in Canada. Live fascines are used in various configurations for soil bio-engineering, in some cases they may incorporate LPD-typical functions.

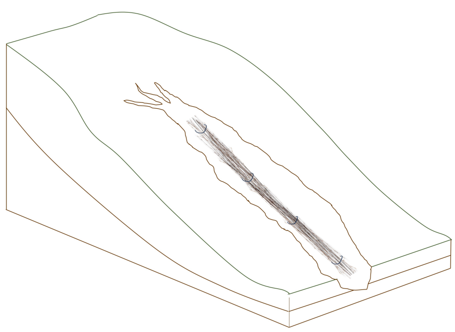


Figure 1: Live Pole Drain placed in a gully

What would we still like to know about LPDs?
Despite being used in practice and appearing in some NbS toolboxes (Gray and Sotir, 1996), the long-term hydro-ecological behavior of LPDs is not well understood (Benschop, 2022). Many questions need to be answered, such as: How does the partitioning of water between runoff and infiltration evolve over growth stages and seasons? How does the LPD affect water quality?

How can we learn more about LPDs? To study the LPD's water balance, the seasonal and life-span changes in hydrological behavior, as well as the impact of an LPD on surface runoff water quality, LPDs can be better understood through monitoring LPDs installed in real field conditions, such as those in Catterline however, due to the lack of control or monitoring of sub-surface fluxes, it is difficult to close the water balance.
Another option is to monitor them by building controlled experimental setups, and model their behavior based on physical processes and observations.

1.2 Thesis Objectives and Research Questions

The objectives of the thesis are:

1. To co-design, build, instrument, and prepare a data management plan and modeling suggestions for a nature-based drainage system with 'smart' environmental sensors to evaluate its long-term eco-hydrological performance at TU Delft Open Air Lab (OAL).
2. To establish a conceptual model for the behavior LPDs at the TU Delft SuDS Facility.

Based on these objectives, the following questions are defined:

1. How can an open-air lab be designed and constructed to support long-term monitoring and short-term experiments of the eco-hydrological behavior of LPDs and other NbSuDS?
2. What measurable processes and parameters on the experimental LPD setup can be combined with an understanding of physical processes to conceptually model the ecohydrological behavior of LPDs?

The thesis objectives and activities designed to answer the research questions align with the activities described in the Sponge Campus project application (See Appendix B).

1.3 Outline

This report is structured in three parts. Part I regards lessons learned from field and lab work with Glasgow Caledonia University, this includes an overview of the site and objectives of data collection, methodologies used in field and lab (Ch. 2), and a discussion of relevant results in the context of the SuDS facility in Delft (Ch. 3). Part II provides an overview of the process of design and construction (Ch. 4) and the monitoring plan (Ch. 5) for the SuDS facility in Delft. Part III regards modeling the eco-hydrological behavior of the LPD with a conceptual model (Ch. 6 and 7). Finally, the report is concluded with a Synthesis (Ch. 8).

Part I
Catterline Fieldwork

This part of the report regards the findings and insights gained from a visit to the Applied Ecology research group at Glasgow Caledonian University (GCU) and their field site in Catterline Bay in late September 2023. The fieldwork described in this section was designed to build on previous work on the hydrological behavior of LPDs at Catterline (Benschop, 2022), adding to a dataset on the transient characteristics of LPDs. Lessons were taken from the various monitoring efforts in Catterline to apply in the design of the OAL at TU Delft.

2 Field Monitoring and Experimentation Methodology

In this Chapter, descriptions are provided of the study site including the configuration of the monitored LPDs, then the monitoring methodologies are presented for above- and below-ground ecohydrological states and processes.

2.1 Study Site

The land adjacent to Catterline Bay, Aberdeenshire, UK (WGS84 Long: -2.2152 Lat: 56.8955), is characterized by cliffs presenting shallow and deep landslides, surface erosion, and coastal erosion. Slope instabilities have been triggered by heavy rain events. Due to these hydrometeorological hazards, the location was selected as an open-air lab for Nature-based Solutions (NbS) for erosion control by OPEn-air laboRAtories for Nature baseD solUtions to Manage hydro-meteo risks (OPERANDUM) in collaboration with Glasgow Caledonian University and other partners. Research on various topics related to slope protection is actively conducted at the site: erosion and plant-soil systems used to mitigate it including the hydrological (Gonzalez-Ollauri and Mickovski, 2017a) and mechanical (Gonzalez-Ollauri and Mickovski, 2017c) effect of vegetation on slope stability, the evolution of ecosystems on eroding slopes and their self-regulating effect (Gonzalez-Ollauri and Mickovski, 2017d); tools have been developed to detect landslides (Gonzalez-Ollauri and Mickovski, 2021) and to select plants for slope protection (Gonzalez-Ollauri and Mickovski, 2017b), additionally, the site has provided insights into public acceptance of NbS (Anderson et al., 2022). A Live Pole Drain at this site was studied by Benschop (2022).

Three LPDs are present at the site (Figure 2), they are referred to as LPD21, LPD22, and LPD23 in this report according to the years of their installation. LPD21 was installed by GCU in the summer of 2021, it is made up of one live fascine of Basket Willow (*Salix Viminalis*) installed on a 25 to 30-degree slope and has a length of 12 meters. LPD21 has a Y-shape at the top and its lower end drains to the edge of the Catterline harbor access road. LPD22 was installed in the summer of 2022, it is made up of three fascines of various species and staked with basket willow, it is installed on a 30 to 35-degree slope and has a length of 17 meters. LPD22 has a Y-shape at the top and the lower end of the LPD drains into a live fascine ribalta along the edge of the Catterline harbor access road for 12 meters. LPD23 was installed in the summer of 2023, it is located along the left side scarp of a shallow landslide, with three branches located below the head scarp, and each of two minor scarps, the main drain of the LPD has a slope of 25 to 35 degrees, and the branches have slopes varying from 5 to 25 degrees, the main drain and two of the branches are made with fascines of basket willow and staked with basket willow and goat willow (*Salix caprea*), one branch is made with a fascine of goat willow. LPD23 drains into a drainage well and brush layer.

2.2 LPD Hydrological States and Processes Monitoring

To confine the hydrological description of an LPD to a manageable unit of analysis, a control volume was defined around the LPD, exchange of water between the control volume and the exterior occurs via in-fluxes and out-fluxes. External forcing and processes within the control volume dictate the partitioning of out-fluxes. The hydrological processes within an LPD can be classified as above-ground processes or below-ground processes (Benschop, 2022).

Influxes include precipitation, overland flow, subsurface macropore flow, and groundwater. All three LPDs at Catterline are dominated by an influx of groundwater or surface water at the top and/or along the length of the LPD, LPD22 and LPD23 are placed under outlets of drain pipes, whereas LPD21 intersects a seepage zone at its top and middle. Out-fluxes include percolation, lateral flow out the down-slope end of the LPD, evaporation, and transpiration. All three LPDs showed active lateral flows at the down-slope ends.

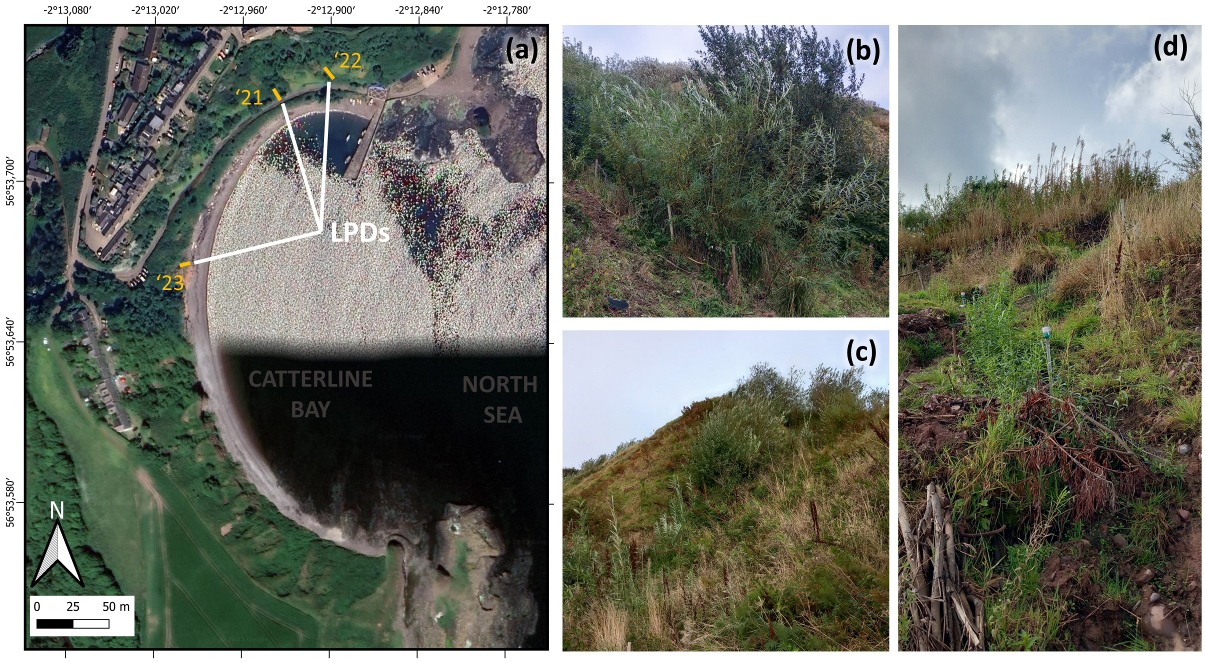


Figure 2: Catterline Bay with (a) LPD locations, (b) LPD21, (c) LPD22, (d) LPD23.

Within the above-ground portion of an LPD, precipitation is intercepted by vegetation and, partitioned between stem flow, free throughfall, intercepted throughfall, and canopy storage which is available for evaporation, all precipitation that eventually reaches the ground is called effective precipitation. Interception can be estimated using Leaf Area Index (LAI) as a proxy. When interception capacity is reached, the excess precipitation is split between stem flow and throughfall. Willow stem flow is relatively high (Gonzalez-Ollauri and Mickovski, 2017b) channeling a fraction of intercepted rainfall toward the roots of the tree.
Within the below-ground portion of the LPD, effective precipitation, incoming overland flow, subsurface macropore flow, and groundwater flow can be partitioned by the below-ground media between percolation, and lateral flow, or stored within the control volume. The properties of the soil, such as particle size distribution, abundance of macropores, and vegetation induced preferential flow paths, can all influence how water moves below ground.

Within this framework, observations and experiments were made on the above-ground and below-ground portions of the LPDs. The observations are not meant to comprehensively describe the origins and destinations of every flux passing through the control volume, but to understand what processes are at play and to get an idea of their order of magnitude. Most observations were conducted on LPD21 and LPD23 (Figure 3).

2.2.1 Above-ground characteristics and processes

Above ground characterisation of the state of the LPDs includes measuring canopy LAI, and calculating total above-ground biomass for each LPD through allometric relationships. The hydrological process of rainfall-throughfall partitioning was observed.

Growth stage description of LPD. Specific Leaf Area (SLA) and Leaf Area Index (LAI) were estimated following Wolf et al. (1972) (Appendix F). Basket willow samples were taken from LPD21 and from other basket willows in the bay to estimate SLA. Data was collected on the location, height, diameter, and angle of willow sprouts and poles to describe the growth stage of each LPD. The growing elements of LPD are the fascine of branches placed along the slope, and the stakes placed vertically to hold the bundle in place. To extrapolate the results of the estimation of LAI for a single willow pole to saplings and poles of varying dimensions allometric relationships were found from literature and field data collection. Measurements were made of sapling and pole diameters, heights, numbers of leaves, and branches, and correlation coefficients were calculated to select parameters that could be used for extrapolation.

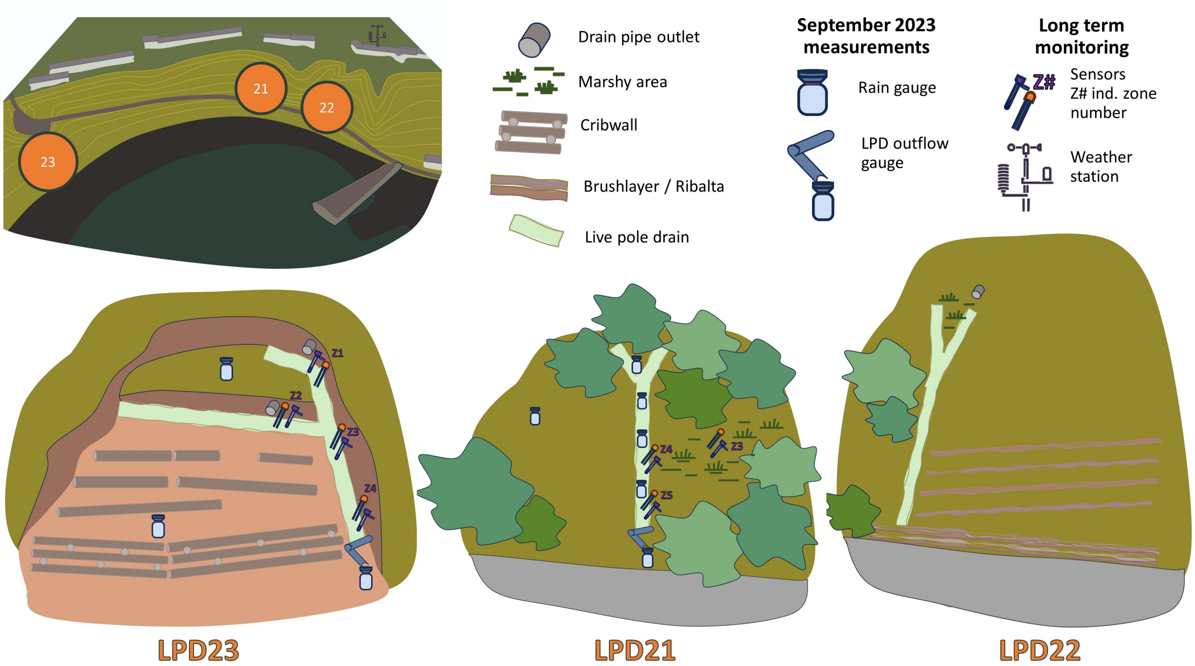


Figure 3: Schematic representation of LPD layout and sensor locations. Not to scale.

Rainfall and throughfall. Meteorological data was available from a private weather station (Davis Vantage Pro2®) located in Catterline village at 56.896° N, 2.214° W, 100 meters from the bay. Rain gauges made from two-liter containers with a funnel attached to the top were placed at four locations around the bay to compare to weather station data. Four rain gauges were placed under the vegetation covering LPD21 to capture throughfall. Rain and throughfall gauges were checked daily and the contents were measured using a volumetric flask.

2.2.2 Below-ground characteristics, states, and processes

Below-ground characterisation included measuring soil properties including organic matter content, bulk density, porosity, soil macro-fauna population, and finding van Genuchten parameters to fit the wetting and drying Soil Water Retention Curves of the soil. The temporal variations in the state of the unsaturated zone were observed through measurements of soil moisture, matric suction, and temperature. The lateral flow process was studied through observation and experimentation.

Unsaturated zone characteristics. Soil properties around the LPD are expected to change over its development time, leaf litter produced by the LPD vegetation and the micro-biome around the LPD fix carbon in the soil. Depending on the substrate, organic-rich soil may provide a layer of higher or lower permeability, it was expected that the organic matter layer contribute more to infiltration due to the overland flow velocity reduction in leaf litter, and the macro-pores within the decomposing organics. Undisturbed soil samples were taken from the topsoil horizon in the top, middle, and toe of LPD21 and LPD23, as well as from the soil near each LPD. Laboratory analysis was performed on these samples to find relevant soil parameters to model the unsaturated zone (Kuang et al., 2021): bulk density and soil organic matter content. These were measured per standard method (ISO, 2004) and by loss on ignition (Tabatabai, 1996), respectively. Soil water retention curves were found following lab protocol by Gonzalez-Ollauri (2018). The wetting curves were found for soil samples from the topsoil horizon of LPD21 and LPD23, a drying curve was only found for soil from LPD23 due to lack of resources. See all protocols in Appendix E. Alongside non-biological soil properties, the abundance of macro-invertebrates in the soil can indicate macropores (Oades, 1993). Soil biodiversity was expected to be higher in patches vegetated with native tree species than in grassy areas, native tree species tend to present higher levels of insect and fungus diversity, willows, in particular, are one of the tree genera with the highest insect diversity in the UK (Kennedy and Southwood, 1984). There are many soil biodiversity survey methodologies, however, focusing on a single species of soil macro-fauna such as earthworms as an indicator of soil health is a common approach (Pulleman et al., 2012). The earthworm monitoring protocol by the Agriculture and Horticulture Development Board (see Appendix F) was adapted to include other soil macro-fauna.

Unsaturated zone state and dynamics. Soil Moisture (SM) and Matric Suction (MS) are indicators of the state of the unsaturated zone. LPD21 and LPD23 were equipped with sensors since July 2023. Soil moisture sensors (Campbell Scientific CS616®), field tensiometers (Irrometer ®), and temperature sensors (Cambell Scientific T-107®), collect data at 15-minute intervals and store it on data loggers. Data from August and September was retrieved. The data from these monitoring points at Catterline was not analyzed in depth in this report, however, the data was visualized to check spatial and temporal variations in observations for patterns that could indicate processes such as infiltration and percolation.

Lateral flow in LPD21 and LPD23. There was constant lateral flow out of the bottom of all three LPDs for the duration of the fieldwork week. The lateral flow out of the lower end of LPD21 and LPD23 was measured by capturing it in gutters at the base of the end of the LPD fascines, the water was collected in jugs with a funnel and then measured with a volumetric flask (Figure 4). LPD21 had an existing gutter in place, whereas for LPD23 the gutters were installed shortly before the measurement campaign began; one spanning the bottom of the LPD, and another slightly below the gutter capturing flow from a macropore that became visible after installing the first gutter. LPD21 lateral outflow was measured using a 20-liter jug and measured at one-hour intervals. LPD23 lateral outflow was measured using a 2-liter jug at daily intervals. There was also a constant flow into the top of LPD23 from a drain pipe, this flow was measured using a 2-liter jug at an hourly interval on days when the out-flow was not measured. An experiment was conducted on LPD23 to compare lateral flow and percolation partitioning for inflow rates of different intensities. This was done by applying a known volume of water to the top of the LPD and making the following measurements: time from inflow until the start of increased outflow, and rate of outflow for three intervals after inflow. Eight repetitions of the applied lateral flow in experiments were completed, four with an inflow of 1500 ml, and four with an inflow of 2000 ml, measurements of outflow rate were 15 minutes, 1 hour, and 2 hours after inflow.

Figure 4: Gutter to capture outflow of LPD23

3 Field Monitoring and Experimentation Results

In this chapter, the results of each set of observations and experiments from Catterline are presented and discussed. Each result provides insight into possible design criteria or monitoring protocols for the experimental setup at TU Delft.

3.1 Above-ground characteristics and processes

The objective of the above-ground characterization of the LPDs was to find their LAI, this was helpful to develop a monitoring protocol for the above-ground growth of the LPDs in the experimental setup at TU Delft. The objective of measuring the above-ground process of rainfall interception was to see whether it is worthwhile to measure it.

3.1.1 Growth stage description of LPD

To find the average LAI for each LPD, first, the Specific Leaf Area was found, and then allometric relationships were found for each of the two growth stages (sapling and pole), then metrics of the willows in each LPD were taken, finally, SLA was scaled by the growth metrics using the allometric relationships to find LAI.

Specific Leaf Area (SLA). The specific leaf area of basket willow samples taken from trees near LPD21 was determined to be 0.122 m2/g following protocol by Wolf et al. (1972), calculating leaf area as the sum of products of length, width and a factor of 0.74 (Verwijst and Wen, 1996). The leaf area index (LAI) of each of the three LPDs (table 2) was calculated by multiplying the specific leaf area (SLA) by the estimated weight of leafy biomass estimated based on observations on growth metrics. The leafy biomass per meter of LPD was calculated with allometric relationships between stem length and leaf mass for willow sprouts (typical in LPD23), and allometric relationships between diameter at breast height, and number and length of branches were used to estimate leaf mass of saplings (typical in LPD22 and LPD21). In the case of steeply bowed (>45 degrees) saplings, the vertical branches are treated as individual saplings.

Allometric relationships. Allometric relationships were determined by relating measurements of leaves per branch by length, branches per stem, and weight of leaves per branch by length, results are summarized in table 1.

Table 1: Simple linear regressions between Basket willow attributes, as $y = mx + b$

x	y	m	b	r^2
Sapling height (cm)	# leaves	0.4	8.5	0.82
Pole diameter (cm)	# branches	9.9	-3.5	0.73
Branch length (cm)	mass of leaves (g)	0.1	-0.1	0.97

Growth metrics LPD23 and LPD21 showed growth from both the fascine and the stakes along the length of the LPD, whereas LPD22 primarily showed growth of the stakes, with some growth from the fascines near the top of the slope. A schematic of the LPD growth is shown in Figure 5. The branch of LPD23 with little growth was made from a Goate Willow (*Salix caprea*) fascine, but did not grow, this makes sense because *Salix caprea* are difficult to propagate with stakes, especially male plants (Liesebach and Naujoks, 2004). The average height of the sprouts in LPD23 was 40 cm, and the heights of saplings in LPD22 and LPD21 were 2 m and 3 m respectively. The average diameter at breast height in LPD22 and LPD21 was 1.2 cm and 2.0 cm, respectively. LPD22, with a base slope of 35 to 40 degrees showed many bowed saplings, primarily in saplings sprouting from stakes. This behavior was not observed in saplings in LPD21, and the sprouts in LPD23 were too small to develop this growth pattern.

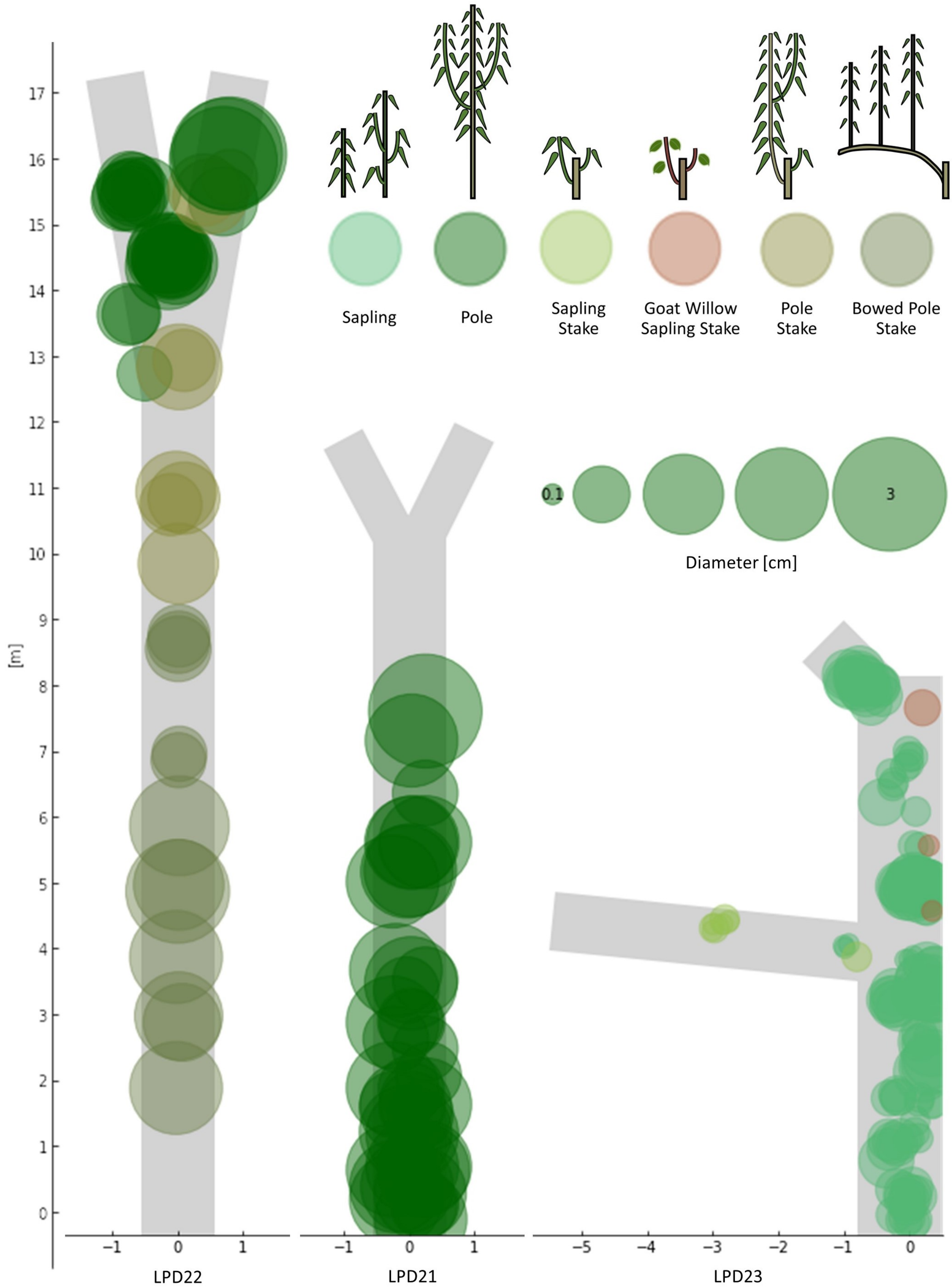


Figure 5: Growth metrics of LPDs

Table 2: LAI and per LPD and allometric relationships used to estimate

	LAI	Extrapolation process
LPD23	7	Sapling: leaf mass per shoot length
LPD21	6	Tall poles: branches per DBH, branch length per average pole, leaf mass per branch length
LPD22	3	Tall poles + stakes with short poles: branches per pole length, etc

3.1.2 Rainfall and throughfall

Limited data was collected due to the lack of frequent or heavy rain during the week of fieldwork. Three events of light rainfall were recorded, in which the average rainfall collected in rain gauges was similar to that recorded by the weather station in Catterline Village. Throughfall gauges captured 0 to 130% of average rainfall (Figure 6). A longer time series of data would be necessary to perform any analysis on the partitioning of rainfall into interception, throughfall, and stemflow.

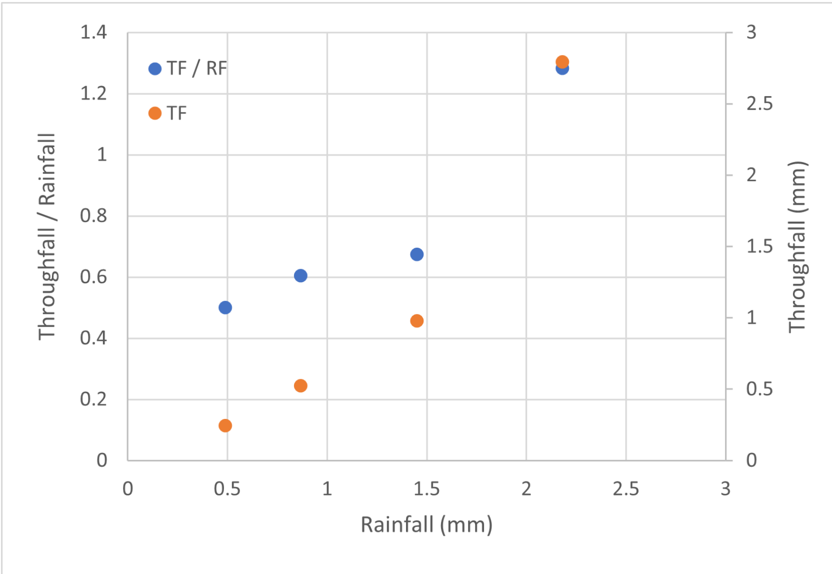


Figure 6: Rainfall (RF) vs throughfall (TF) and rainfall vs the ratio of throughfall to rainfall (TF/RF)

3.2 Below-ground characteristics, states and processes

The objective of the below-ground characterization was to understand what soil properties influence the behavior of the unsaturated zone, how they can be measured, and how often they should be measured. Looking into the fluctuations in the storage state in the unsaturated zone was meant to provide an indication of relevant time scales for measurements and analysis. Finally, observations on the lateral flow processes were meant to provide an indication of the capacity of the LPD to attenuate and convey high-volume, short-term events.

3.2.1 Soil Properties

Bulk Density, Porosity, and Organic matter found in September 2023 are compared to the soil parameters found in April 2022 (Benschop, 2022), there is a slight decrease in average values of bulk density and an increase in porosity and organic matter content, however, the difference between the parameters is less than the standard deviation of observations (Table 3). See Appendix G for a full report on the results of each experiment. Wetting curves were found for Horizon I soil in LPD21 and LPD23, and a drying curve for LPD23 (Figure 7). Van Genuchten parameters were found visually to fit curves to experimental data (Table 4), the van Genuchten approximation is best suited to the shape of drying curves.
The soil in an area vegetated by willows was found to be more diverse and have a higher content of macrofauna, where an average of four times as many specimens were found in sampled soil compared to samples in a grassy

area, in the grassy area only worms were found, whereas in the forested areas, there were worms, centipedes and snails.

Table 3: Overview of the results of lab and field soil tests on the samples taken from locations in LPD21 and LPD23 at horizon I.; $\rho : drybulkdensity(Mg/m^3); n_{por-a}$: porosity (-) calculated as $(\rho - \rho_{wet})/\rho_{wet}$; n_{por-b}: porosity (-) calculated as 1 - $\rho/\rho_{particle}$; OM: organic matter content (%). The standard deviation of each set of measurements is shown in parentheses.

	ρ	n_{por-a}	n_{por-b}	**OM (%)**
LPD21 04/22, Benschop (2022)	0.78 (0.09)	0.38 (0.03)	0.71 (0.03)	9.32 (1.29)
LPD21 09/23, This study	0.77 (0.05)	0.43 (0.06)	0.71 (0.02)	11.86 (1.72)
LPD23 09/23, This study	1.49 (0.14)	0.15 (0.02)	0.44 (0.05)	4.23 (0.33)

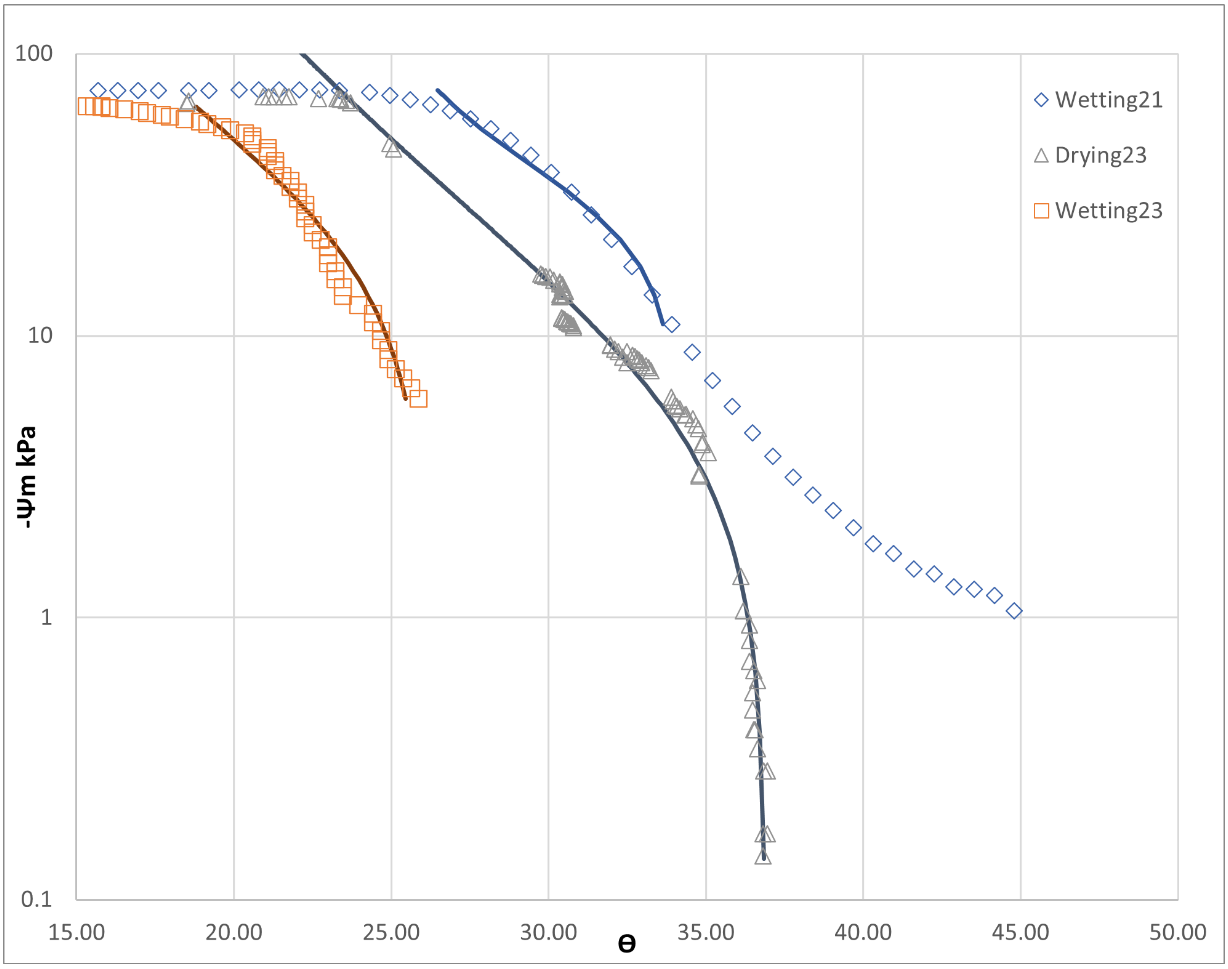


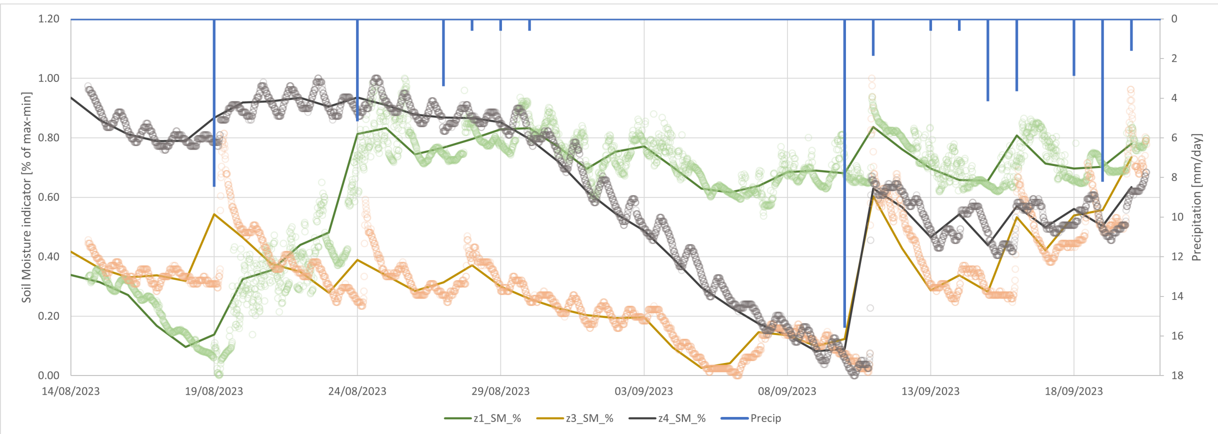
Figure 7: Soil Water Retention Curves. (a) Wetting curve for soil sample from LPD21 in, blue diamonds, (b) Drying curve for soil sample from LPD23, gray triangles, and (c) Wetting curve for LPD23, orange squares.

Table 4: Van Genuchten parameters; θ_r: Residual water content (m^3/m^3), θ_s: saturated water content (m^3/m^3), n: fitting parameter (-), α: fitting parameter(m^{-1}. *For wetting curves, full saturation (i.e. matric suction = 0) was not reached, therefore the fitting parameters are not fit to the entire curve

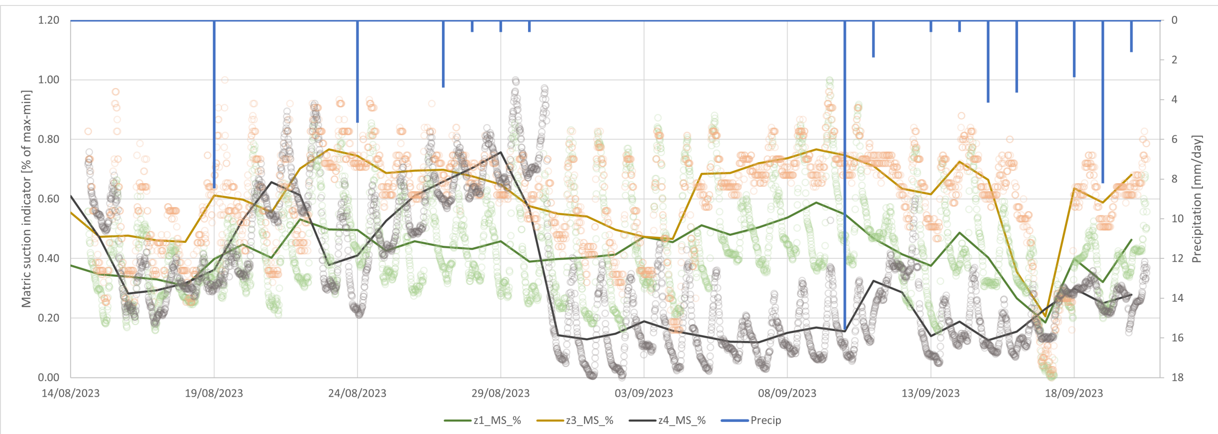
	θ_r	θ_s	$\boldsymbol{n}$	α
LPD21 Wetting	0.24	>0.34	2.5*	0.03*
LPD23 Wetting	0.15	>0.26	2.8*	0.04*
LPD23 Drying	0.02	0.37	1.2	0.15

3.2.2 Unsaturated zone dynamics

Matric suction was measured in units of kPa and soil moisture in m^3/m^3, however, due to differences in measured values of up to four orders of magnitude for matric suction and a high percentage for soil moisture, the results are normalized to a percentage of the difference between the min and max value measured during the visualized time; this allows us to focus on the fluctuations in each of the measured parameters rather than its absolute value. In both LPDs daily fluctuations in matric suction are visible, in LPD23 there are also daily fluctuations in Soil Moisture (Figure 8). Soil moisture recession curves are visible at a time scale of less than 24 hours at the middle location of LPD23. Only zone 4 on LPD23 appears to react to rainfall, with higher absolute values of suction in the days following a rain event. Matric suction increases steeply around sunrise, peaks at astronomical noon, and decreases at night, this is typical behavior for matric suction influenced by plant water uptake, and evaporative forcing (Woon et al., 2011). Besides this daily fluctuation, no clear pattern nor immediate response is seen in the matric suction data. The period of visualized data may be too short, but it would be interesting to look at sensor data from September 2022 to July 2023 for LPD21.
No clear pattern in the spatial distribution of soil moisture was observed in the Catterline LPDs, this could mean that it doesn't vary much along an LPD or that the spatial heterogeneity in the field site causes too much noise in the measurements to see a pattern. Another possibility is that the high groundwater level, springs and constantly flowing drains keep the soil near saturation. These unknowns make it difficult to fully describe the processes within the unsaturated zone at Catterline; the experimental setup at Delft will be designed to avoid these uncertainties.

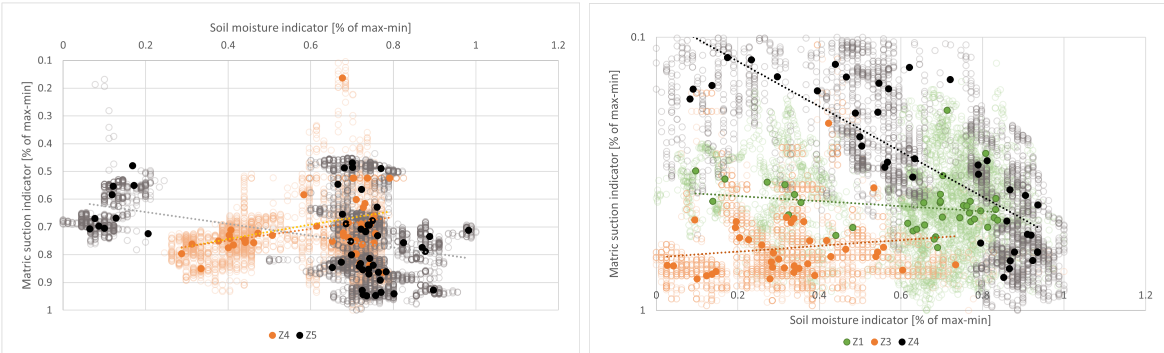


(a)



(b)

Figure 8: Observations of (a) Soil Moisture, and (b) Matric suction, in top (green), middle (orange), and toe (gray) of LPD23 from August 14st to September 20th, 2023. Units are in percentage of the difference between minimum and maximum value observed during the measurement period.



(a) (b)

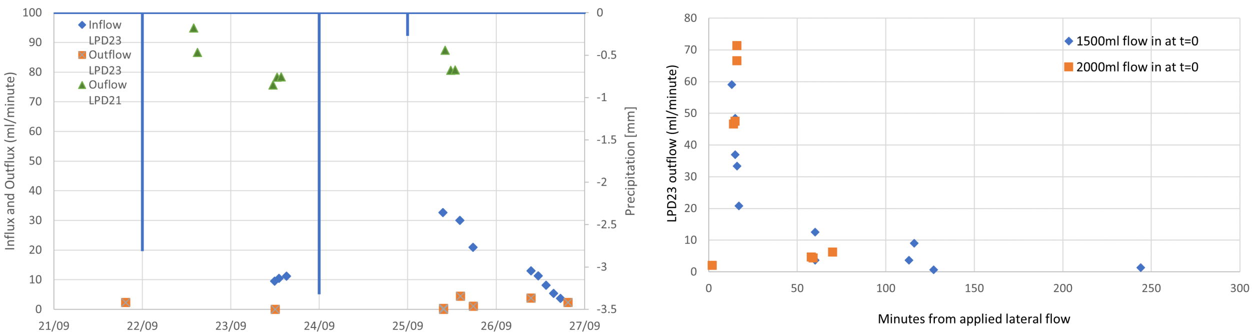
Figure 9: Soil moisture vs matric suction in (a) LPD 21 and (b) LPD23, blank circles show 15-minute data points, filled circles show daily average values.

3.2.3 Lateral flow in LPD21 and LPD23

For LPD21, data was collected on the natural out-flow rate on eight occasions for one-hour intervals over three days (Figure 10-a). For LPD23, there isn't a clear relationship between the inflow and outflow, which may be due to the gutter settling and the formation of new flow paths. It appears that the inflow is higher after rain events, and decreases over the next days. However, due to the short time series with the low measurement frequency and inconsistent interval, no conclusion can be drawn.

The results of the applied lateral flow experiments on LPD23 are shown in Figure 10-b. The inflows of 1500 ml triggered an increase in outflow from a drop of water every few seconds, to a constant ribbon of water after 3:00 minutes, and the inflow of 2000 ml triggered an increase in outflow after 2:40 minutes.

This experiment provides valuable lessons for the experimental setup and modeling LPD's lateral flow process. Especially the fact that lateral flow can be conveyed through the LPD very rapidly on young (< 4 month) LPD, time scale of minutes from inflow to outflow, this should be considered in modeling as it would require high temporal resolution or another creative solution.

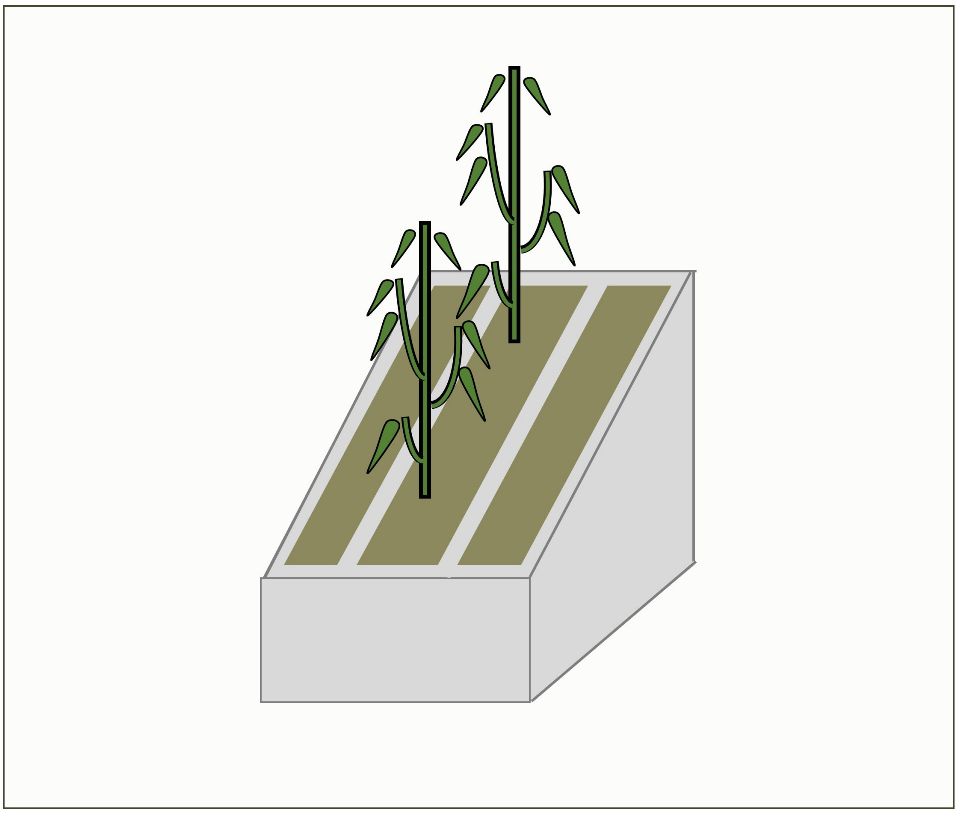


(a) (b)

Figure 10: Observations of (a) Outflow of LPD21 and LPD23 in natural conditions, and (c) Outflow of LPD23 vs. time after applied lateral flow

Part II

Open Living SuDS facility design, construction, and instrumentation



This part of the Report regards the co-design of the **R**oots **H**arnessing **I**nfiltration for **Z**ero-flooding **O**pen-air Lab (RHIZO Lab), a Nature-based Sustainable Drainage System (Nb-SuDS) Open Air Lab (OAL) at Flood Proof Holland (FPH) on the TU Delft campus and the detailed design, construction, and development of a monitoring plan for an experimental Live Pole Drain (LPD) setup within the RHIZO Lab.

4 Design and Construction

In this chapter, first, the establishment of the RHIZO Lab is discussed, then, the design of the LPD setup within the RHIZO lab.

4.1 Establishment of the RHIZO Lab

The RHIZO Lab was proposed as the *Sponge Campus Project*, a Climate Action and Education Seed for the TU Delft Climate Action Program, to inform research, practice, and educational activities for eco-based sustainable water management. The first steps in its establishment are presented in this report: collaborative design and lab layout.

4.1.1 Site Description

The proposed site is located in Flood Proof Holland (FPH) (51.98533, 4.38922) on the TU campus in Delft. FPH is an outdoor experimental facility and demonstrative site for innovations often visited by policymakers and practitioners of water management and urban planning, it is run by VP Delta and the Green Village. The area allocated to the RHIZO Lab approximately 220 m^2, situated between two ditches to the north and east, a sandy parking and storage area to the south, and woody vegetation to the west. The site was covered in piles of sand and brush.

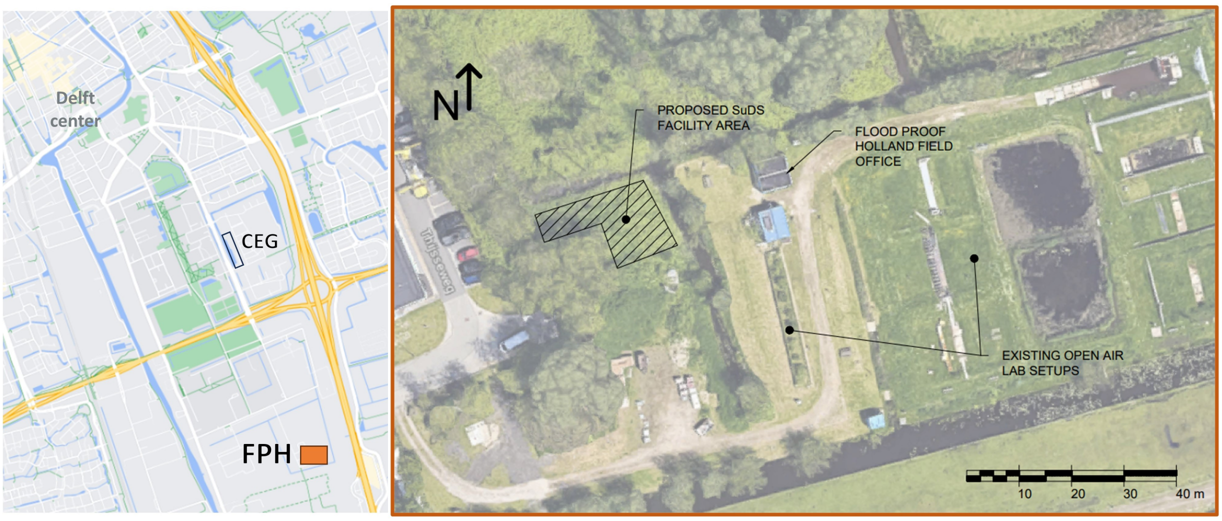


Figure 11: Location of Flood Proof Holland (FPH) on TU Delft Campus, and proposed area for the RHIZO Lab within FPH.

4.1.2 Collaborative Design

Collaborative design, or participatory design, includes three steps: information, design discussion, and feedback (Bødker et al., 2022). Per the Sponge Campus Project proposal (Appendix B, activities A1 and A2), various stakeholders were to be involved in the design process. Therefore, thoughts and advice were sought from people who could become stakeholders in this initiative through interviews held in the first week of May, 2023. Some potential stakeholders were found through snowball interviews, starting with parties already involved in the project. These stakeholders belonged to areas of research and education in water management and urban drainage, as well as to innovation demonstration in climate resilience. Another set of interviews was performed with stakeholders with an interest in ecology that were sought out through a search of biodiversity-related initiatives on campus. All stakeholders are listed in Appendix B.

To inform the participants in the co-design process, they received a copy of the project proposal and a short presentation on the project's purpose. For the discussion, participants were asked to answer a few questions. Most parties expressed interest and had ideas of what they would like to see in the SuDS facility. Some important design priorities that came out of the discussions with participants were:

- Generating long time series of data, therefore regular measurements should be possible with little to no maintenance.
- Plot scale testing and demonstration of theoretical or lab-scale experiments.
- Flexible spaces for short-term experiments and educational demonstrations

Although there were no major compromises nor wishes from participants that did not fit in the long-term plan of the lab, prioritizing which parts of the facility to start construction on is based on how actively involved with the experiments each participant intends to be. These interests, as well as an understanding of the feasibility and available budget, were taken into account moving forward.

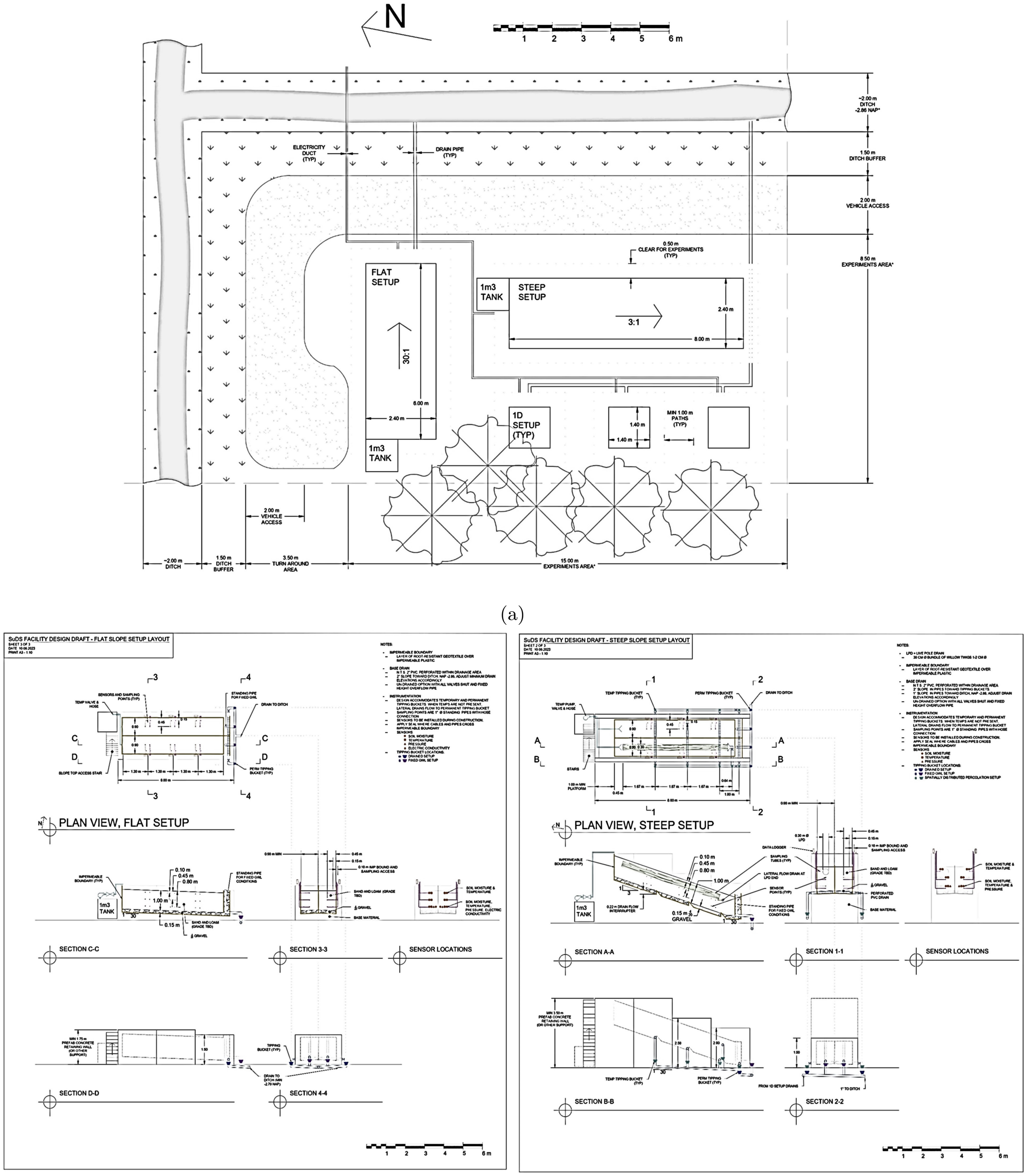
In the realm of feasibility: spatial division, temporal limitations, material availability, and monitoring capability, all played a role. The spatial division was considered for the lab plot: dimensions and layout of experiments leaving room for mobility and utilities; and for each setup: slope angle, soil depth, presence, and elevation of an artificial water table. The temporal division was considered in proposing the number of plots with long-term setups, and the number available for short-term experiments, considering growth phases of vegetation and LPD life cycle duration. Material availability was considered for experimental medium: specifications for the soil type and installation; and structure: ideas from other similar experiments, and experiences with locally available materials. Monitoring capability and feasibility of experimental objectives were considered in proposing types of sensors and locations, manual vs automated data collection, application of synthetic (for example, rain or runoff simulation) or natural forcing, and maintenance expectations. Considering the available budget, the original Seed Fund was combined with support from VP Delta.

4.1.3 Lab Layout

The design process led to concrete construction objectives: One steep slope divided into two or three sections to monitor LPD hydrological and ecological behavior in comparison to bare/grassy slope behavior. One gradual slope (referred to as the *flat* setup in this report) is divided in two or three sections to monitor long-term vegetated swale hydrological and bio-chemical behavior. Six to eight small flat plots for various short-term experiments with a focus on 1D behavior in the vertical direction. One or two educational plots for educational demonstrative activities. This report covers the facility layout to include all proposed construction but only provides the complete design for the first two objectives. Two experimental setups were designed, a flat setup and a steep setup, each divided into three compartments. See figure 12.

4.2 Live Pole Drain experimental set-up design and construction

The specific design of the LPD setup was developed in collaboration with GCU, informed by the LPD characterization from Catterline. Some of the design criteria observed were to: Measure or control as many fluxes as possible in order to facilitate the identification and quantification of hydrological and biological processes. To allow for long-term monitoring, in order to study the transient behavior of the LPDs. And, to include duplicates and a control setup for comparison and destructive analysis. The design process included making decisions on the LPD specification, setup geometry, base structure, drainage system design, and selection of specific media to fill.



(a) (b) (c)

Figure 12: Preliminary design of RHIZO Lab facilities (a) Layout, (b) flat setup, (c) steep setup. High-resolution images in Appendix C.

4.2.1 LPD Specification

The selected material for the LPDs is *Salix viminalis*, commonly known as basket willow (Dutch: *katwilg*). This species is used widely in soil and coast bioengineering in western Europe.

A fascine diameter of 30 cm was selected based on LPD design standards from practical design guides. For live pole drains, the twigs and branches of a fascine should be oriented down-slope, to encourage an even distribution of sprouting and rooting along the bundle, accounting for apical dominance. To encourage the growth of axillary buds, the apical or terminal bud should be pruned. Fascines should be soaked before installation(Sennerby-

Forsse et al., 1993), as higher moisture content of cuttings leads to a higher survival rate (Miller-Adamany et al., 2017). The fascine should only be covered with up to 5 cm of topsoil Edelfeldt et al. (2015) experimented with horizontally and vertically placed cuttings at different depths, and found the best performance in vertically placed cuttings and in longer horizontally placed cuttings at shallow depth.

Upon construction, procured *Salix viminalis* materials were insufficient, therefore cuttings of *Salix alba* available on the site were used as well, this species is expected to also grow well from stakes (i.e. produces adventitious roots). (Kuzovkina et al. (2004), Liu et al. (2011), Koop (1987), San-Miguel-Ayanz et al. (2016)).

4.2.2 Setup geometry

To observe the behavior of two-dimensional flow on the slope, the aim was to make the slope as steep as possible, without becoming unstable, therefore maximizing the height-to-length ratio up to a target of 3:1 and accepting a minimum of 4:1. Meanwhile, to observe differences between the top, middle, and toe of the LPD, the length of the LPD was also maximized. The maximum height was limited to 3.0 m by available materials for the structure, allowing a length of 6.5 meters, to maintain a slope greater than 4:1.

The depth of the soil layer under the LPD was minimized to not waste vertical space that could be used to make the slope steeper, but limited by the need for space for natural root growth. While willows are notorious for their deep tap roots developing from early years seeded saplings which present more vertical growth and a tap root (Lubbe et al., 2023), root growth in the LPDs is expected to not show early tap root formation due to its adventitious nature (Khuder et al., 2007). Other experiments involving basket willow were reviewed to develop an expectation on the root depth in the first years of growth. For example, in field soil root reinforcement experiments in silty sand reached a depth of 0.9 meters at 0.5 meters from the trees (Zydroń et al., 2018). The soil type and water availability in which the roots grow also influence their depth. Rytter (2001) compares the distribution of biomass in sand and clay for three-year willows. In the first year, sand allocates more biomass (than clay) below-ground to fine roots, and slightly less than clay in the consecutive years. Fine roots in clay have a higher production and mortality rate than in sand in absolute value, but are similar in proportion to other biomass percentages. According to Gorla et al. (2015) basket willow root growth concentrates around the mean annual groundwater level. Based on this information, a depth of 75 cm below the LPD is selected, and an option to set a fixed groundwater table within the experiment is included in the design criteria.

A minimum of one LPD slope and one bare slope was desired, with a preference for two LPD slopes, therefore, the with of the setup was maximized to include two divisions into three hydraulically disconnected slopes, divided by a stiff barrier and impermeable boundary.

4.2.3 Base structure

A few options were considered to support the experimental setup slope. First, earthwork support was considered, however, there was not sufficient space on the lab site to do this. Glass panel siding on a wooden structure was also considered, comparable to a setup of similar dimensions by Apollonio et al. (2021), however, this idea was discarded due to technical difficulty, possible fragility for the long term, and wanting to avoid disturbing natural subsurface processes by exposure to light. L-shaped precast concrete retaining wall elements were chosen due to their durability, and apparent availability. The design included walls around all four sides of the experimental slope, forming a container. To achieve the desired slope to place the experimental media over, the container was to be filled up to the desired level with sand available on-site.

4.2.4 Setup division and impermeable boundary

Through discussions with the contractor on available materials, wooden dividers were chosen to isolate the three experimental slopes. Different types of plastic were considered for the impermeable lining of the setup, including LDPE, HDPE, EPDM. While EPDM would have been the more durable option, an LDPE of 0.5 mm was chosen, considering quality for price.

4.2.5 Drainage specification

The decision to isolate the experimental setup slope from the natural subsurface arose from the want to avoid interaction of the unsaturated zone with groundwater and to measure percolation fluxes. A drainage layer within the impermeable boundary of the setup including controlled locations allowing outflow was necessary to achieve this. In order to measure differences in percolation along the length of the slope, four drainage points were proposed. Each drainage point consisting of a 32 mm PPC pipe perforated with slits, placed perpendicular to the slope at a 2% angle to drain out the side of the setup. To provide a continuous path for water from the finer fill media to the drain pipes, a layer of fine gravel was proposed. During the first growth season of the

Table 5: Planting soil options properties

	Teelgrond	Bomen zand	Bomen grond
d10	<0.063	<0.063	<0.063
d50	0.197	0.537	0.175
d90	>1.940	1.735	0.85
Ribbon test classification	Sandy Loam	Sandy Loam	Clay Loam
Infiltration rate [mm/h]	10	30	3
Quick runoff test	medium	low	high

LPDs it may be important to maintain irrigation or fix the groundwater level to ensure growth conditions and shallow root establishment for cuttings (Gorla et al., 2015). Additionally, experiments with a fixed groundwater level may be of interest to compare LPD behavior in drained and un-drained conditions. Therefore the setup is designed with an option to create a fixed groundwater level by inverting the drain pipes.

4.2.6 Selection of fill media

Two fill media are selected according to unique purposes: the lower layer must allow rapid and predictable percolation, and easily monitored unsaturated zone dynamics, and the upper layer should provide a healthy environment for LPD growth. A sand was selected for the lower layer, and planting soil for the upper layer. To minimize costs, the specific class of each material type was selected from commonly available construction materials. The criteria for material selection included: avoiding sharp changes in grain size distribution between the materials, d50 below 0.125 for the sand layer to match typical swale design, a well-sorted planting soil with a low content of fines to avoid ponding.

There was only one commercially available sand (Dutch: drainagezand) meeting the requirements. For gravel, the finest commercially available gravel was also selected. Three options for planting soil were considered: a sandy loam *Teelgrond*, a loamy sand *Bomen Zand*, and a sandy clay laom *Bomen Grond*. Wet sieve analysis, ribbon test (a texture-by-feel test of ribbon length and grittiness, this test is used widely in agriculture and citizen science and is expected to have an accuracy of 40 to 70% (Salley et al., 2018)), quick infiltration tests (non-standard), and quick runoff tests (non-standard) were performed with each soil type (protocols in Appendix D, detailed results in E). Teelgrond was selected due to its lower content of fines, well-sorted particle size distribution, and moderate infiltration capacity.

Standard protocols were followed for bulk density, organic matter content, and porosity, for grain size distribution, and dry sieve analysis. The saturated hydraulic conductivity of sand was measured using submerged pressure sensors (Van Essen TD-Diver®) placed in piezometers installed in the experimental setup using the inverse auger test adapted from Kessler and Oosterbaan (1974). The hydraulic conductivity of the gravel was too high to estimate with this method, it is assumed to be three orders of magnitude higher than that of the sand layer. The k_{sat} of the planting soil was based on the quick infiltration tests. All k_{sat} values were checked for order of magnitude against typical values for each soil class in literature (García-Gutiérrez et al., 2018).

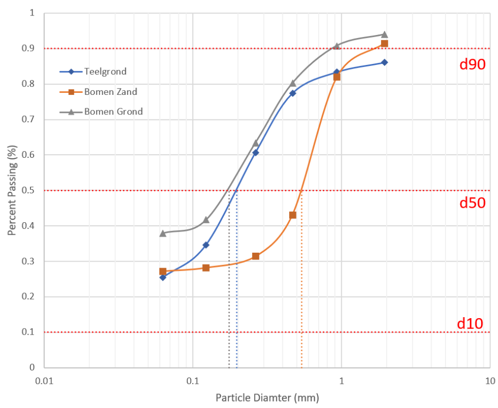


Figure 13: Wet sieve grain size distribution of planting soil options

Table 6: Selected Media properties. d10, d50, and d90: maximum diameter [mm] of passing percentage. Sand and gravel (*Note: for the planting soil, dry sieve analysis the oven-dried sample had clumps of fines of >2mm, therefore the wet sieve results are more representative)

	Planting soil		Sand	Gravel
	wet sieve	dry sieve*		
d10	<0.063	0.15	0.3	1.7
d50	0.2	0.5	0.59	>4.75
d90	>1.94	>4.75	4.75	>4.75
Bulk density [g/cm^3]	0.96		1.81	1.60
Porosity [-]	0.64		0.32	0.40
Organic Matter [%]	7%		0.13%	0.20%
Clay [%]	15%		<0.1%	<0.1%
Silt [%]	10%		<0.1%	<0.1%
$k_[sat]$ **[m/s]**	1.4e-5		2e-3	>2
Field Capacity [m^3/m^3]	0.2		0.02	0.04

4.3 Construction

The construction of the facility was executed by a contractor managed with The Green Village and Flood Proof Holland. The first steps were taken in Summer 2023, and the steep setup was completed in January 2024. Construction phases included clearing the site, laying out of experimental setup locations, installation of foundations for each setup, structural element and base fill installation, drilling drains, installing dividers and impermeable boundary, drainage layer installation: pipes and gravel layer, and experimental media installation and soil state sensors. Further details on the construction process are in Appendix C.

Some components of the design were not yet completed by January 2024. The installation of the drainage system from the setup, and the installation of tipping buckets.

Figure 14: Experimental setup under construction.

5 Maintenance and Monitoring

Long-term data collection on the experiment includes automated and manual measurements. Short-term experiments are also suggested. To ensure everything continues to function, maintenance tasks are also necessary.

5.1 Automated Monitoring - Smart Sensors

To record data over a multi-year period, sensors with cloud-connected data loggers for real-time data collection were installed. Sensors and data loggers from METER Instruments and van Essen Instruments were chosen because these are used by other projects in The Green Village (TGV) and Flood Proof Holland (FPH). Two of the experimental slope compartments were instrumented; the bare slope and one of the two LPD slopes. To capture the 2-dimensional behavior of the experimental setups, two profiles within each slope were instrumented with soil moisture and temperature sensors the lower one at 1.5 m from the bottom of the slope and the upper one at 4.6 m from the bottom of the slope, each profile includes soil moisture and temperature sensors at 30 cm below the top of the sand layer, 5cm below the top of the sand layer, and 5cm below the top of the planting soil layer or LPD. The upper cross-section includes a matric suction sensor 5cm below the top of the sand layer, and the lower cross-section includes an electric-conductivity (EC) sensor at 30 cm below the top of the sand layer. Three piezometers were installed in each slope, at 1.0 m, 3.0 m, and 5.1 m from the base of the slope. A pressure sensor was placed in the lowest piezometer. Tipping buckets are to be placed at two points on each of the two instrumented cross-sections, one to measure percolation from all drains, and the other to measure the lateral flow. A weather station from the Delft Meet Regen project will be installed on the site. The current proposed configuration is recommended for long-term monitoring of the LPDs, if sensors are found to be redundant after a season of data collection, the locations could be reconfigured. Sensors can be fitted to future research, flexible plan. If more sensors become available, it would be interesting to fully instrument the second LPD slope, for complete replication of the experiment. Other uses for additional sensors could be to add another instrumented profile in the middle of each slope to improve sampling density along the length of the LPD. Placing additional matric suction sensors at different depths within each profile could help us understand the distribution of roots (Zhu et al., 2018).

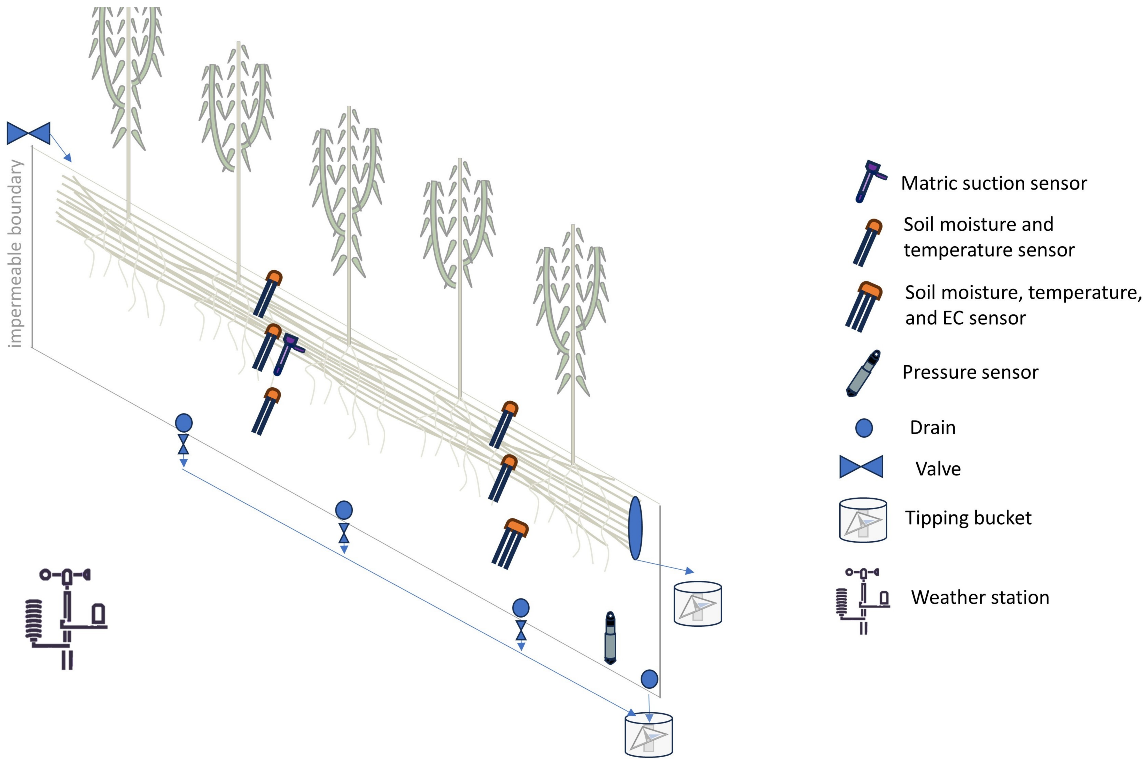


Figure 15: Smart sensor placement in the experimental setup (Not to scale).

Table 7: Smart sensors

	TEROS11	TEROS12	TEROS21	5TM	ECRN100	CTD-Diver	Baro-Diver
Soil Moisture	X	X		X			
Matric potential			X				
Temperature	X	X	X	X			
EC		X				X	
Pressure						X	X
Volume					X		
Qty 1st Phase	8	4	2	5	4	0	3

5.2 Manual monitoring

Manual monitoring tasks include regular measurement of indicators of the LPD's transient state. Vegetation growth metrics are to be taken seasonally. Canopy cover can be determined through photos; and estimations of LAI and above-ground biomass through non-destructive adaptation of Wolf et al. (1972), and described in Appendix C and D. Notes are to be taken seasonally on the presence of pioneer plants and leaf litter cover on the topsoil. Below-ground biomass is to be measured yearly using Electric Resistance Tomography (ERT), which can be used to detect root mass density (RMD) (Amato et al., 2008) and root area ratio (RAR) (Giambastiani et al., 2022). The final root distribution and root length density (RLD) are to be found through destructive analysis. In situ soil bulk density is to be measured after the experimental fill material has settled, and soil organic matter content by loss on ignition (Tabatabai, 1996) is to be measured yearly, in the spring. Soil biodiversity to be measured yearly in the late spring and early fall by counting macro-invertebrates present in the soil (ISO, 2008). Additional soil biodiversity monitoring options are to be discussed with the Biodiversity on Campus initiative (Appendix F).

Monitoring vegetation growth at the RHIZO Lab at TU Delft can be compared to the LPD growth in Catterline, taking the differences in soil properties and climate into account. The RHIZO Lab LPDs grow in sand, whereas the Catterline LPDs are in a silty soil with a higher clay content. Higher fine root density and less above-ground biomass have been reported for sandier soils (Rytter and Hansson, 1996). The biomass allocation of approx 35% to below-ground stool, 40% to fine roots, and 25% to coarse roots and a clayier site vs 55% stool (i.e. the base where roots sprout from in coppiced willows), 20% coarse, and 25% fine in a sandy soil (Cunniff et al., 2015).

5.3 Short-term experiments

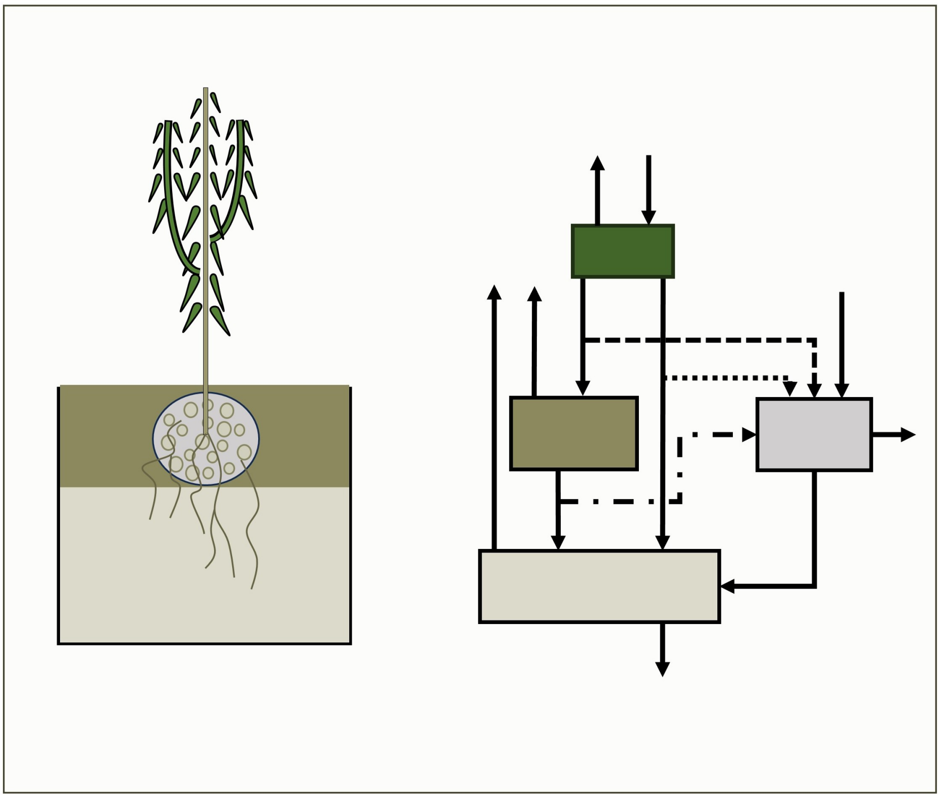
Short-term experiments including applied flow to the top of the experimental slopes and synthetic rain over the entire slope are recommended to study the behavior of LPDs under meteorological extremes and high runoff scenarios, which would not occur naturally during the long-term data collection period. Two 1 m^3 tanks are available for these experiments, a pump can be loaned from the Water Lab, and a rain simulator can be loaned from TGV.

Tracer experiments are recommended to determine hydraulic conductivity, infiltration capacity, and movement of lateral flow within the setup.

5.4 Maintenance

Tipping bucket sensors should be checked for debris monthly in the initial stages, and then as necessary. Depending on how the site is maintained, pioneer plants may be present. These may influence the infiltration capacity and water uptake from the soil (Gonzalez-Ollauri and Mickovski, 2016). maintenance options include removal, which would disturb the topsoil, or trimming, which is recommended. Seeding the soil with a cover vegetation such as turf or alfalfa is another option to avoid unpredictable pioneer plant growth.

Part III
LPD Modeling



6 Modeling Methodology

The first conceptual model for LPD hydrology was developed by Benschop (2022). In this study, Benschop's model was adapted to fit the configuration of the experimental setup at FPH. Changes were made in the configuration of sub-surface processes, an approach to distributing the model processes along the length of the LPD was proposed, new sub-modules were evaluated for lateral flow and infiltration, and a function was introduced to control time-variable parameters. This Chapter provides an overview of the model structure, sub-models, parameters, forcing data, and modeling scenarios.

6.1 Conceptual Model Structure

In this section, the changes made to adapt the structure of Benschop's model to LPDs in the experimental setup at FPH are discussed (Figure 16). The model by Benschop (2022) was based on the LPDs at Catterline and a lab experiment at approximately 2% scale. It is made up of two parts; Part I includes above-ground interception processes and Part II below-ground unsaturated zone processes. Each part partitions in-fluxes between storages and out-fluxes using sub-models with physically based equations. Sub-model processes include rainfall interception, infiltration, percolation, evapotranspiration, and lateral flow through the LPD, these will be treated in more detail in the following section.

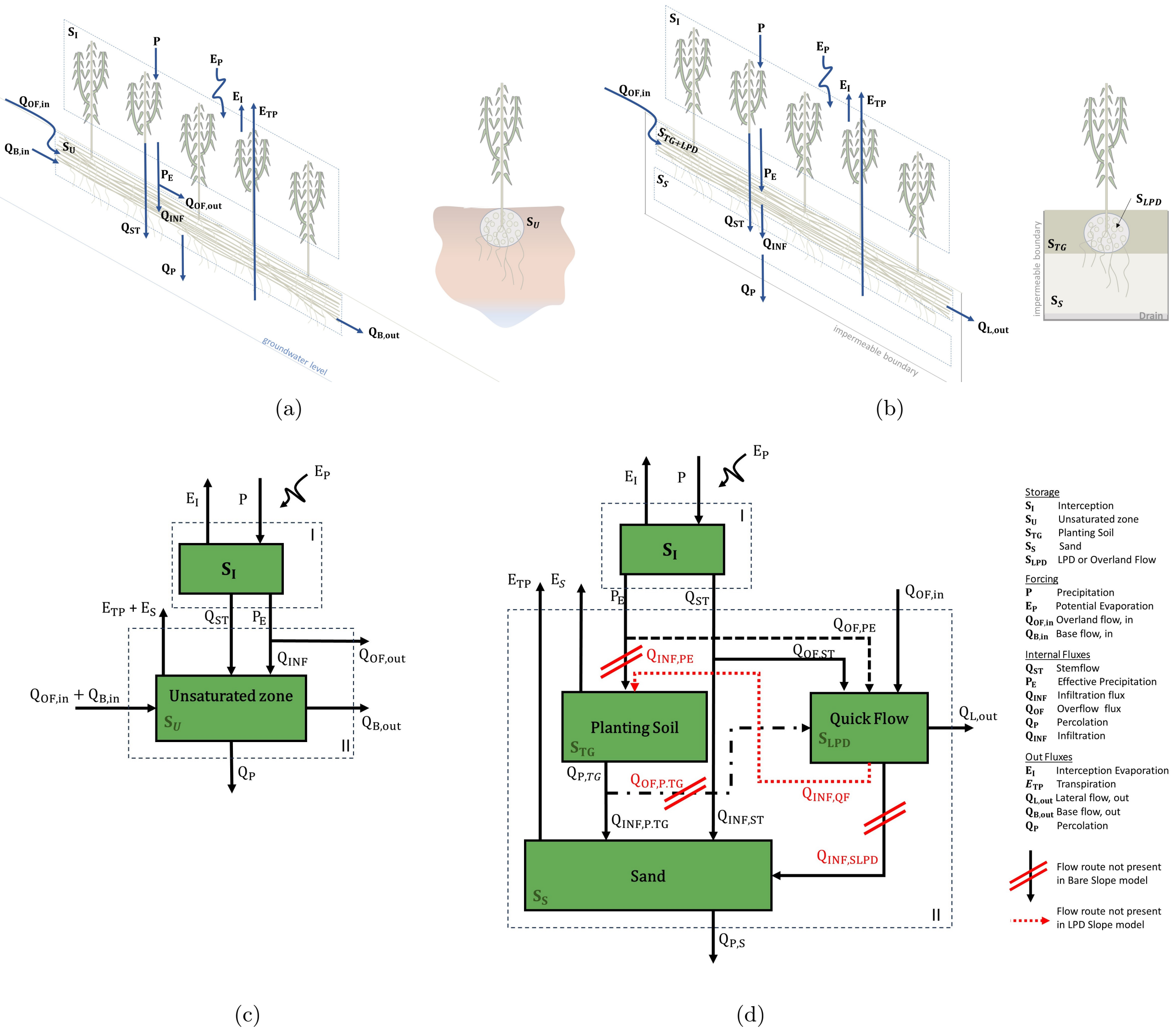


Figure 16: Hydrological processes represented in the model by Benschop (2022) and in this study; illustration of the physical setup with modeled fluxes for (a) Benschop's model, and (b) this study; conceptualization of processes showing modeled storages and flux partitioning for (c) Benschop's model, and (d) this study.

There are two model storage units in Benschop's model, one for the vegetation canopy in the above-ground part, and another for the unsaturated zone in the below-ground part. The below-ground storage is represented as an unsaturated porous media, below-ground sub-model processes are governed by this storage's state and its associated parameters. In this study, to provide a better representation of the experimental setup at FPH, which contains three distinct media in the subsurface, two unsaturated porous media storages are included, one for the sand layer S_S, and one for the planting soil (Dutch: *Teelgrond*) S_{TG}. The third storage is a quick flow storage representing the LPD and overland flow.

In-fluxes to Benschop's model include precipitation, overland flow, and base flow. Overland flow and base flow are combined into a single lateral flow in-flux into the unsaturated zone. The overland flow in-flux is assumed to occur whenever there is precipitation, its magnitude is the product of precipitation and a constant parameter representing the up-slope area that drains into the LPD. For the LPDs at Catterline, the magnitude of base flow in-flux is constant and represents the flow from perennial springs and marshy areas that the LPDs drain. In this study, the experimental setup's isolation from the ground, and the absence of an up-slope area mean these fluxes are null unless applied manually.

Out-fluxes from Benschop's model include evaporation fluxes, overland flow, and base flow. The overland flow out-flux results from the overflow of effective precipitation in exceedance of the infiltration capacity of the unsaturated zone. Base flow is estimated with one-dimensional Darcy flow, although in her discussion, Benschop mentions that this estimation is unlikely to represent reality. In this study, the overland flow out-flux is removed, instead, all effective precipitation exceeding the infiltration capacity of the planting soil is routed to the LPD. This assumption is based on informal field observations at Catterline, where Hortonian overland flow occurred in areas without woody vegetation, and would infiltrate rapidly in areas with basket willows, such as the LPD. This can be explained by the higher infiltration capacity of willow-rooted soil as compared to fallow soil, according to Leung et al. (2018) it can be an order of magnitude higher and increases linearly with willow growth. In this study, Benschop's estimation of base flow is also discarded. The assumption is made that flow within the soil matrix is one-dimensional in the vertical direction. To validate this assumption, finite element modeling in Hydrus 2D was used. The Hydrus model was set up with two soil layers of similar dimensions and properties to those of the planting soil and sand used in the experimental setup. The Hydrus model was run for scenarios of varying initial soil moisture conditions from field capacity to near saturation and varying rates of inflow at the top of the slope from 1 mm/hr to 100 mm/hr. The distribution of soil moisture in a lateral direction only reached 1.2 meters down-slope, showing changes in soil moisture of 3% in the planting soil and 2% in the sand at one meter from the in-flux location, this is considered insignificant at the scales represented in the LPD model (Figure 17). Based on this conclusion, all flow occurring in the lateral direction is represented as flow within the LPD. This applies to cases with groundwater levels deep enough below the LPD to disregard saturated zone flow. If groundwater is present, the original Darcy flow assumption could be added back.

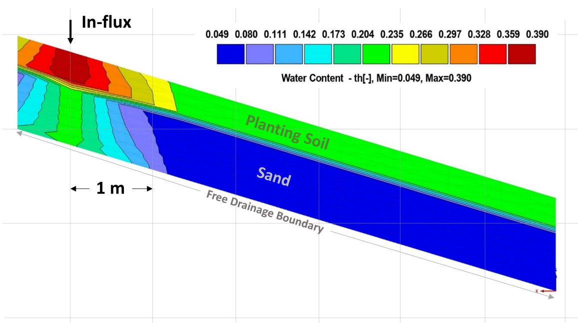


Figure 17: Hydrus2D model results on lateral distribution of a point influx.

There are no internal fluxes in the below-ground part of Benschop's model. In this study, due to the discretization of below-ground media in separate storages, fluxes between the storages were introduced. Both unsaturated porous media storages receive in-fluxes which they partition into infiltration and overflow. The overflow can either remain in the source storage or be routed to the quick-flow storage.

The bare slope (i.e. no LPD) in Benschop's model only differs from the slope with an LPD by adjusting vegetation and soil parameters. In this study, due to the change in the structure of the unsaturated zone, the bare slope model differs from the LPD model in both parameter selection and in the routing of internal fluxes.

With an LPD present, all overflows are channeled to the quick flow storage and are available to infiltrate into the sand. With no LPD present, the quick flow reservoir represents overland flow, and the storage in it is available for infiltration into the planting soil.

Benchop's model lumps the unsaturated zone along the entire length of the LPD into one storage. This does not allow for the distinction of lateral flow distribution in LPDs of different lengths. It is expected that a longer LPD would allow higher infiltration of discontinuous lateral flows that enter the LPD near the top. A pulse of high lateral inflow that does not infiltrate in the first meter of the LPD length may infiltrate in the second or third meter of its length. To represent this, a longitudinally distributed model was created by repeating the lumped model over an n-number of zones, with identical parametrization and processes, but with the lateral out-flux of cell n assigned as the lateral in-flux to zone n+1. (figure 18).

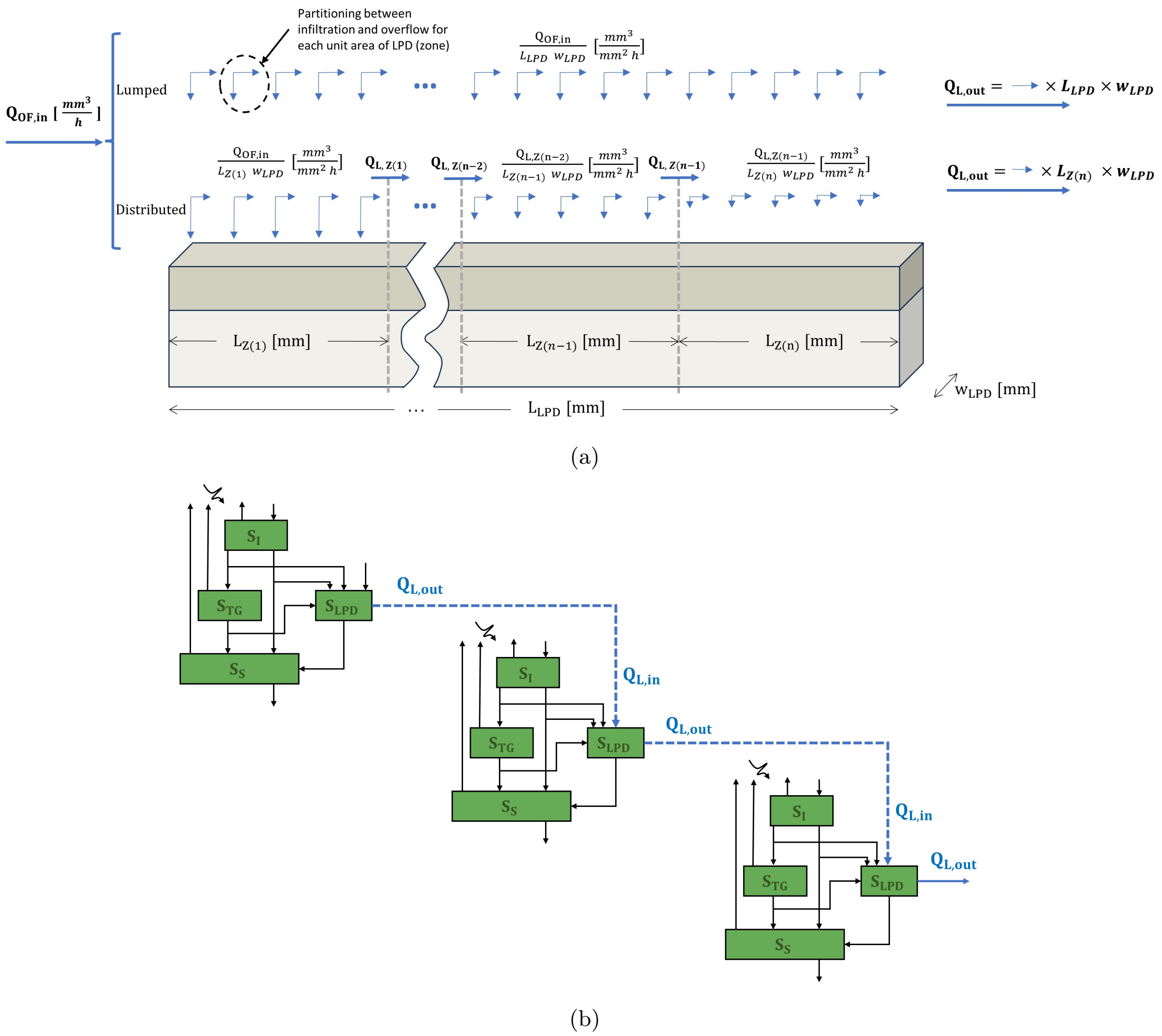


Figure 18: Model configuration for longitudinally distributed along the LPD length. (a) comparison of treatment of lateral flows in lumped and distributed models, (b) model schematic.

The model time-step in both Benschop's model and this study was set to 1 hour. Testing the model performance with different time steps and spatial distributions for the distributed model is recommended as this is expected to influence the infiltration partitioning. Another option would be to include a flow velocity function which would limit the amount of time that transient overland flow could infiltrate within a zone for a given time step.

6.2 Sub-models

The above-ground sub-models were taken from Benschop (2022), these processes include partitioning of precipitation into direct throughfall, indirect throughfall, stemflow, and interception evaporation, these processes are explained in detail by Benschop (2022) and have not been adjusted in this work. The below-ground sub-models are identical for each of the porous media storages and unique for the Live Pole Drain storage. Three sub-models govern in and out fluxes of the porous media: the partitioning of infiltration runoff of surface fluxes and deep fluxes, and percolation. One sub-model governs lateral out-flux from the LPD: the Manning equation. All subsurface sub-modules are functions of the governing storage state and various parameters (figure 22 and Appendix I). Sub-models that were adapted, or were recommended to be adapted for the original model are discussed here. It is not an exhaustive overview of the model processes that could be relevant to represent reality, for example, it is still missing a sub-model to deal with snow.

Infiltration and Overflow Partitioning for surface fluxes. Surface fluxes refer to fluxes that enter one of the model storage units from above. Each of these fluxes may either infiltrate or overflow. This includes effective precipitation reaching the planting soil with overflow toward the LPD, percolation from the planting soil reaching the sand with overflow toward the LPD, and standing water in the LPD in contact with the sand, where the overflow remains in the LPD. The partitioning between infiltration and overflow is calculated using the unsaturated hydraulic conductivity of the storage unit, k_{th}. Benschop (2022) calculates k_{th} as a function of the water content of the storage receiving the infiltration flux at field capacity and at its current state, and both van Genuchten parameters α_{vG} and n_{vG} using the Brooks and Corey-Burdine adaptation of the Mualem-van Genuchten (MVG-BCB) model. Benschop (2022) found high sensitivity of the state of the unsaturated storage S_U to both van Genuchten parameters, expressed as standard deviation as a fraction of the mean, S_U sensitivity to n_{vG} was 3.2, and it's sensitivity to α_{vG} was about one sixth of that, but still high compared to other parameter sensitivities. In this study, the MVG-BCB model is replaced by the MVG model does not include α_{vG} (Van Genuchten, 1980) (Mualem, 1976). This change was made to avoid over-parametrization and due to the lack of certainty in the choice of van Genuchten parameters for the soil types used in the experiment. This change in the model was only made for the current study; for future work on the transient behavior of the unsaturated porous media storages, the MVG-BCB model may be better suited. The change in unsaturated hydraulic conductivity of a fallow soil to a rooted soil can best be explained by changes in α_{vG}, less so by changes in n_{vG} (Leung et al., 2015).
Regardless of the choice between MVG and MVG-BCB the partitioning between infiltration and runoff likely underestimates infiltration because it assumes a homogeneous storage with the same water content everywhere, therefore it cannot simulate the accumulation of higher pressure and water content at a wetting front which would move through the soil faster than the unsaturated hydraulic conductivity near field capacity. A higher spatial and temporal resolution could help solve this problem, or an additional analytical submodel with rainfall intensity within the hourly time step as an input. Another approach could be to incorporate a 'wetness parameter' and function distributing inflow between the unsaturated zones and quick flow bucket (i.e. LPD flow), as applied in the Wageningen Lowland Runoff Simulator (WALRUS) model (Brauer et al., 2014). A third approach could be a more accurate physically based model incorporating the roots' influence on the unsaturated zone: Root-to-shoot ratio (RSR) and Root Length Density (RLD) per growth season could be included in the properties of the unsaturated zone as parameters governing the infiltration capacity, resulting in hortonian overland flow being less frequent in a rooted soil (Song and Wang, 2019).

Infiltration and Overflow Partitioning for deep fluxes. Stemflow is assumed to infiltrate directly into the sand beneath the LPD, the assumption that the roots channel water deep in the storage means infiltration is not governed by the state of the storage. Deep infiltration of stemflow is a binary function, equal to stemflow as long as the storage is under saturation, and zero if it is at or over-saturation. This function is taken directly from Benschop (2022). While the stemflow flux can be much smaller than the lateral influx, or effective precipitation, the increase in water content in the sand due to stemflow increases its infiltration capacity. This sub-model helps represent the process where flow of water along the roots could contributes to the formation of preferential flow paths for infiltration (Ghestem et al., 2011).

Percolation. The percolation rate from each soil varies linearly increasing from 0 when the soil is at field capacity to a maximum rate when saturated. This function is taken directly from Benschop (2022). This sub-model likely overestimates percolation for low water contents. Based on informal field observations, the rate of percolation appears to decrease significantly long before field capacity is reached. For percolation between soil layers of different pore size distributions, a capillary boundary can be present, this can be evaluated using FEM software such as Hydrus, an initial check for soils with similar properties to those in the experiment was completed following a method by Mancarella and Simeone (2012) which showed a buildup of water content beyond field capacity in the finer top soil before percolation into the sand below (see Appendix H). The same applies to the transition between the sand layer and the gravel layer.

Lateral flow in LPD. The lateral flow in the unsaturated zone in the original model is represented as lateral flow within the soil matrix, the decision to remove this process is discussed in the previous section. Particularly during the initial growth stages of the LPD, lateral flow within the LPD likely moves through large macropores. Therefore, an approach is presented here in which the lateral flow is represented by the Manning equation as open-channel flow. This allows easy adjustment of macropore friction as it increases during LPD growth stages by adjusting n_M, Manning's channel roughness parameter. Another approach could be to gradually reduce the LPD area available to convey flow, and increase the unsaturated zone around it, representing the sedimentation of the LPD. The same sub-model is used to simulate overland flow for the case of a bare slope without an LPD. A similar approach is used to describe overland flow in Hydrus 2D (Šimnek, 2015).

Ultimately, there are four types of functions in the sub-models (Figure 19). Binary functions are constant until a threshold is reached, and then jump to another constant value, this type of function is in the evaporation and stemflow infiltration sub-models. The van Genuchten function is constant until a threshold is reached, then increases as a function of van Genuchten parameters until another threshold is reached and it becomes constant again, this function controls the partitioning of infiltration and runoff. The Linear function is constant until a threshold is reached, then increases linearly to another threshold where it becomes constant again, this control percolation. The Manning function takes a constant value until a threshold is reached, then varies according the to Manning function until reaching another threshold, then increases linearly, this controls lateral outflux from the quick flow reservoir.

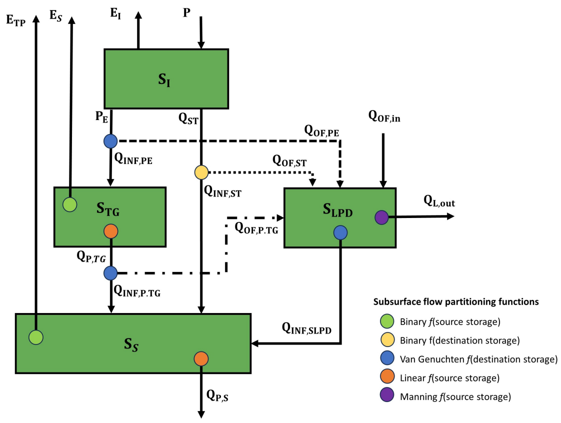


Figure 19: Types of sub-model functions in the below-ground part of the model.

6.3 Model Parameters

Model parameters associated with each storage and associated fluxes are shown in table 8. All minimum and maximum values of vegetation-related parameters besides were taken from Benschop (2022). LAI is a time-variable input in this model, and will be discussed in the following section. Saturated hydraulic conductivity and soil moisture at field capacity of each experimental media were found by lab experiments which are described in chapter 4 and Appendix D. The van Genuchten parameters were selected based on grain size distribution, organic matter content, and percent of fines from a review of measured and modeled parameters by Benson et al. (2014), the values were compared to results of pedotransfer functions based on soil texture (Rajkai et al., 2004), and neural network pedotransfer predictions available in Hydrus software (Schaap et al., 2001). The pedotransfer functions resulted in much lower values of α_{vG} and n_{vG} compared to the values found in the review by Benson et al. (2014), ultimately the latter was chosen because it includes additional areas of comparison such as the coefficient of uniformity (see appendix I).

Table 8: Model parameters. LAI: Leaf Area Index, p: Free throughfall coefficient, p_s: Stemflow fraction coefficient, S: Canopy storage capacity, $A_{c'}$: Canopy covered ground area, k_c: Light extinction coefficient, $\theta_{fc,}$: Soil moisture at field capacity, $k_{sat,}$: Saturated hydraulic conductivity, d: layer depth, $n_{por,}$: porosity, $n_{vG,}$: van Genuchten pore size distribution parameter,

Parameter	**Unit**	**Default/Dormant**	**Growing**	**Source**
Vegetation				
LAI	-	0	7	This study
p	-	1	0.5	Benschop (2022)
p_s	-	0.05	0.1	Benschop (2022)
S	mm/m^2	0	0.72	Benschop (2022)
A_c	m^2	0	1	Benschop (2022)
k_c	m^2	0	0.6	Benschop (2022)
Planting soil				
$\theta_{fc,TG}$	-	0.2		This study
$k_{sat,TG}$	mm/h	50.4		This study
d_{TG}	mm	260		This study
$n_{por,TG}$	-	0.64		This study
$n_{vG,TG}$	-	2.4		Benson et al. (2014)
$\alpha_{vG,TG}$	-	0.12		Benson et al. (2014)
Sand				
$\theta_{fc,S}$	-	0.2		This study
$k_{sat,S}$	mm/h	50.4		This study
d_S	mm	260		This study
$n_{por,S}$	-	0.64		This study
$n_{vG,S}$	-	2.4		Benson et al. (2014)
$\alpha_{vG,S}$	-	0.12		Benson et al. (2014)
Live Pole Drain				
$\theta_{fc,LPD}$	-	0.2		This study
d_{LPD}	mm	260		This study
$n_{por,LPD}$	-	0.64		This study
$n_{manning,LPD}$	-	0.08		Chow (1959)
i_{LPD}	-	0.27		This study

6.4 Data Sets

The input data for the model are time series of precipitation, overland flow, potential evapotranspiration, temporal variation in LAI, and LAI-variable parameters. Model inputs for 2023 are shown in figure 20.

Precipitation data and meteorological inputs for the potential evapotranspiration calculation were sourced from citizen science project *Delft Meet Regen* station DMR-Deltares, accessed through the Met Office Weather Observations Website (WOW, 2023). This dataset was chosen because a similar measuring point from the *Delft Meet Regen* project will be installed at FPH. The data was converted from 10-minute intervals to hourly intervals, see Appendix I.

The overland flow in-flux ($Q_{OF,in}$) is a synthetic input, for an LPD in a natural, or in a built landscape it can be calculated as the up-slope area that drains toward the LPD times the precipitation times a reduction factor to account for the portion of precipitation that infiltrates before reaching the LPD. In the rural setting in Catterline, an area equal to the LPD was assumed to drain towards it and a reduction factor of 0.2 was used (Benschop, 2022). In an urban setting, an LPD could be placed where it captures runoff from a paved surface. Here, it is arbitrarily assigned a value of 3 times precipitation for precipitation intensities greater than 3 mm/h, i.e., it would drain all precipitation from an area of three times the area of the LPD. If this model is applied to the experimental setup at FPH, where no natural overland flow occurs above the LPD, this input should be replaced by manually applied volumes of flow at the top of the LPD.

Leaf Area Index (LAI) is the only independent time variable vegetation parameter. The trend in willow LAI over the months is based on personal observations from 2023 and from citizen science project *De Natuurkalendar* a citizen science program of the Environmental Systems Analysis Group of Wageningen University running for over 10 years (van Vliet et al., 2014), from which data from 2019 to 2022 was taken. From the start of leafing in late April, reaching a maximum in late August and then decreasing until October. This is supported by observations and literature studies of LAI variation over the growing season from studies in the temperate region of the northern hemisphere including Sweden (Linderson et al., 2007), central Germany (Richter et al., 2015), eastern Estonia (Merilo et al., 2006), and mid-west USA (Kabenge and Irmak, 2012) all show a nearly parabolic shape, skewed toward a maximum in late summer. Based on findings from fieldwork in Catterline (see Chapter 3), and literature cited above, a maximum LAI value for the month of August was assumed to be 7 corresponding to a basket willow of three years.

If the model is to be applied to a general case, phenological parameters can be scaled as a function of abiotic stresses, for example, the start of the growing season could be calculated as a function of GDD (growing degree days) (McMaster and Wilhelm, 1997), and the end of the growing season can be indicated by low temperature (Alvarez-Uria and Körner, 2007).

Dependent time variable vegetation parameters are all scaled by LAI linearly from their value in the dormant season to their value at the peak of the growing season (Equation 1), this applies to p: Free throughfall, ps: Stemflow fraction coefficient, S: Canopy storage capacity, Ac': Canopy covered ground area, kc: Light extinction coefficient. This equation is currently run outside of the model, and the time-variable LAi-dependent parameters are input to the model alongside the meteo data time series. To streamline the input data preparation, this function could be included within the model. This way the inputs would only be the meteorological data, a max LAI value, and min and max values of LAI-dependent parameters.

$$X_{LAI-dependent} = X_{dormant} + LAI \times \frac{X_{growing}}{LAI_{max}} \tag{1}$$

Potential evapotranspiration was calculated using the Penman-Monteith equation (Penman (1948), Monteith (1965)) with meteorological data from *Delft Meet Regen*, radiation data from a KNMI station in Rotterdam was used (KNMI, 2023), accessed via KNMI's open data API (Appendix I). Input parameters include the stomatal resistance is approximated based on studies of poplars and willows in central Germany and the USA, with similar climate conditions to the Netherlands range between 56 and 150 for well-watered conditions (Richter et al., 2015) and (Irmak et al., 2022), for this study the value of 150 is selected; the roughness length of momentum transfer is set at 0.1 meters, which is typical for crops of over 1-meter height (Van der Kwast et al., 2009). Other parameters and constants were set to default values and can be found in Appendix I.

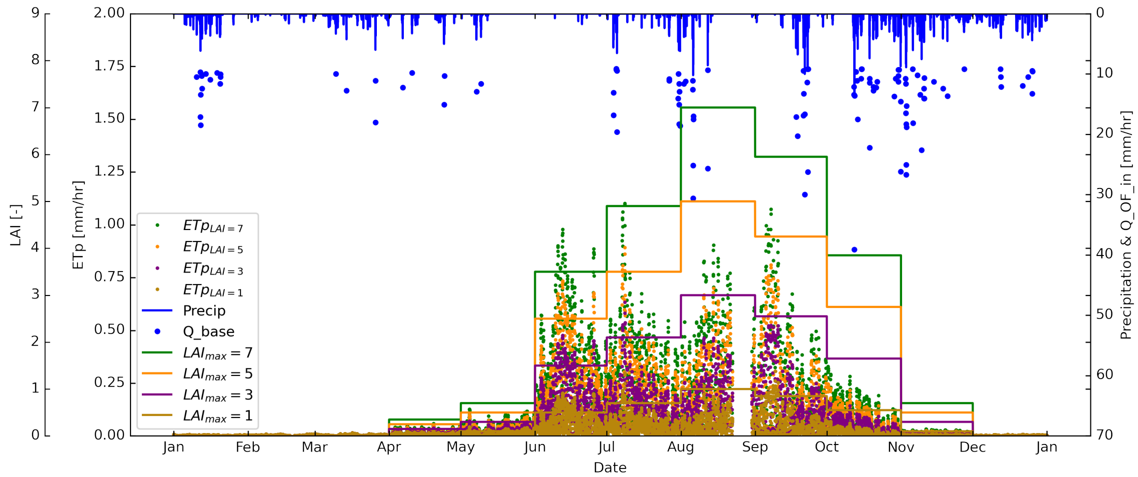


Figure 20: Meteorological data, Leaf area index, and overland flow inputs to R model

6.5 Model Sensitivity and Scenarios

To understand the behavior of the model some key processes and outputs are visualized. First, the sensitivity of key sub-model parameters and storage unit state on the internal model fluxes was evaluated to explain each model process. Next, the sensitivity of these parameters on the yearly cumulative lumped model out-fluxes, was performed to check how responsive the model output is to them. For both sensitivity analyses, a one-at-a-time approach (Daniel, 1973) was used, keeping all variables constant except one that was varied, except LAI-scaled parameters which were varied with LAI. Next, the lumped model is run for a selection of synthetic rain events of varying intensity, to analyze their impact on out-flux partitioning. Finally, the distributed model was run for synthetic lateral in-flow events of varying intensity with varying initial conditions, to explain the selected approach to water flow along the length of the LPD.

Sub-model process sensitivity. Soil evaporation from the planting soil was calculated as a function of the storage state. LAI was varied from 1 to 7 along with LAI-dependent parameters. Lateral flow in the quick flow storage was calculated as a function of the storage state. Manning's roughness n_M was varied from 0.06 to 0.14. Partitioning between infiltration and overflow was calculated for each of the unsaturated porous media destination storages (i.e. Sand and Planting Soil), as a function of the storage state. Van Genuchten parameter n_{vG} was varied from 2.0 to 2.6 for the planting soil and from 3.0 to 4.5 for the sand, and the influx intensity was varied from 1 to 7 mm/h.

Lumped model out-flux sensitivity. A selection of parameters is varied these are summarized in table 9. Higher values of LAI were expected to increase interception and transpiration fluxes and reduce the soil evaporation flux. For van Genuchten's parameter n_{vG} for each of the unsaturated storages, a smaller value of n_{vG} means a broader pore size distribution and higher values of unsaturated hydraulic conductivity for lower water content. Manning's n_M for the LPD storage in the lumped model, a higher value of n_M reduces the velocity of lateral flow in the LPD. One year is simulated for each model run using input data from 2023. A spin-up period of one month was added at the beginning of each input file. *Lumped model response to rainfall intensity.* Synthetic

Table 9: Parameters tested in sensitivity analysis

Parameter	Default Value	Varied values						
LAI	3	1	2	3	4	5	6	7
$n_{vG,S}$	4.0	3.6	3.8	4.0	4.2	4.4	4.6	4.8
$n_{vG,TG}$	2.4	1.8	2.0	2.2	2.4	2.6	2.8	3.0
$n_{Manning}$	0.08	0.04	0.06	0.08	0.10	0.12	0.14	0.16

precipitation and overland flow events were run to evaluate flow partitioning for different input intensities. Two sets of events were run using the lumped model. In the first set, rainfall intensities varied from 4 mm/h to 60 mm/h and were applied for one hour, with no overland flow input, and with no precipitation during the 24-hour spin-up period nor for the 47 hours of the simulation after the rain event. All other input values and parameters were set to typical values for January to minimize the effects of interception and evaporation. The second set was based on realistic mean and extreme values of hourly rainfall for each month of the year, from a study on rainfall extremes in North Holland from 2008 to 2017 (Manola et al., 2020). Mean and 99^{th} percentile event intensities were taken directly from Manola et al. (2020), and 62.5^{th}, 75^{th}, and 87.5^{th} percentiles were calculated assuming a normal distribution of intensities (Figure 21). overland flow input of four times the precipitation intensity was applied in all scenarios; similarly to the previous set of scenarios, the model was run for a spin-up period of 24 hours, 1-hour rain and overland flow event, followed by 47 hours of no precipitation; all other input values and parameters were set to typical values for each month of the year. This approach was chosen to provide an indication of the expected flow partitioning for each month of the year.

Distributed model response to overland flow in-flux rate. Model runs with varying lateral inflow were run to evaluate the behavior of the LPD along its length using the distributed version of the model, for an LPD length of four meters, with model runs for lateral inflow rates of 10, 20, 40, 60, 80 and 100 mm/h, with initial conditions of soil moisture of 2% (field capacity), 8% and 20%. For this set of model runs, the saturated hydraulic conductivity values for sand and planting soil were adjusted to 45 mm/h and 30 mm/h respectively.

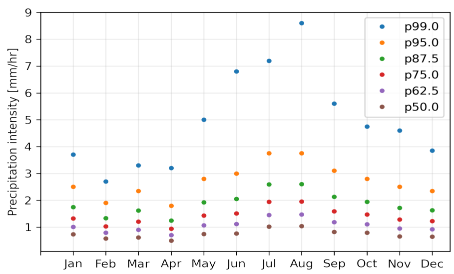


Figure 21: Monthly mean and extreme intensities of hourly rainfall, adapted from Manola et al. (2020)

7 Modelling Results and Discussion

7.1 Sensitivity Analysis

7.1.1 Sub-model process sensitivity

The sensitivity of sub-model outputs to parameters and forcing can help explain the final model output (figure 22). For example, non-linear sub-model function outputs can be more sensitive to a parameter within a specific interval of forcing magnitudes. This is the case for the infiltration-overflow partitioning sub-model which is more sensitive to n_{vG} for a range of storage states above the minimum storage threshold. For higher values of n_{vG} and higher values of surface in-flux, the range of sensitive storage states becomes smaller. Meanwhile, the lateral flow sub-model is more sensitive to n_M for higher values of storage.

7.1.2 Lumped model out-flux sensitivity

The results of the sensitivity analysis on the lumped model out-fluxes provide insights into the yearly average behavior of the model (Figure 23). LAI was found to have little influence on the yearly average out-flux partitioning. Total evaporation fluxes increase and percolation flux decreases by only 2% from LAI=1 to LAI=7. While LAI may be less significant than other parameters at its yearly average impact on out-flux partitioning, it may be more significant during the summer months. Varying the van Genuchten parameter for the sand storage '$n_{vG,S}$' shows the highest sensitivity, with lateral outflow decreasing by nearly 10% from the lowest value to the highest. This makes sense because the infiltration capacity of the sand, which is a function of this parameter, governs the rate at which water in the LPD can infiltrate into the sand and therefore, how much stays in the LPD and is available to flow out. The van Genuchten parameter for the planting soil '$n_{vG,TG}$' has little impact on the distribution of out-fluxes, however, it is important in the partitioning of internal flows in the LPD which has implications for water availability for soil evaporation and transpiration. Finally, the Manning parameter '$n_{Manning}$' of the LPD shows a higher fraction of the out-fluxes as lateral outflow for lower values, this makes sense because a lower channel roughness means the water can flow out more quickly.

7.1.3 Sensitivity discussion

The sensitivity of both specific processes and yearly-averaged model outputs to certain parameters was evaluated. Comparing the two analyses can roughly indicate the frequency distribution of storage states. The infiltration fluxes are highly sensitive to n_{vG} when the storage state is near its minimum value; because the yearly-averages model outputs also showed a high sensitivity to n_{vG}, it may be due to the fact that the storage drains quickly and the state is often its minimum value (this was indeed the case). Therefore, rather than taking a one-at-a-time approach, it would be interesting to take a two-at-a-time approach, to check the sensitivity of model outputs to each parameter for a selection of values of another parameter.

Each model parameter represents a physical aspect of the experimental setup, and these are not varied across the LPD replicates, therefore insights into the sensitivity of the outfluxes to the parameters can be found by understanding the seasonal and lifetime variations in the parameters. Experiments can also be designed to capture the experimental setup response starting from different initial conditions, for example by comparing the behavior of the setup near saturation to its behavior after long periods with no rain events.

7.2 Lumped and distributed model response to influx intensity

7.2.1 Lumped model response to rainfall intensity

From the rainfall scenarios (figure 24), it can be observed that mean or 50th percentile monthly events (0.60 to 1.04 mm/hr) only generated lateral flow for August, with a mean precipitation of 1.04 mm/hr. For the rainfall scenarios above the 62.5^{th} percentile, evaporation fluxes become smaller than lateral outflow. Events of less frequency generated lateral flow for all events over 1.03 mm/hr. The fraction of out-fluxes as lateral outflow increases with increasing precipitation rates, and reaches a maximum at 2.75 mm/hr, the 99^{th} percentile event for February, then it decreases slightly. This can be explained by the increased infiltration capacity reached by the sand for higher influxes. This is further observed in the rainfall scenarios in which only the rainfall intensity is varied, with no lateral inflow 25. For higher rain intensities, the sand and planting soil also reach saturation and therefore have higher hydraulic conductivity, thus channeling more of the flow to percolation.

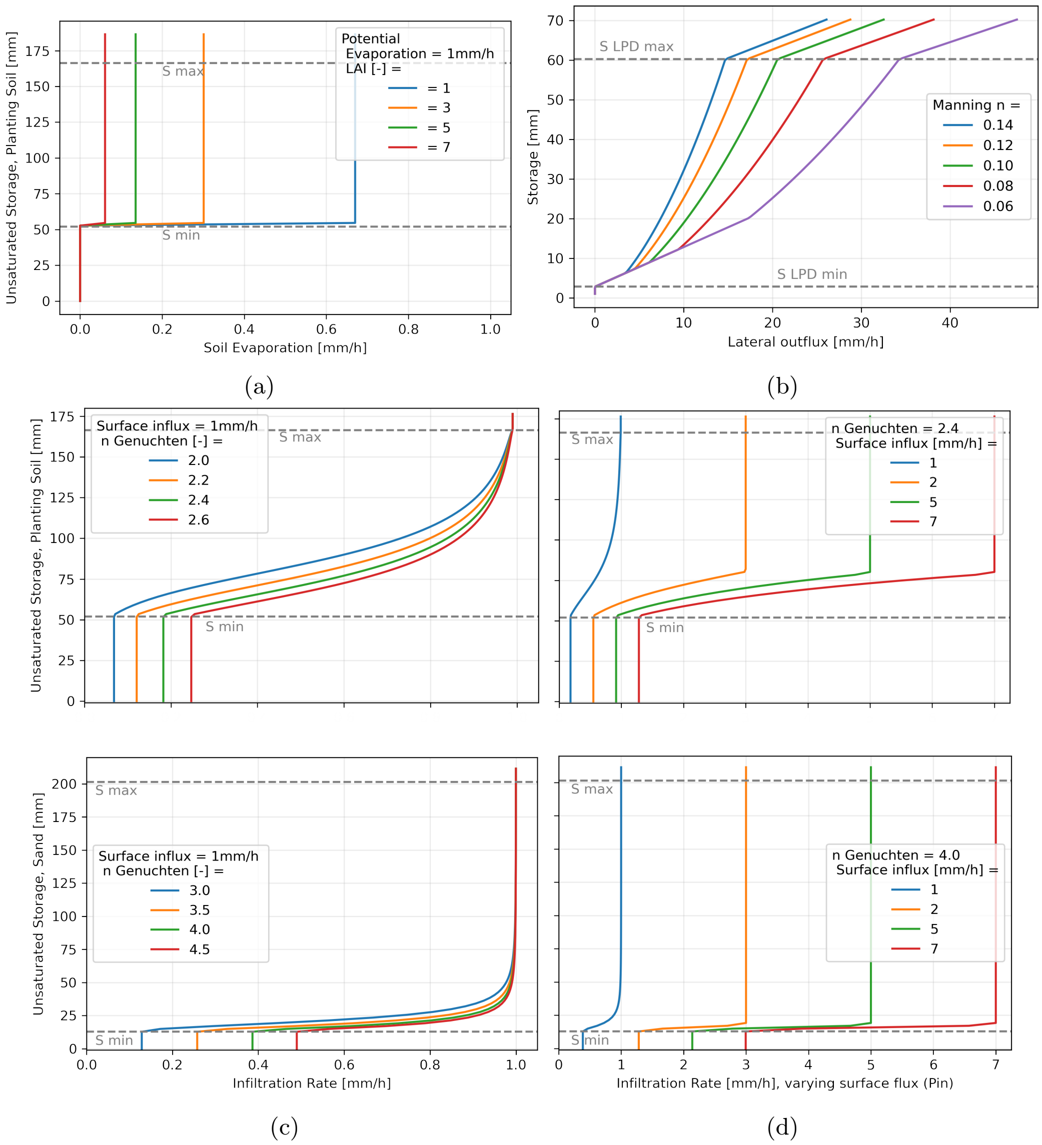


Figure 22: Subsurface flow partitioning sub-models (a) Schematic of model processes. (b) Lateral outflux from LPD. (c-f) Partitioning between infiltration and runoff for (c) varying van Genuchten n parameter, (d) varying surface influx.

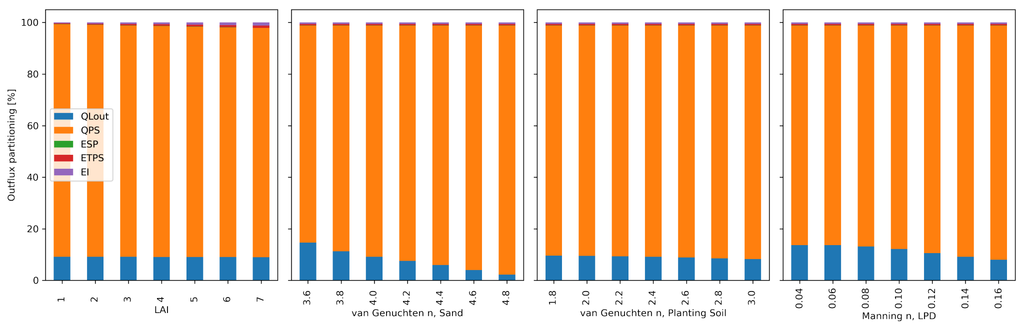


Figure 23: Sensitivity of out-fluxes (QLout: Lateral Outflow, QPS: percolation from sand, ESP: Soil evaporation from planting soil, ETPS: Transpiration from sand, EI: Interception Evaporation) to selected parameters.

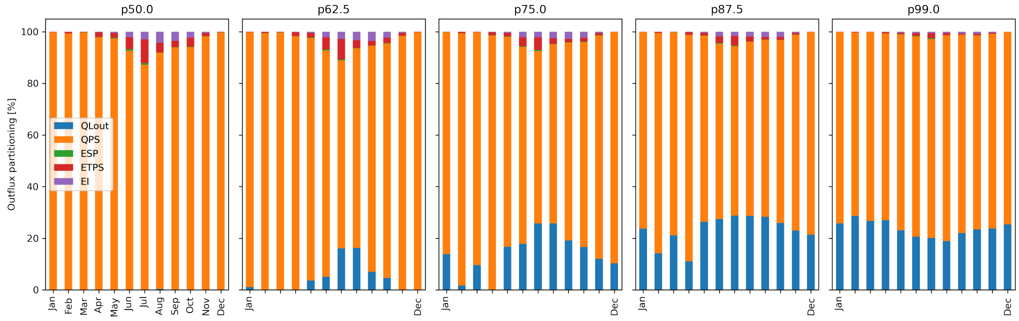


Figure 24: Partitioning of outfluxes between QLout: lateral outflow, QPS: percolation from sand, ESP: Soil evaporation from planting soil, ETPS: Transpiration from sand, EI: Interception Evaporation, for precipitation events of mean (p50.0) to 99th percentile events (p99.0) for each month of the year.

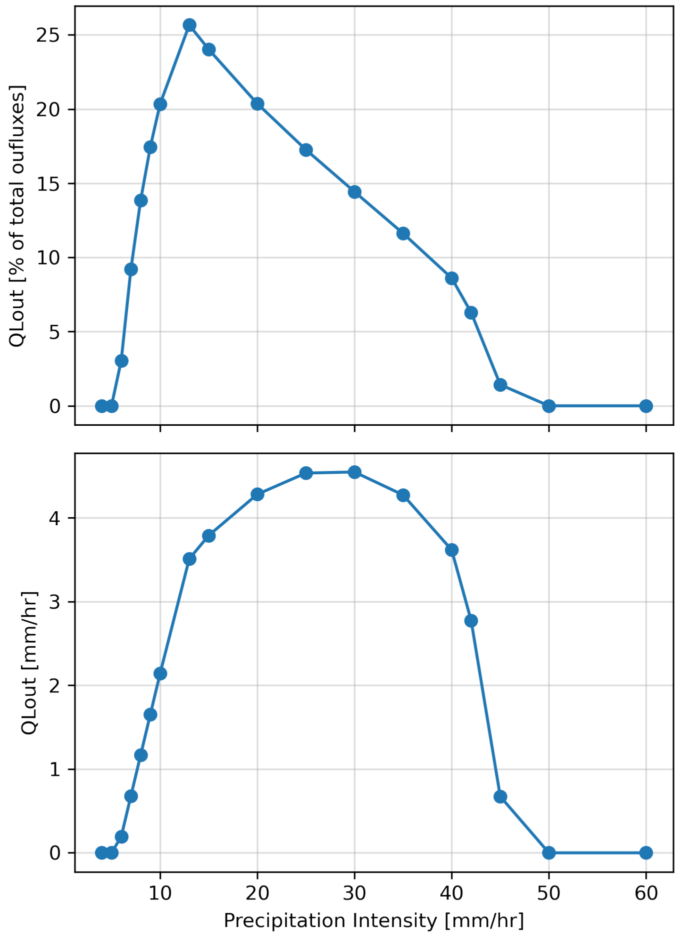


Figure 25: Lateral outflow rate and percentage of total outflux for varying precipitation intensity, with initial conditions of soil moisture in sand at field capacity.

7.2.2 Distributed model response to overland flow in-flux rate

The longitudinally distributed model shows that a pulse of lateral flow decreases and spreads out as it moves along the length of the LPD (figure 26). For the scenario with initial conditions at field capacity, lateral flow is highest due to the reduced infiltration capacity of the sand, for scenarios with increasing water content, more of the lateral inflow infiltrates in each time step. For the scenario with initial conditions of 20% water content, all of the lateral inflow infiltrates into the sand, however, percolation from the planting soil ends up in the LPD, causing a delayed peak compared to the other cases. This second peak can also be observed in the case of initial water content = 8% and inflow = 80 mm.

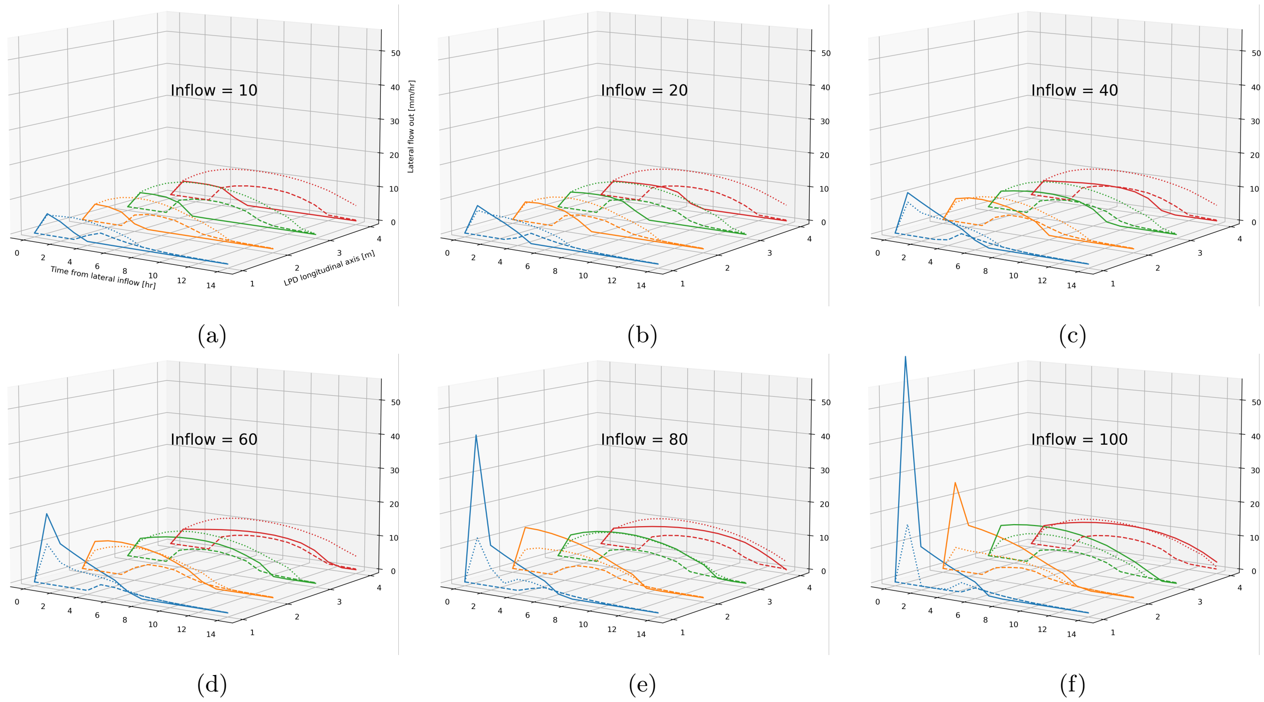


Figure 26: Lateral outflow from each meter of length of LPD for initial soil moisture conditions of field capacity or 2% (solid lines), 8% (dotted lines), and 20% (dashed lines) with applied inflows at t=1 with the following depths in the first meter of the LPD: (a) 10 mm, (b) 20 mm (c) 40 mm, (d) 60 mm (e) 80 mm, (f) 100 mm.

7.2.3 Comparison of lumped and distributed model

The lumped model takes the lateral inflow volume, $Q_{OF,in}$, as a water depth available for infiltration in every unit surface area of the LPD. Whereas, the lumped model takes the inflow volume and converts it to a water depth available for infiltration within the first zone of the LPD. This means that for a distributed model with four zones, the water depth in the first zone would be four times the depth of the water in every unit surface area for the lumped model. If the infiltration capacity did not depend on water depth, this would not produce a difference between the models in the outcome. However, because a higher water depth produces a higher infiltration capacity, more water will be infiltrated within the first zone(s) of the distributed model, and less in the last zone(s). In this study, each model configuration was presented independently, with a different set of input data to feature unique functions of the model, therefore the magnitudes of the results were not compared.

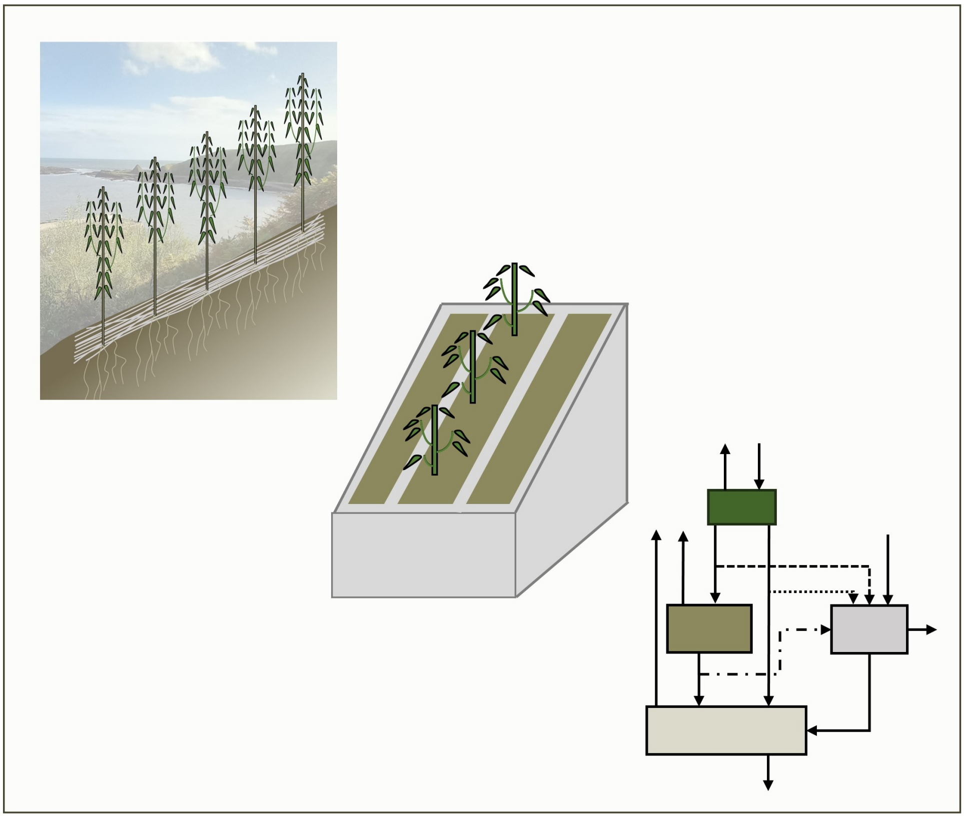
7.3 Model calibration and further development

The conceptual model functions well according to the physically based sub-models that it is composed of, however, it is still unclear if it accurately represents LPD behavior. The LPD setup in the open-air lab at FPH is kitted with sensors to measure out fluxes and storage states. The data that will be collected over the next year(s) can be used to calibrate the model. Soil moisture profiles at the middle and toe of one LPD and one bare slope include sensors at two depths within the sand layer, and at one depth in the planting soil to capture wetting and drying events. The soil moisture data can be compared to the states of the unsaturated storages S_S) and S_{TG} in the model. Drains to capture percolation are placed at four locations along the length of the LPD, the outflux from these drains can be taken together and compared to the percolation flux Q_P in the lumped model, or taken individually to compare to the percolation from each zone of the distributed model. Only one tipping bucket is currently installed to capture the percolation fluxes on each setup, therefore, lumped model calibration could be possible from long-term data collection, and short-term experiments with buckets to capture the distributed percolation could be compared to the distributed model. A drain to capture lateral flow in the top layer is placed at the end of the setup, to compare to model output $Q_{L,out}$. A monitoring plan is in place to measure above-ground plant growth for vegetation-related input parameters. The only fluxes that are not measured are soil evaporation, vegetation transpiration, and interception evaporation, the evaporation potential can be calculated using meteorological data.

Once the experiment runs for a sufficient period, patterns in each observation point can be used to evaluate whether the selected sub-models represent the physical processes, then, the magnitude of observations can be used to calibrate sub-model parameters. One challenge in calibration is that all parameters are meant to be based on the physics of the system or the material, therefore parameters can't be adjusted too much before no longer describing the media they represent.

Once the basic hydrological processes within the model are validated, applications can be explored by using this model as a baseline. for example, additional processes could be incorporated to understand the impact of the LPD on water quality; or it could be analyzed under urban drainage system design scenarios to measure its capability to attenuate, infiltrate, and convey stormwater runoff.

Part IV
Synthesis



8 Synthesis

In this chapter, the fieldwork at the OAL in Scotland, the design of the experimental setup, and the development of the conceptual model will be discussed in the context of the research questions.

The first research question was: ***How can an open-air lab be designed and constructed to support long-term monitoring of, and short-term experiments on, the eco-hydrological behavior of LPDs and other Nb-SuDS?*** This question was answered through a broad range of activities described in Parts I and II of this report.

Part I of this report describes observations that were made at GCU's Applied Ecology Open Air Lab (OAL) at Catterline Bay in Aberdeenshire, Scotland. The objective of the site visit was to estimate the eco-hydrological processes around the LPDs within an order of magnitude. The observations informed the dimensioning of the experimental setup at the OAL in Delft, the development of a monitoring plan, and the selection of processes and parameters for the conceptual model of the setup. To these ends, three LPDs at different growth stages were described in terms of their above-ground and below-ground states and processes.
The above-ground state refers to the state of the vegetation. Many vegetation metrics were taken to describe the growth stage, such as the number and location of stems, and their height. Strong ($r^2 > 0.7$) linear allometric relationships were found between stem length and the number of leaves and branches for saplings and poles. The Leaf Area Index (LAI), a standardized metric of canopy density, for each LPD was calculated by extrapolation using the linear relationships that were found. Above-ground processes include the split between precipitation falling freely to the ground, and precipitation intercepted by the canopy, then the split between the intercepted precipitation between filling the interception storage, overflowing from it as indirect throughfall or as stemflow. Only total precipitation and total throughfall were measured in this study. Based on an analysis of four rain events, an indication of canopy storage capacity was found. All above-ground states and processes aligned with expectations from literature on willow growth and rainfall interception.
The below-ground state is made up of the soil matrix, the decomposing biomass of dead components of the LPD vegetation, and live components of the LPD vegetation such as fascine poles and stakes with adventitious root growth. In this study, only the soil properties were described. Soil macro-fauna biodiversity, organic matter content, and bulk density were measured, and parameters were found that describe the soil water retention curves. It was recommended to estimate the below-ground vegetation state based on knowledge of the originally installed LPD fascine and the above-ground vegetation state through allometric relationships such as the root-to-shoot ratio. Below-ground processes refer to the movement of water through the soil and LPD fascine media. These were observed through the dynamics in soil moisture, matric suction, and lateral flow through space and time. Both soil moisture and matric suction measurements showed high diurnality and sensitivity to rain events, however, no trend was found in variations along the length of the monitored LPDs. Meanwhile, in experiments in which a pulse flow was applied at the top of an LPD, reduced and attenuated outflow suggests that this flow varied along the LPD length. The natural in-fluxes and out-fluxes of the below-ground zone of the LPD were difficult to measure in Catterline due to the high heterogeneity of the subsurface, including unknown sources such as seepage zones and sinks such as macropores or fractured bedrock. Challenges in measuring fluxes, the low frequency of both high-intensity events and long periods of drought, and discrepancies between observations and expectations led to recommendations to study the processes in a more controlled environment.
Some key design decisions that made it into the OAL setup in Delft from Catterline and the Applied Ecology group at GCU included best practices in LPD installation, dimensioning spatial accommodation for LPD growth, monitoring, and experimentation methodologies. For the conceptual model, the observations from Catterline resulted in an additional process being added based on the observations of lateral pulse flow through the LPD.

Part II of this report describes the design of the RHIZO Lab at TU Delft and the design and construction of an experimental setup for the eco-hydrological behavior of LPDs. The objective of the RHIZO Lab establishment was to encourage and facilitate research on Nature-based Sustainable Drainage Solutions. The objective of the LPD experimental setup was to begin the collection of a long-term data set on the transient behavior of LPDs.
The design of the RHIZO Lab started with discussions between stakeholders, through which design criteria were found. Ideas came up on what could be researched, how the lab could be used for education and demonstration, and what hard and soft infrastructure would be needed to maintain it. Besides the LPD setup, which was

pre-determined as part of the lab, a setup with vegetated swales was selected as the next priority due to its importance as a widely used Nb-SuDS and the motivation shown by stakeholders to be involved in its design, construction, and monitoring. The swale setup was only developed to a preliminary design state within this project, general dimensions, slope, and filter media were proposed.
The design of the LPD experiment began with the knowledge of LPDs found in the field visit to GCU's OAL in Catterline, and from previous research from Catterline, particularly Benschop (2022). The objective of the setup did not explicitly lead to a research question, necessitating the identification of a research gap. While LPDs have not been researched extensively, some of the components that make up their eco-hydrological behavior are well understood, for example, willow growth and propagation by stakes from the field of coppiced willows for production, and the impact of willows on the unsaturated zone from work on slope stability at Catterline (Gonzalez-Ollauri and Mickovski, 2017a). A gap was found regarding lateral flow: how does partitioning of flow within large macropores in a live fascine placed parallel to the slope evolve over its lifespan? To address this question the transient behavior of each component of the LPD must be understood. This question is not answered with this project, but it guided the design of the experimental setup and the structure of the conceptual model.
After establishing a research question that could be answered with the setup, more punctual design tasks were carried out. First, the general geometry of the setup was designed: two LPDs and one bare area on a 6.5 m long, 15-degree slope with a depth of 1 meter. The fill media for below and around the LPD was selected from locally available materials. A sand below the LPD to maximize percolation, and a planting soil around the LPD to maintain a moisture- and nutrient-rich growth environment for the LPD twigs. The setup was made as long as possible to allow multiple observation points along its length. Drains to capture percolation were designed at four locations along the length of the setup for the same purpose. To build the setup, a structure made of retaining walls was erected, and filled with a base fill up to the required slope gradient. Then, dividers were installed to divide the slope into three compartments. Each compartment was lined with an impermeable layer and the drainage system was installed. Finally, the fill media was layered in the LPDs were installed. Sensors were placed strategically to capture the two-dimensional processes in the LPD. Monitoring methodologies and some short-term experiments are suggested to evaluate the long term behavior of the setup. The final design of the experimental setup and the monitored states and processes were modeled in Part III.

The second research question was: ***What measurable processes and parameters on the experimental LPD setup can be combined with an understanding of physical processes to conceptually model the ecohydrological behavior of LPDs?*** This question was answered in Part III of the report. The development of the conceptual model began with the adaptation of a conceptual model by Benschop (2022) to the experimental setup. The model consisted of lumped above-ground and below-ground fill-and-spill storages and sub-models as functions of storage states and parameters governing the partitioning of fluxes. First, to adapt the model to the experimental setup, the configuration of storages and fluxes was adjusted to include separate storages for each type of porous media in the setup. Then, to enhance the usability of the model for simulating transient behavior, the seasonal variation in vegetation-related parameters was incorporated as a time-variable input. Finally, to improve the model's representation of flow partitioning, potential improvements to the model processes were explored. Changes to the lateral flow sub-model stemmed from Benschop's recommendation and were based on observations from Catterline where lateral flow attenuation was observed through experiments on LPD23 and the lateral outflow of LPD21 seemed to emerge from macropores. Lateral flow was originally modeled as one-dimensional Darcy flow through porous media along the slope direction. In this study, it is suggested to model the lateral flow as open channel flow using Manning's equation. With this approach, lateral flow is assigned its own storage called quickflow. This approach assumes that all lateral flow occurs in unconfined macropores or as overland flow. This sub-model can be used for slopes with LPDs, which are assumed to have a high laterally oriented macropore volume near the surface, and for bare slopes, where overland flow may be more relevant. Another potential improvement to the model that was explored was the distribution of processes along the length of the slope. To do this, the modeled slope is split into an n-number of zones, each of which has all the processes and storages of the lumped model, but with the lateral flow out-flux of each zone routed to the next zone as a lateral flow in-flux. Isolating all lateral flow into a quickflow storage simplified this step. Recommendations were made for sub-models that were evaluated but not modified. For example, in the partitioning of infiltration and overflow, some options were discussed to better represent transient behavior in this sub-model by allowing higher infiltration to a rooted soil than to a bare soil. Recommendations are also made to improve the percolation sub-model.
A sensitivity analysis to variations in key parameters was performed. High sensitivity to the parameters and unsaturated porous media state governing the infiltration and overflow partitioning was found, and low sensitivity to vegetation parameters. Updating the infiltration-overflow sub-model to represent the increased infiltration

capacity of a rooted soil is expected to reduce the sensitivity to the unsaturated media state and increase the sensitivity to vegetation-related parameters.
Besides the limitations to each evaluated sub-model discussed above, a general limitation of the proposed model is that while the movement of fluxes is assumed as a continuous process, vegetation growth and LPD sedimentation were fully parameterized as a series of states. This leads to the possibility of over-parametrization.
Moving forward, it is recommended to compare the dynamics of each state and flux in the model to observations from the experiment to evaluate each sub-model. Soil moisture measurements in each of the experimental media can be compared to the dynamics of the modeled unsaturated porous media storages. The partitioning between percolation and quickflow in the model can be compared to the percolation and lateral flow out-flux measured in the experimental setup. Below-ground processes can also be better understood by performing tracer experiments on the setup. Monitoring vegetation growth each season is recommended to update vegetation-related model parameters accordingly. below-ground vegetation structure (i.e. roots), can be approximated using allometric relationships, or measured using electric resistance tomography. Short-term experiments on the experimental setup are suggested to capture the LPDs response to extreme events, this is important due to the non-linearity of the expected response, and due to the fact that the setup does not naturally receive a lateral in-flux.

In conclusion, this report presents three steps toward improving our understanding of Live Pole Drains: describing, experimenting, and modeling. Although these steps do not provide an exhaustive analysis individually, each contributed toward establishing a framework for the long-term observation and experimentation on LPD behavior.

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A Appendix: Thesis Objectives Alignment with Sponge Campus Project

1. To (1.1) co-design, (1.2) build and instrument the Nature-based drainage system with 'smart' environmental sensors in order to evaluate its long-term eco-hydrological performance at TU Delft Open Air Lab (OAL).

1.1. Co-Design
1.1.1. One-day initiation workshop to gather ideas and establish collaboration between TU Delft staff, students, and connected societal partners for an Open Living SuDS facility, both for research and educational and outreach activities. Coupled learning objectives will be discussed. (A1)
- Brainstorming through interviews: such as digital interactive design, physical sand box.
- Come up with ideas for indicators/metrics will eventually be evaluated for activity A5 (Assessment of the effectiveness of the SuDS in terms of sustainability indicators (environmental, financial, societal). Educational and demonstration materials will be developed.)

1.1.2. A one-day technical workshop on co-design of SuDS and monitoring programme for hydrometeorological variables including basic water quality and drainage parameters. (A2)
- Make decisions on spatial and temporal division of living lab installations.
- Come up with design specifications for setup components
- Design monitoring programme

1.2. Build and Instrument Co-deployment and instrumenting the SuDS, establishing real-time streaming and analysis of monitoring. Technical specification will be developed for research and education purposes. (A3)
- Design and specifications for non-experiment-specific components
- Construction Logistics (Contractor, Construction timeline, Budget)
- Monitoring

2. To further develop a mathematical, conceptual coupled model of vegetation growth and drainage performance of the system (build in R-package) = Development of a coupled model of vegetation growth and water use in the constructed SuDS (A4)
2A. Experiments with simulated rain and runoff on LPD
2B. Modelling
- Improving Model Structure
o Vegetation: Modelling willow growth, water uptake by willows
o Drainage performance
o Distributed vs lumped model sensitivity analysis
- Model Calibration
o Flexibility for temporal evolution of parameters
o Incorporating long term measurements into model validation

Climate Action Research and Education Seed Call Application Form

I. General information

- Project title : Sponge campus: creating climate-proof campus with innovative, vegetation-based sustainable drainage systems for research and education
  Dr. Thom Bogaard, dep. Water Management, CEG,

II. Summary of the proposed research project/program

1. Project description

This project strives to establish an experimental, vegetation-based Sustainable Drainage System (SuDS) on Campus. The SuDS will be co-designed with the University's community (e.g., students, staff, etc.) with the aim of managing the Campus water cycle and its water quality. Moreover, it aims to become the nucleus of Nature Based Solution (NBS) projects where quantitative knowledge of eco-hydrological behaviour is pivotal, such as in flood, erosion and landslide mitigation projects. The SuDS will be connected to existing Open Air Lab (OAL) facilities such as "Flood Proof Holland" and "Green Village". It will be constructed using locally available vegetation and earth materials, and it will incorporate "smart" environmental sensors to monitor its eco-hydrological performance over time. As such, the experimental SuDS will constitute an additional open-living laboratory at TUDelft, where primary evidence will be collected to inform research, practice, and educational activities for eco-based sustainable urban water management.

The specific objectives of the project are:

(i) To engage with the TUDelft community and its societal partners for co-designing and co-deployment of a SuDS and link to research, education and valorisation activities
(ii) To instrument the SuDS with 'smart' environmental sensors in order to evaluate its long-term eco-hydrological performance and inform the development of a coupled model of vegetation growth and drainage performance of the SuDS
(iii) To develop and arrange the SuDS facility to transfer the eco-hydrological knowledge. support educational activities and societal debate

The approach and proposed activities are:
A1: A one-day initiation workshop to gather ideas and establish collaboration between TUDelft staff, students, and connected societal partners for an Open Living SuDS facility, both for research and educational and outreach activities. Coupled learning objectives will be discussed.
A2: A one-day technical workshop on co-design of SuDS and monitoring programme for hydrometeorological variables including basic water quality and drainage parameters.
A3: Co-deployment and instrumenting the SuDS, establishing real-time streaming and analysis of monitoring. Technical specification will be developed for research and education purposes.
A4: Development of a coupled model of vegetation growth and water use in the constructed SuDS
A5: Assessment of the effectiveness of the SuDS in terms of sustainability indicators (environmental, financial, societal]. Educational and demonstration materials will be developed.

The proposed project is multi- and inter-disciplinary and involves participation and collaboration between such as water managers, environmental engineers, landscape architects, ecologists, and urban planners. The project will strengthen the existing collaborations in sustainable urban planning and water management. Part of the funding will be used for setting-up joint research activities, and preparation for larger research grant applications between EU industry and non-EU academia. Collaboration will be established in the frame of the proposed project with Glasgow Caledonian University (UK) through their Open-air laboratory and with Naturalea (Spain) and their Urban River Lab facility (https://urbanriverlab.com/).

The proposed project will generate an evidence base of the performance and public perception of SuDS. The latter will inform policy, standards, and strategies seeking to replicate and upscale SuDS to effectively manage storm water runoff and pollution as part of climate change adaptation strategies in the urban/built environment. The project will foster collaborative research links with other OALs in which SuDS have been established to understand the impact of the sustainability attributes on SuDS performance. We also envisage future collaborative research to explore the potential of the experimental SuDS for urban greening, rewilding, carbon capture, heat island mitigation, enhancing

B Appendix: Stakeholder Engagement

Stakeholder 1st round interviews

Interview general overview

- **Format**: Informal interviews of 30 minutes to an hour with open questions for brainstorming.
- **Questions**
  - Interest in participating
  - How they would like to use the facility for education/research
  - If they were familiar with similar projects from experience or literature
  - If they know others who want to participate
- **Participants**
  - Thijs de Bruijn (TdB), Green Village / VP Delta+
  - Lindsey Schwidder (LS), Green Village / VP Delta+
  - Jean-Paul de Garde (JPdG), Green Village / VP Delta+
  - Isabel Hille (IH), Green Village
  - Martine Rutten (MR), Dept WM + Green Village
  - Job van der Werf (JvdW), Dept WM, Urban Drainage
  - Jan Willem Foppen (JWF), Dept WM, hydrology + chemistry
  - Thom Bogaard (TB), Dept WM, hydrology
  - Bobby Mickovski (BM), Glasgow Caledonian University
  - Alejandro Gonzalez-Ollauri (AGO), Glasgow Caledonian University
  - Nico Tillie (NT), Biodiversity on Campus, Architecture, TU Delft

  - Flood Proof Holland (FPH) – Lindsey Schwidder; The setup will be built at FPH, Lindsey is facilitating this through Jean-Paul de Garde and a contractor hired through the Green Village or FPH. Discussed construction feasibility and logistics, not much on what sort of experiments they are interested in seeing; everything we proposed fits with FPH objectives.
  - The Green Village (TGV) and Flood Proof Holland (FPH) – Jean-Paul de Garde Jean-Paul is working directly with the contractor and building the setup. He is involved in the iterative design process.
  - The Green Village (TGV) – Thijs de Bruin and Isabel Hille; Thijs and Isabel are involved in managing spaces and data around the Green Village, brief discussion on how the SuDS facility fits in with other ongoing research projects.
  - TU Delft Water Management / Water Resources and The Green Village– Martine Rutten: Martine is interested in involvement in the project for education and research. Some ideas on the design of experiments and monitoring to meet interdisciplinary objectives are:
    * Making sure the installation is there long enough to evaluate ecological variables. Plant growth and organic matter in soil could be measured regularly over logn periods of time. Biological monitoring can be performed in a 1m2 setup.
    * Water quality concerns related to how pollution accumulates in the soil.
    * Public health concerns such as mosquitoes, risk of urban "forest fires" fuelled by grassy or woody vegetation.

    Martine also provided some examples of work by other students (Max de Boer, Josine) on urban and catchment-scale nature-based solutions. For education, the setup could be interesting for Special tours from secondary schools or BSc students in hydrology.
  - TU Delft Water Management / Water Resources – Jan Willem Foppen is interested in using the setups for research related to tracers and removal of contaminants in SuDS, for example scaling lab-scale experiments on removal of vehicle-related pollutants to a 1m2 plot. It would be interesting to have a "sand box" area where short term experiments could be performed. Instrumentation options were discussed such as BGS Troll for pressure sensors and Keller sensors, CTD divers, Lysimeter from Julich for idea of having one of the 1m2 plots suspended.

  - TU Delft Water Management / Sanitary – Job van de Werf: Job discussed research ideas and design suggestions for the flat slope setup as well as instrumentation ideas. The flat setup could resemble a typical swale per typical construction standards, slow infiltration but quick enough to drain within 24 hours, see standards from CIRIA. For sensing, it would be ideal to continuously collect basic data, and have options for temporary sensing setups, for example by leaving pre-installed piezometers. Sporadic observations could be made of biomass and of accumulation of contaminants in biofilm. Geophysical testing of root distribution could be done using Electric Resistance Tomography (ERT), a camera could be used to get a time series of images to measure vegetation growth and seasonality. For sensors, suggestion to look into CoUD Labs.
  - Glasgow Caledonia University - Mickovski, Slobodan (Bobby):
    * On design process: Bobby stressed importance of involving non-academic stakeholders.
    * On slope steepness selection: all ok with 1:3 slope, consider that gully formation depends on soil properties, lateral flow rate, etc.
    * On biological/ecological monitoring: above ground observations typically inform assumptions about the subsoil (root) conditions: allometry. Could do a GPR scan for root material? Or grow plants under identical conditions nearby and uproot after a period of time. Or build a rhizotrone (this would also be in the separate area with allowance for disturbances).
    * On testing slope stability: take samples for shear test from "sand box" area. Find examples from LEO Biodome

- Other Possibly Relevant Parties for future involvement:
  - Companies such as HKV or Deltares (Su Kalloe researching willows)
  - Policymakers public water management.
  - Startups
  - Others from the WM department: Kim, Boris
  - Other labs: Naturalea Spain

Interview details

Questions: 0. Brief explanation about the project purpose
1. Are you interested in participating in the project? How involved would you like to be? Participate in design workshops, use the facility for education or research?
TdB –> Would be available to discuss feasibility of constructing setup, the space in the Green village is divided by managers, Thijs is in charge of the WaterStraat and the Heat Square.
IH –> In charge of some education programs.
MR –> Advising and connections.
JvdW –>Yes, interesting for testing urban SuDS
JWF –> Yes

2. How would you like to use the facility for your education and research projects? Use the facility for education, e.g. for short experiments as part of a course you teach would these happen in a certain quarter?, for demonstrations to the public?; To use the facility for research, what sorts of experiments would you be interested in implementing? What space and time dimensions would they require? ; Is there research currently performed at lab-scale or just with modelling that you would like to test in a larger outdoor setting?
TdB –> Matching with current research, there is a company that looks into retaining water around the roots of trees. They are testing it with lysimeters in the heat square
JvdW –> Could be interesting to look at changes in performance of vegetated swale over time
JWP –> Could be interesting for research to test tracers

3. Do you have any recommendations for the setup based on experience with similar projects or experiments you have come across in literature? Have you been involved in similar projects in the past? Any advice or lessons learned?, or gaps to fill?
MR –> Look into: how infiltration rate is influenced by organic matter (time scale of decades), Root dynamics:

time scale of seasons, Water quality: water companies concerned with infiltrated water carrying unknown pollutants, how to accumulate pollutants in the “ground water” of the setup?, Ecology: minimum area to measure ecological variables is 1 m2, Other concerns with urban NBS: urban forest fires, Ecology/Health: working with brackish water, use salt tolerant plants.
MR’s MSc students –> NBS that could be tested: filter strip, infiltration basin, tilted standard conveyance swale, wet swale, infiltration basins (Geiger et al., 2009, space vs infiltration), all for pluvial flooding

4. Do you know of anyone else who may like to participate or have valuable design inputs? We are looking for water managers, environmental engineers, landscape architects, ecologists, and urban planners.
TdB –> expert on sensors in the GV is Marijn (marijn.leeuwenberg@thegreenvillage.org), Entrepreneur New Urban Standard is Erwin van Herwijnen (erwin@tgs.nl) he is growing trees in crates with water storage. Objective: equal capillary rise to evaporation.
MR –> Relevant student projects: Max de Boer, Vietnam = MCA for selecting NBS for urban area, Chantal and Josine, Limburg The effect of ’Natural Sponges’ as flood prevention in the Geul catchment building with nature, wflow sbm, SWAP, runoff, Perrin Keesmat, Suriname = Applicability of a conceptual tool in quantifying the effectiveness of Nature-Based Solutions in tropical urban flood mitigation. Other education interest: BSc students in Hydrology, Hoogeschool Rotterdam students, other school groups.
JvdW –> Jeroen for SuDS, Kim for water quality, CoUD for sharing instrumentation.

Available resources from stakeholders

• Arjan Droste – weather stations testing from Alecto, 25 on campus and 25 different places, also Davis pro. Ask about placing a weather station at flood proof holland, working with Marlijn van Esch
• Possible to use regen douche, ask Jean Paul

Sponge campus: creating climate-proof campus with innovative, vegetation-based sustainable drainage systems for research and education

1

0
About the project

- Co-design and build an outdoor living lab
- Monitor and model innovative SuDS
- Transfer eco-hydrological knowledge

2

1
Are you interested in being involved in the project?

To what extent?

3

2
What would you like to see in the living lab…

…for education?

…for research?

Space and time scale of use?

4

3
Do you have any recommendations from…

…experience with other projects?

…literature?

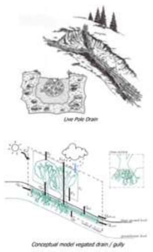
5

4
To keep the ball rolling, who else should be involved?

6

Solutions

Planned

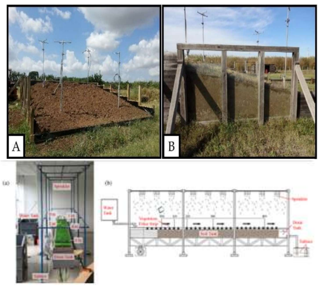


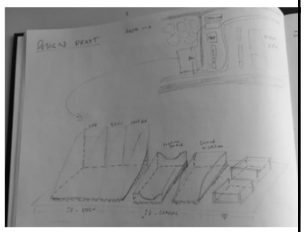
New ideas

?

7

Set up ideas





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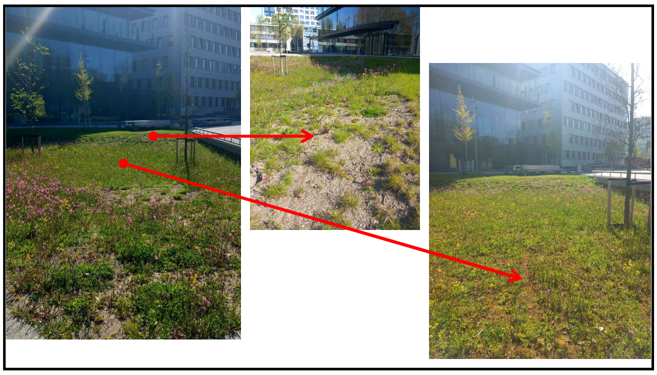

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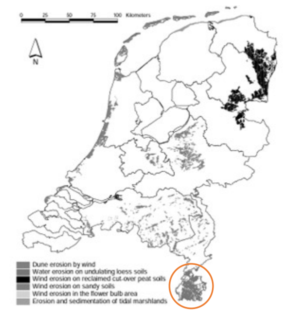


Figure 12: Location of the erosion types in the Netherlands (after Epping & Spaan (1998))

Not just Limburg

11

In [6]:
```python
import numpy as np
import matplotlib.pyplot as plt
```

In [21]:
```python
"""
Function to plot an LPD cross section for quick design brainstorming during stakeholder interactions
"""

def branches(bw_pct, bh_pct, willow_h, willow_w, willow_stem):
    w_branch = (willow_w / 2) * bw_pct
    h_branch = (willow_h - willow_stem) * bh_pct
    xb = np.linspace(0, w_branch, 20)
    zb = (h_branch / w_branch**2) * xb **2 + willow_stem
    return xb, zb

def roots(root_width_pct, root_depth_pct, root_split_pct, root_depth, willow_w):
    x1_root = (willow_w / 2) * root_width_pct
    z0_root = root_split_pct * root_depth
    z1_root = root_depth_pct * root_depth
    x_root = np.linspace(0, x1_root, 20)
    z_root = (z1_root - z0_root) / x1_root * x_root + z0_root
    return x_root, z_root


def parabola(h, W, x, z_offset):
    z = h / W**2 * x**2  + z_offset
    return z

def line(h, W, x, z_offset):
    z = h / W * x + z_offset
    return z

def plot_xsect(tot_W, buffer, r_buffer, l_buffer, deg_imp_bound, shape_imp_bound, deg_soil, soil_layer, shape_soil, willow_h, root_depth, willow_stem, willow_w, willow_trunk, spacing_
    b1x, b1z = branches(1,   1/3,     willow_h, willow_w, willow_stem)
    b2x, b2z = branches(3/4, 9/12,     willow_h, willow_w, willow_stem)
    b3x, b3z = branches(1/2, 11/12,   willow_h, willow_w, willow_stem)
    b4x, b4z = branches(1/4, 1,       willow_h, willow_w, willow_stem)

    r1x, r1z = roots(3/4, 3/4, 1/8, root_depth, willow_w)
    r2x, r2z = roots(1/100, 1, 0, root_depth, willow_w)
    r3x, r3z = roots(1/2, 7/8, 1/3, root_depth, willow_w)
    r4x, r4z = roots(1/2, 1/4, 1/5, root_depth, willow_w)
    r5x, r5z = roots(1/4, 7/8, 1/2, root_depth, willow_w)


    W =  tot_W - buffer - r_buffer - buffer_top #m, width
    h_imp_bound = np.tan(deg_imp_bound * np.pi / 180) * W
    h_soil = np.tan(deg_soil * np.pi / 180) * W
    marginbelow = W/20 #m, hashed area anuder x-section
    x_trees = np.arange(buffer_LPD_down, (W - buffer_LPD_up - r_buffer) + spacing_x, spacing_x)

    x = np.linspace(0, W, 100)
    x_imp = np.linspace(0, W+buffer_top, 100)
    if shape_imp_bound == 'flat':
        z_imp_bound = line(h_imp_bound, W+buffer_top, x_imp, 0)
    elif shape_imp_bound == 'parabolic':
        z_imp_bound = parabola(h_imp_bound, W+buffer_top, x_imp, 0)
    if shape_soil == 'flat':
        z_soil  = line(h_soil, W, x, soil_layer)
        z_trees = line(h_soil, W, x_trees, soil_layer)
    elif shape_soil == 'parabolic':
        z_soil = parabola(h_soil, W, x, soil_layer)
        z_trees = parabola(h_soil, W, x_trees, soil_layer)

    fig = plt.figure(figsize=(10,10))
    ax = fig.add_subplot(111)
    ax.set_aspect(1)

    #Impermeable bound
    ax.plot(x_imp, z_imp_bound, 'k')
    ax.plot((W+buffer_top, W+buffer_top), (z_imp_bound[-1], z_soil[-1]), 'k')
    ax.plot((-buffer, -buffer), (z_imp_bound[0], max(gwl, z_soil[0])), ':k')
    ax.plot((-buffer, 0), (0,0), 'k')

    #Soil layer
    ax.plot((-buffer, 0), (soil_layer, soil_layer), '#DEB887')
    ax.plot(x, z_soil, '#DEB887')

    #GWL
    ax.plot((-buffer-l_buffer, W+r_buffer), (gwl, gwl), "#8EE5EE")

    #Hatch Soil
    ax.fill_between(x, z_soil,  color= "#DEB887",alpha= 0.7, linewidth=0.0)
    ax.fill_between((W, W+buffer_top), (z_soil[-1], z_soil[-1]), color= "#DEB887",alpha= 0.7, linewidth=0.0)
    ax.fill_between((-buffer, 0), (soil_layer, soil_layer), (0,0), color= "#DEB887",alpha= 0.7, linewidth=0.0)

    #Hatch GWL
    ax.fill_between((-buffer-l_buffer, W+r_buffer), (gwl, gwl), -marginbelow,  color = "#8EE5EE", alpha=0.5, linewidth = 0.0)

    #Hatch impermeable
    ax.fill_between(x_imp, z_imp_bound, hatch='xx', color= "#DCDCDC", alpha= 1, linewidth=0.0, edgecolor = '#858585', facecolor = '#DCDCDC')
    ax.fill_between((-buffer, W+buffer_top), (0, 0), -marginbelow, hatch='xx', color= "#DCDCDC",alpha= 1, linewidth=0.0, edgecolor = '#858585', facecolor = '#DCDCDC')
    ax.fill_between((W+buffer_top, W+buffer_top+r_buffer), (z_soil[-1], z_soil[-1]), -marginbelow, hatch='xx', color= "#DCDCDC",alpha= 1, linewidth=0.0, edgecolor = '#858585', facecol
    ax.fill_between((-buffer, -buffer-l_buffer), (0,0), -marginbelow, hatch='xx', color= "#DCDCDC",alpha= 1, linewidth=0.0, edgecolor = '#858585', facecolor = '#DCDCDC')


    ax.yaxis.tick_right()

    if LPD == 1:
        x_LPD = np.linspace(buffer_LPD_down, W-buffer_LPD_up, 100)
        for j in range(n_branches_LPD):
            y_LPD = line(h_soil, W, x_LPD, soil_layer-diameter_LPD/n_branches_LPD * j - soil_cover_LPD)
            ax.plot(x_LPD, y_LPD, "#686822")
        #diameter_LPD, soil_cover_LPD, buffer_LPD_down, buffer_LPD_up, n_branches_LPD, LPD

    if trees == 1:
        for i in range(len(x_trees)):
            x0 = x_trees[i]
            z0 = z_trees[i]
            ax.fill_between((x0-willow_trunk/2, x0+willow_trunk/2), (z0+willow_stem, z0+willow_stem), (z0, z0), color= "#8B6508",alpha= 0.7, linewidth=0.0)
            #branches
            ax.plot((x0,x0), (z0 + willow_stem, z0 + willow_h), "#556B2F")
            ax.plot(x0 + b1x, z0 + b1z, "#556B2F")
            ax.plot(x0 + b2x, z0 + b2z, "#556B2F")
            ax.plot(x0 + b3x, z0 + b3z, "#556B2F")
            ax.plot(x0 + b4x, z0 + b4z, "#556B2F")
            ax.plot(x0 - b1x, z0 + b1z, "#556B2F")
            ax.plot(x0 - b2x, z0 + b2z, "#556B2F")
            ax.plot(x0 - b3x, z0 + b3z, "#556B2F")
            ax.plot(x0 - b4x, z0 + b4z, "#556B2F")
            #roots
            ax.plot(x0 - r1x, z0 - r1z, "#8B6508")
            ax.plot(x0 + r2x, z0 - r2z, "#8B6508")
            ax.plot(x0 - r3x, z0 - r3z, "#8B6508")
            ax.plot(x0 + r4x, z0 - r4z, "#8B6508")
            ax.plot(x0 + r5x, z0 - r5z, "#8B6508")
```

```
    ax.set_xlabel('x (m)')
    ax.set_ylabel('z (m)')
    ax.yaxis.set_label_position("right")
    #ax.grid()
    return

shape_opts = ['flat', 'parabolic']

def plot_planview(tot_L, path_width, plot_width, r_buffer, l_buffer, tot_W):
    L_plots = tot_L - path_width
    n_plots = np.floor(L_plots/(plot_width+path_width))
    act_plot_width = L_plots / n_plots

    z = (0, tot_W-r_buffer)
    x_vals = np.arange(0, tot_L, act_plot_width)

    fig = plt.figure(figsize=(16,16))
    ax = fig.add_subplot(111)
    ax.set_aspect(1)
    for i in range(len(x_vals)):
        ax.plot((x_vals[i], x_vals[i]), z, 'k')
        ax.plot((x_vals[i] + path_width, x_vals[i] + path_width,), z, 'k')
        ax.fill_between((x_vals[i], x_vals[i] + path_width), (tot_W, tot_W), hatch='xx', alpha= 1, linewidth=0.0, edgecolor = '#858585', facecolor = '#DCDCDC')
    for  i in range(len(x_vals)-1):
        ax.fill_between((x_vals[i]+ path_width, x_vals[i+1]), (tot_W, tot_W), (tot_W-r_buffer, tot_W-r_buffer),hatch='xx', alpha= 1, linewidth=0.0, edgecolor = '#858585', facecolor =
        ax.fill_between((x_vals[i]+ path_width, x_vals[i+1]), (tot_W-r_buffer, tot_W-r_buffer),alpha= 0.7, linewidth=0.0, facecolor = '#DEB887')
        ax.plot((x_vals[i]+path_width, x_vals[i+1]), (tot_W-r_buffer, tot_W-r_buffer), 'k')
        ax.plot((x_vals[i]+path_width, x_vals[i+1]), (l_buffer, l_buffer), ':k')
    ax.set_xlim(0,30)
    return
```

Space Available

In [22]:
```
#total space available
tot_W = 9 #m, width
r_buffer = 1 #m, width outside impermeable boundary
l_buffer = 0.2 #m, width outside impermeable boundary
```

Vegetation

In [23]:
```
#Vegetation dimensions

#Small
# willow_h = .5 #m, height of willow
# root_depth = .35 #m, maximum depth of willow roots
# willow_stem = 0 #m, height of willow stem
# willow_w = .15 #m, width
# willow_trunk = 0.05 #m, stem diameter

#Medium
# willow_h = 1.5 #m, height of willow
# root_depth = .75 #m, maximum depth of willow roots
# willow_stem = .1 #m, height of willow stem
# willow_w = .65 #m, width
# willow_trunk = 0.03 #m, stem diameter

#Large
willow_h = 3 #m, height of willow
root_depth = .65 #m, maximum depth of willow roots
willow_stem = .3 #m, height of willow stem
willow_w = 1 #m, width
willow_trunk = 0.1 #m, stem diameter


spacing_x =1.2 #m, spacing between trees
```

LPD

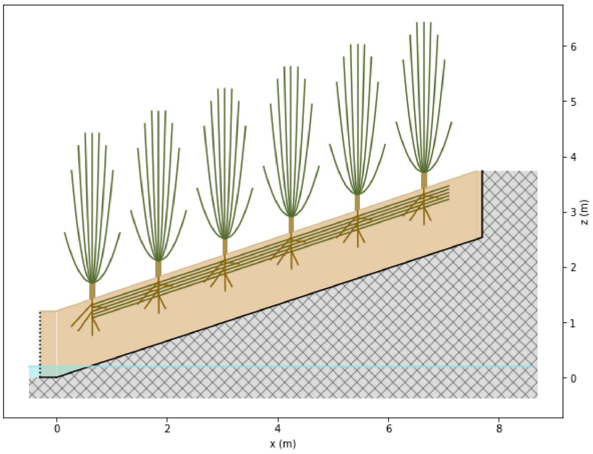
In [24]:
```
#LPD
diameter_LPD = 0.3 #m, diameter of LPD
soil_cover_LPD = 0.10 #m, soil on top of LPD
buffer_LPD_down = 0.65 #m, distance from end of LPD to bottom of slope
buffer_LPD_up = 0.50 #m, distance from end of LPD to top of slope
n_branches_LPD = 5 #-, number fo branches in the LPD.
LPD = 1 # change to zero if no LPD present
trees = 1 #change to zero if no trees present
```

Input parameters for steep slope section

In [25]:
```
#Impermeable boundary dimensions
buffer = .3 #m, width flat area at slope base
buffer_top = .1 #m, wodth flat area at slope top
deg_imp_bound = 18.43 #degrees, slope impermeable bound
shape_imp_bound =  shape_opts[0]

#Soil layer dimensions
deg_soil = 18.43 #degrees, slope soil
soil_layer =1.2#m, thickness of soil layer
shape_soil = shape_opts[0]

#Ground water level
gwl = 0.2#m above impermeable boundary
plot_xsect(tot_W, buffer, r_buffer, l_buffer, deg_imp_bound, shape_imp_bound, deg_soil, soil_layer, shape_soil, willow_h, root_depth, willow_stem, willow_w, willow_trunk, spacing_x, g
```



Input parameters for Swale

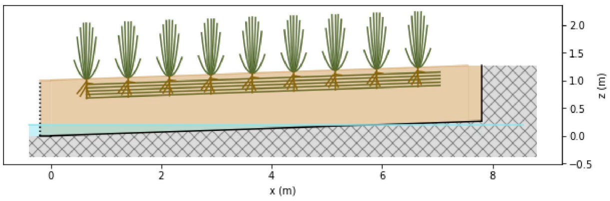
In [26]:
```
#Impermeable boundary dimensions
buffer = .2 #m, width flat area at slope base
buffer_top = .25 #m, wodth flat area at slope top
deg_imp_bound = 2 #degrees, slope impermeable bound
shape_imp_bound =  shape_opts[0]

#Soil layer dimensions
deg_soil = 2 #degrees, slope soil
soil_layer = 1 #m, thickness of soil layer
shape_soil = shape_opts[0]

#Ground water level
gwl = 0.2#m above impermeable boundary

#trees
LPD = 1 # change to zero if no LPD present
trees = 1 #change to zero if no trees present
willow_h = 1 #m, height of willow
root_depth = .35 #m, maximum depth of willow roots
willow_stem = 0 #m, height of willow stem
willow_w = .45 #m, width
willow_trunk = 0.03 #m, stem diameter
spacing_x = .75 #m, spacing between trees

plot_xsect(tot_W, buffer, r_buffer, l_buffer, deg_imp_bound, shape_imp_bound, deg_soil, soil_layer, shape_soil, willow_h, root_depth, willow_stem, willow_w, willow_trunk, spacing_x, g
```



Input parameters for flat section

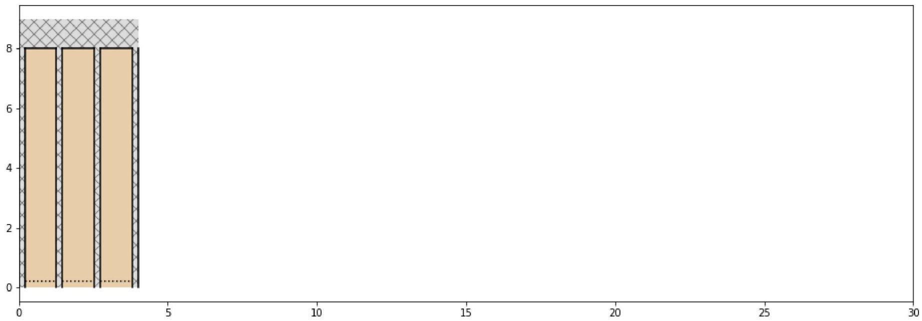
In [18]:
```
#Impermeable boundary dimensions
buffer = .3 #m, width flat area at slope base
deg_imp_bound = 2#degrees, slope impermeable bound
shape_imp_bound =  shape_opts[0]

#Soil layer dimensions
deg_soil = 2 #degrees, slope soil
soil_layer = 0.65 #m, thickness of soil layer
shape_soil = shape_opts[0]

#Ground water level
gwl = 0.25#m above impermeable boundary
plot_xsect(tot_W, buffer, r_buffer, l_buffer, deg_imp_bound, shape_imp_bound, deg_soil, soil_layer, shape_soil, willow_h, root_depth, willow_stem, willow_w, willow_trunk, spacing_x, g
```

Input Parameters for plan view

In [27]:
```
# tot_L = n * plot_width + (n + 1) * path_width
tot_L = 4 #m, length
path_width = .2 #m, path between study sections
plot_width = 3.2 / 3 #m
plot_planview(tot_L, path_width, plot_width, r_buffer, l_buffer, tot_W)
```



In [ ]:

C Appendix: Design and Construction

- Construction process photo log
- Final RHIZO Lab Design Proposal
- Preliminary Design Ideas
- Design Details
- Smart Sensors
- Live Pole Drain Specification
- Swale Design criteria
- Construction Timeline
- Proposed Monitoring Activities

(a) Site before clearing (b) Initial site layout (c) Placement of foundation

(d) Placement of retaining walls (e) Final progress on flat setup (f) Base fill layer

(g) Geo-textile over base fill (h) Dividers (i) Impermeable layer and drains

(j) Gravel drain layer (k) Sand (l) Piezometers

(m) Live Pole Drains (n) Planting Soil (o) Setup settling

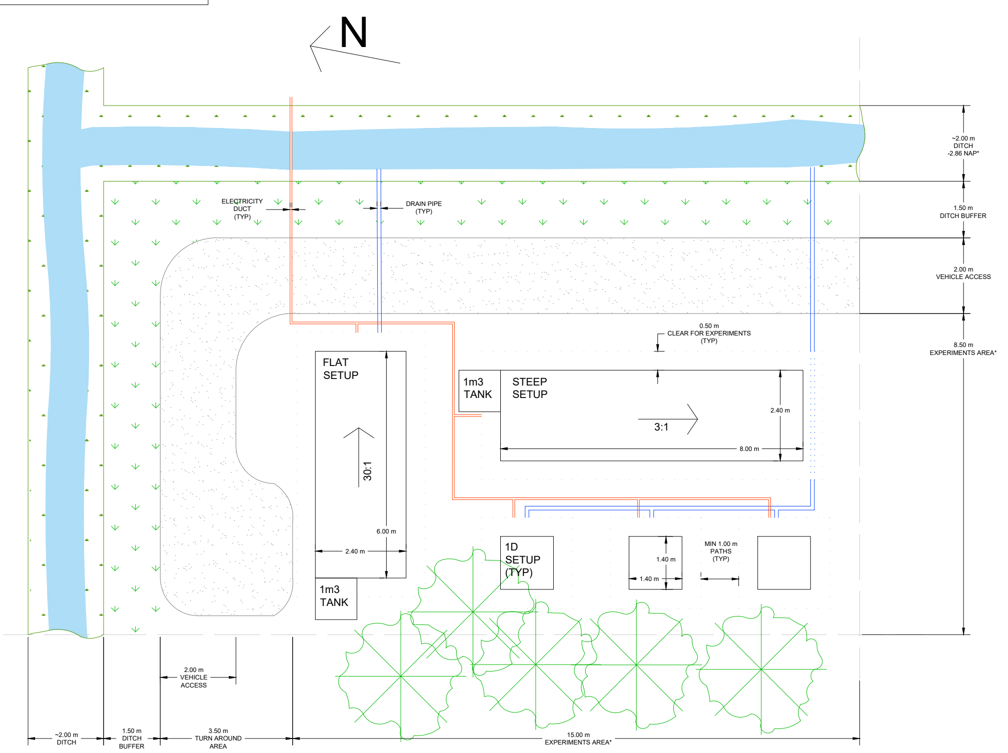
Figure 27: Construction Process.

Final RHIZO Lab Design Proposal

(before changes made during construction)

SuDS FACILITY DESIGN DRAFT - SITE LAYOUT

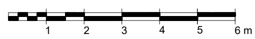
SHEET 1 OF 3
DATE: 10.06.2023
PRINT A3 - 1:10



NOTES:

* SITE DIMENSIONS, DITCH LOCATION AND ELEVATION, AND TREE LOCATIONS MUST BE VERIFIED ON SITE

- PHASE 1
  -- CLEAR VEGETATION FROM SITE
  -- DO NOT REMOVE TREES OVER 20 CM Ø
  -- MOVE LOADING SAND TO MAAIVELD LEVEL
  -- ADJUST OR APPLY STRUCTURAL STABILIZATION FOIL TO PREVENT DIFFERENTIAL SETTLING
  -- INSTALL ELECTRICITY CONNECTION
  -- INSTALL ACCESS ROAD, SITE DRAINAGE AND PATHS
- PHASE 2
  -- CONSTRUCTION OF STEEP AND FLAT SETUP BASES, SEE DETAILS
  -- PREPARATION OF LPD
- PHASE 3
  -- FILLING STEEP AND FLAT SETUPS WITH DESIGNED SOIL SENSOR INSTALLATION BETWEEN LAYERS
  -- INSTALL LPD
- PHASE 4
  -- CONSTRUCTION OF 1D SETUP BASES



SuDS FACILITY DESIGN DRAFT - STEEP SLOPE SETUP LAYOUT

SHEET 2 OF 3
DATE: 10.06.2023
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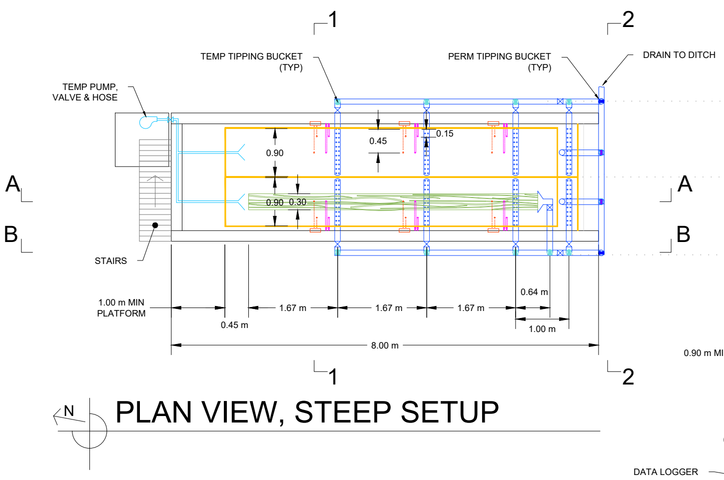
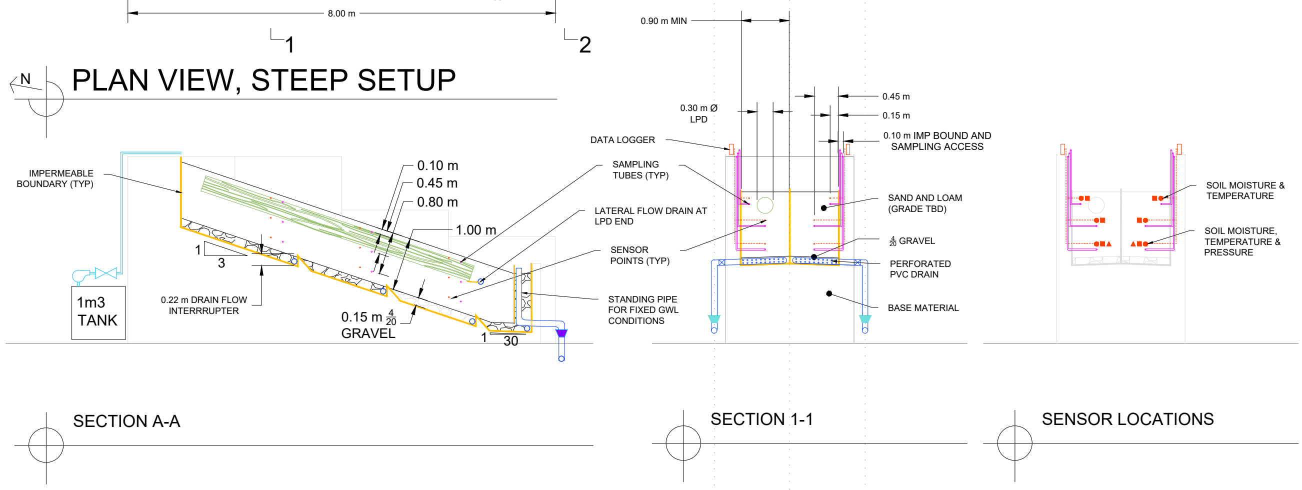
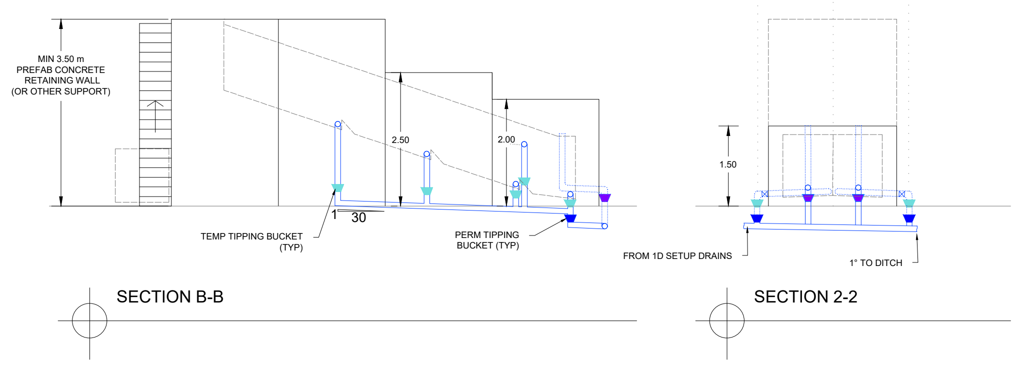
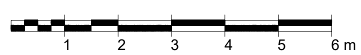
NOTES:

- LPD = LIVE POLE DRAIN
  -- 30 CM Ø BUNDLE OF WILLOW TWIGS 1-2 CM Ø
- IMPERMEABLE BOUNDARY
  -- LAYER OF ROOT-RESISTANT GEOTEXTILE OVER IMPERMEABLE PLASTIC
- BASE DRAIN
  -- N.T.S. 2" PVC, PERFORATED WITHIN DRAINAGE AREA
  -- 2° SLOPE IN PIPES TOWARD TIPPING BUCKETS.
  -- 1° SLOPE IN PIPES TOWARD DITCH, NAP -2.86, ADJUST DRAIN ELEVATIONS ACCORDINGLY
  -- UN-DRAINED OPTION WITH ALL VALVES SHUT AND FIXED HEIGHT OVERFLOW PIPE
- INSTRUMENTATION
  -- DESIGN ACCOMMODATES TEMPORARY AND PERMANENT TIPPING BUCKETS. WHEN TEMPS ARE NOT PRESENT, LATERAL DRAINS FLOW TO PERMANENT TIPPING BUCKET
  -- SAMPLING POINTS ARE 1" Ø STANDING PIPES WITH HOSE CONNECTION
  -- SENSORS TO BE INSTALLED DURING CONSTRUCTION.
  -- APPLY SEAL WHERE CABLES AND PIPES CROSS IMPERMEABLE BOUNDARY
  -- SENSORS:
    - SOIL MOISTURE
    - TEMPERATURE
    - PRESSURE
  -- TIPPING BUCKET LOCATIONS:
    - DRAINED SETUP
    - FIXED GWL SETUP
    - SPATIALLY DISTRIBUTED PERCOLATION SETUP







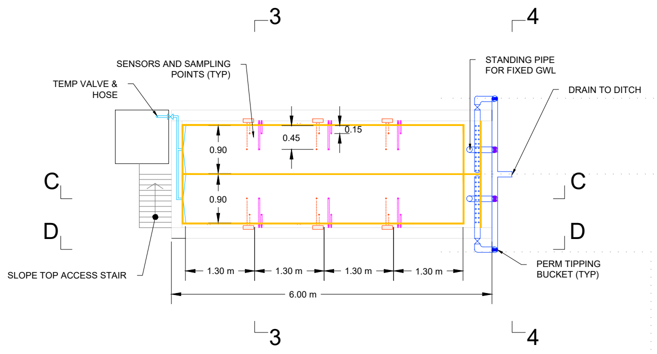


SuDS FACILITY DESIGN DRAFT - FLAT SLOPE SETUP LAYOUT

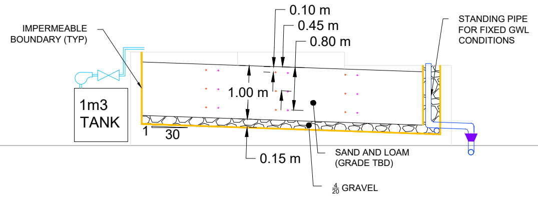
SHEET 3 OF 3
DATE: 10.06.2023
PRINT A3 - 1:10

NOTES:

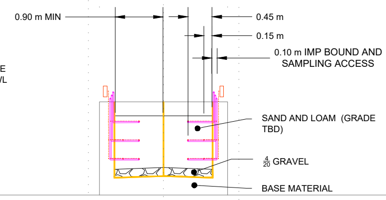
- IMPERMEABLE BOUNDARY
  - LAYER OF ROOT-RESISTANT GEOTEXTILE OVER IMPERMEABLE PLASTIC
- BASE DRAIN
  - N.T.S. 2" PVC, PERFORATED WITHIN DRAINAGE AREA
  - 2° SLOPE TOWARD DITCH, NAP -2.86, ADJUST MINIMUM DRAIN ELEVATIONS ACCORDINGLY
  - UN-DRAINED OPTION WITH ALL VALVES SHUT AND FIXED HEIGHT OVERFLOW PIPE
- INSTRUMENTATION
  - DESIGN ACCOMMODATES TEMPORARY AND PERMANENT TIPPING BUCKETS. WHEN TEMPS ARE NOT PRESENT, LATERAL DRAINS FLOW TO PERMANENT TIPPING BUCKET
  - SAMPLING POINTS ARE 1" Ø STANDING PIPES WITH HOSE CONNECTION
  - SENSORS TO BE INSTALLED DURING CONSTRUCTION.
  - APPLY SEAL WHERE CABLES AND PIPES CROSS IMPERMEABLE BOUNDARY
  - SENSORS:
    - SOIL MOISTURE
    - TEMPERATURE
    - PRESSURE
    - ELECTRIC CONDUCTIVITY
  - TIPPING BUCKET LOCATIONS:
    - DRAINED SETUP
    - FIXED GWL SETUP



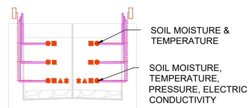
PLAN VIEW, FLAT SETUP



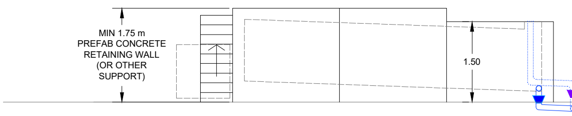
SECTION C-C



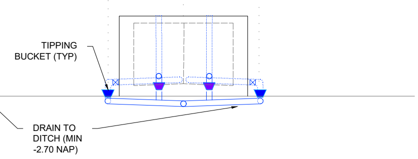
SECTION 3-3



SENSOR LOCATIONS



SECTION D-D



SECTION 4-4

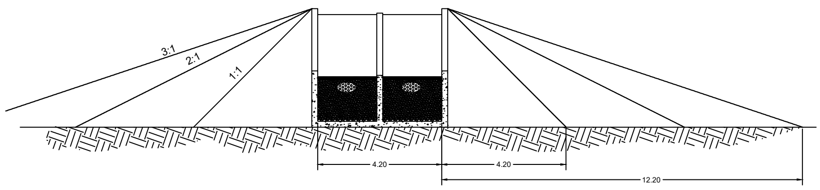
PHASE	ITEM NO.	ITEM	QTY	UNIT	UNIT PRICE	TOTAL	NOTE
PHASE 1 - SITE PREP						**€ 2,267.81**	
	SG1	Clearing and Grubbing	195	m2	€ 2.00	€ 390.00	
	SG2	Tree trimming	3	ea	€ 25.00	€ 75.00	
	SG3	Excavation	50	m3	€ 5.00	€ 250.00	Remove sand to maaiveld level
	SG5	Access road grading	58	m2	€ 10.00	€ 580.00	
	EL1	Electrical cable	45	m	€ 2.00	€ 90.00	
	EL2	Electrical outlets	4	ea	€ 10.00	€ 40.00	
	SG4	Trench excavation	3.36	m3	€ 10.00	€ 33.60	For drain pipe installation, assume avergae .4 m depth .4 m width
	P2	Drainage pipe (4" PVC)	9	m	€ 7.69	€ 69.21	Main drain from setups to ditch
	OT1	Live Pole Drain	2	ea	€ 50.00	€ 100.00	At drain to ditch transition (just an idea to "practice what we preach")
	SM1	Structural foil	128	m2	€ 5.00	€ 640.00	Check whether existing foil can be adjusted
PHASE 2 - BASE CONSTRUCTION						**€ 9,117.28**	
PHASE 2.1 - STEEP SETUP						**€ 5,696.08**	
	SM2	Precast concrete reatining wall 3.5 m	5	ea	€ 600.00	€ 3,000.00	
	SM4	Precast concrete reatining wall 2.5 m	2	ea	€ 500.00	€ 1,000.00	
	SM5	Precast concrete reatining wall 2.0 m	2	ea	€ 450.00	€ 900.00	
	SM7	Precast concrete reatining wall 1.5 m	1	ea	€ 350.00	€ 350.00	
	SM8	2 m tension cables	4	ea	€ 50.00	€ 200.00	
	SG8	Installation and compaction of soil	22	m3	€ 5.00	€ 110.00	fill below impermeable layer with sand available on-site
	SM9	Impermeable plastic	54	m2	€ 1.00	€ 54.00	
	SM10	Root-resistance geotextile	54	m2	€ 1.52	€ 82.08	
PHASE 2.2 - FLAT SETUP						**€ 3,421.20**	
	SM6	Precast concrete reatining wall 1.75 m	5	ea	€ 400.00	€ 2,000.00	
	SM7	Precast concrete reatining wall 1.5 m	3	ea	€ 350.00	€ 1,050.00	
	SM8	2 m tension cables	4	ea	€ 50.00	€ 200.00	
	SG8	Installation and compaction of soil	4	m3	€ 5.00	€ 20.00	fill below impermeable layer with sand availabel on-site
	SM9	Impermeable plastic	60	m2	€ 1.00	€ 60.00	
	SM10	Root-resistance geotextile	60	m2	€ 1.52	€ 91.20	
PHASE 3 - EXPERIMENT INSTALLATION						**€ 19,272.54**	
	INS6	Weather Station	1	ea	€ 0.00	€ 0.00	
PHASE 3.1 - STEEP SETUP						**€ 9,519.34**	
	SG6	4/20 Gravel	2.58	m3	€ 100.00	€ 258.00	
	SG7	Sand and Loam	13.1	m3	€ 100.00	€ 1,310.00	
	SG8	Installation and compaction of soil	13.1	m3	€ 5.00	€ 65.50	
	OT1	Live Pole Drain	1	ea	€ 50.00	€ 50.00	
	SM11	Thin structural barrier	12	m2	€ 10.00	€ 120.00	In between the LPD slope and the bare slope, and at slope base
	P1	Sampling access pipes (1" PVC)	28.8	m	€ 2.66	€ 76.61	
	P2	Drainage pipe (4" PVC)	31.5	m	€ 7.69	€ 242.24	
	P3	Sampling pipe connections (1" PVC)	18	ea	€ 1.50	€ 27.00	
	P4	Drainage pipe connections (4" PVC)	12	ea	€ 1.50	€ 18.00	
	P5	Drainage pipe valves (4" PVC)	12	ea	€ 3.50	€ 42.00	
	P6	1 m3 water tank	1	ea	€ 35.00	€ 35.00	
	P7	Cutting, perforating, installing pipes	1	day	€ 100.00	€ 100.00	
	OT2	Stairs	3.5	m	€ 50.00	€ 175.00	
	INS1	Soil Mositure and Temp sensor	15	ea	€ 300.00	€ 4,500.00	
	INS3	Soil Moisture, Temp and Pressure sensor	3	ea	€ 500.00	€ 1,500.00	
	INS5	Cloud Data Logger	3	ea	€ 200.00	€ 600.00	
	INS4	Tipping bucket	2	ea	€ 200.00	€ 400.00	Two permanent tipping buckets for either drained or fixed GWL setup options.
PHASE 3.2 - FLAT SETUP						**€ 9,753.20**	
	SG6	4/20 Gravel	2.58	m3	€ 100.00	€ 258.00	
	SG7	Sand and Loam	13.1	m3	€ 100.00	€ 1,310.00	
	SG8	Installation and compaction of soil	13.1	m3	€ 5.00	€ 65.50	
	SM11	Thin structural barrier	8	m2	€ 10.00	€ 80.00	
	P1	Sampling access pipes (1" PVC)	28.8	m	€ 2.66	€ 76.61	
	P2	Drainage pipe (4" PVC)	11	m	€ 7.69	€ 84.59	
	P3	Sampling pipe connections (1" PVC)	18	ea	€ 1.50	€ 27.00	
	P4	Drainage pipe connections (4" PVC)	10	ea	€ 1.50	€ 15.00	
	P5	Drainage pipe valves (4" PVC)	4	ea	€ 3.50	€ 14.00	
	P6	1 m3 water tank	1	ea	€ 35.00	€ 35.00	
	P7	Cutting, perforating, installing pipes	1	day	€ 100.00	€ 100.00	
	OT2	Stairs	1.75	m	€ 50.00	€ 87.50	
	INS1	Soil Mositure and Temp sensor	15	ea	€ 300.00	€ 4,500.00	
	INS2	Soil Moisture, Temp, Pressure and EC sensor	3	ea	€ 700.00	€ 2,100.00	
	INS4	Tipping bucket	2	ea	€ 200.00	€ 400.00	
	INS5	Cloud Data Logger	3	ea	€ 200.00	€ 600.00	
Total All						**€ 30,657.63**	
Total Site Prep						**€ 2,267.81**	
Total Steep Setup						**€ 15,215.42**	
Total Flat Setup						**€ 13,174.40**	

ITEM NO	ITEM	UNIT	UNIT PRICE*	NOTE / SOURCE OF PRICE ESTIMATE
SG	**SITE AND GROUND WORK**			
SG1	Clearing and Grubbing	m2	€ 2.00	
SG2	Tree trimming	ea	€ 25.00	Snoeiservice
SG3	Excavation	m3	€ 5.00	Uitgraven, zoofy.nl = 12.5 to 17.5 /m2
SG4	Trench excavation	m3	€ 10.00	Uitgraven, zoofy.nl = 12.5 to 17.5 /m2
SG5	Access road grading	m2	€ 10.00	
SG6	4/20 Gravel	m3	€ 100.00	Grind 8/16, rowill.nl
SG7	Sand and Loam	m3	€ 100.00	Zand per m3, grondverzet.nu
SG8	Installation and compaction of soil	m3	€ 5.00	
SM	**STRUCTURAL MATERIALS**			
SM1	Structural foil	m2	€ 5.00	
SM2	Precast concrete reatining wall 3.5 m	ea	€ 600.00	Must requesta quote to see prices
SM4	Precast concrete reatining wall 2.5 m	ea	€ 500.00	The L-shaped reatining walls in the Green Village are from Kemper.nl, see products available here
SM5	Precast concrete reatining wall 2.0 m	ea	€ 450.00	https://www.kemper.nl/producten/keerwanden/dubbelkerende-keerwanden
SM6	Precast concrete reatining wall 1.75 m	ea	€ 400.00	
SM7	Precast concrete reatining wall 1.5 m	ea	€ 350.00	
SM8	2 m tension cables	ea	€ 50.00	
SM9	Impermeable plastic	m2	€ 1.00	Vochtscherm, Gamma, .73/m2
SM10	Root-resistance geotextile	m2	€ 1.52	Worteldoek, zwartgroen.nl, 795/520 m2
SM11	Thin structural barrier	m2	€ 10.00	could be metal or rubber
P	**PLUMBING**			
P1	Sampling access pipes (1" PVC)	m	€ 2.66	gamma
P2	Drainage pipe (4" PVC)	m	€ 7.69	gamma
P3	Sampling pipe connections (1" PVC)	ea	€ 1.50	gamma
P4	Drainage pipe connections (4" PVC)	ea	€ 1.50	gamma
P5	Drainage pipe valves (4" PVC)	ea	€ 3.50	gamma
P6	1 m3 water tank	ea	€ 35.00	https://www.witgoedhandel-dezwaan.nl/product/ibc-container-1000-liter/
P7	Cutting, perforating, installing pipes	day	€ 100.00	
E	**ELECTRICAL**			
EL1	Electrical cable	m	€ 2.00	gamma
EL2	Electrical outlets	ea	€ 10.00	gamma
INS	**INSTRUMENTATION**			None of the websites provide prices, just guessing
INS1	Soil Mositure and Temp sensor	ea	€ 300.00	METER instruments, TEROS 12 ?
INS3	Soil Moisture, Temp and Pressure sensor	ea	€ 500.00	
INS2	Soil Moisture, Temp, Pressure and EC sensor	ea	€ 700.00	
INS4	Tipping bucket	ea	€ 200.00	
INS5	Cloud Data Logger	ea	€ 200.00	METER instruments, ZL6 ?
INS6	Weather Station	ea	€ 0.00	Provided by another project (Contact Arjan Drost)
OT	**OTHER**			
OT1	Live Pole Drain	ea	€ 50.00	
OT2	Stairs	m	€ 50.00	
OT3	Platform	ea	€ 25.00	A two meter platform that can span 2.4 meters and placed across the top of retaining walls

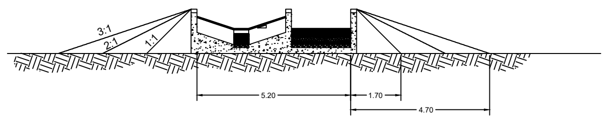
*NOTE, highlighted cells indicate that I have no idea how much the item costs

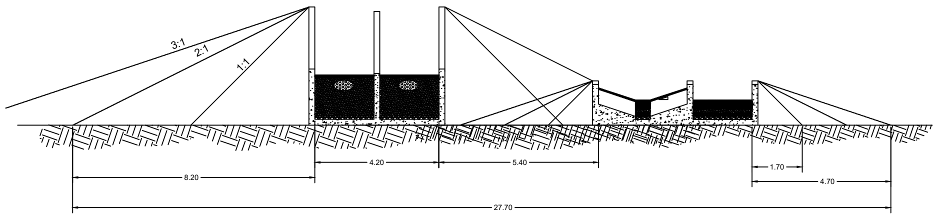
Preliminary Design Ideas

Section A-A

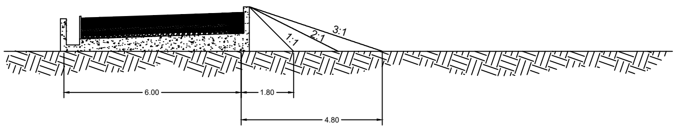


Section B-B

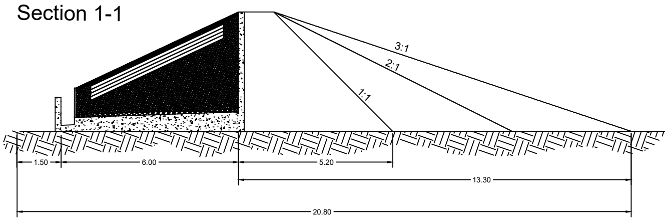


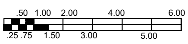


Section 2-2



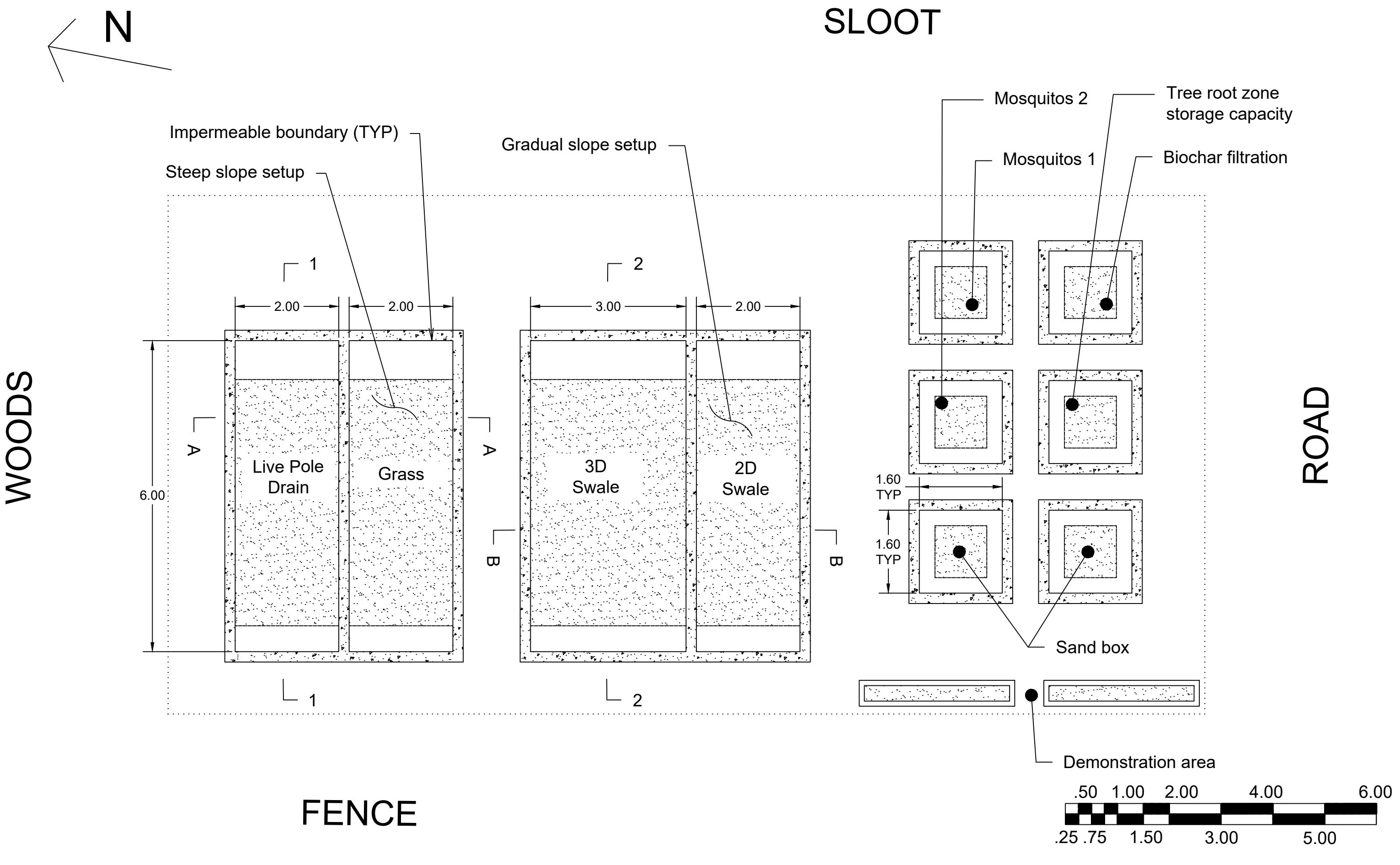
Section 1-1

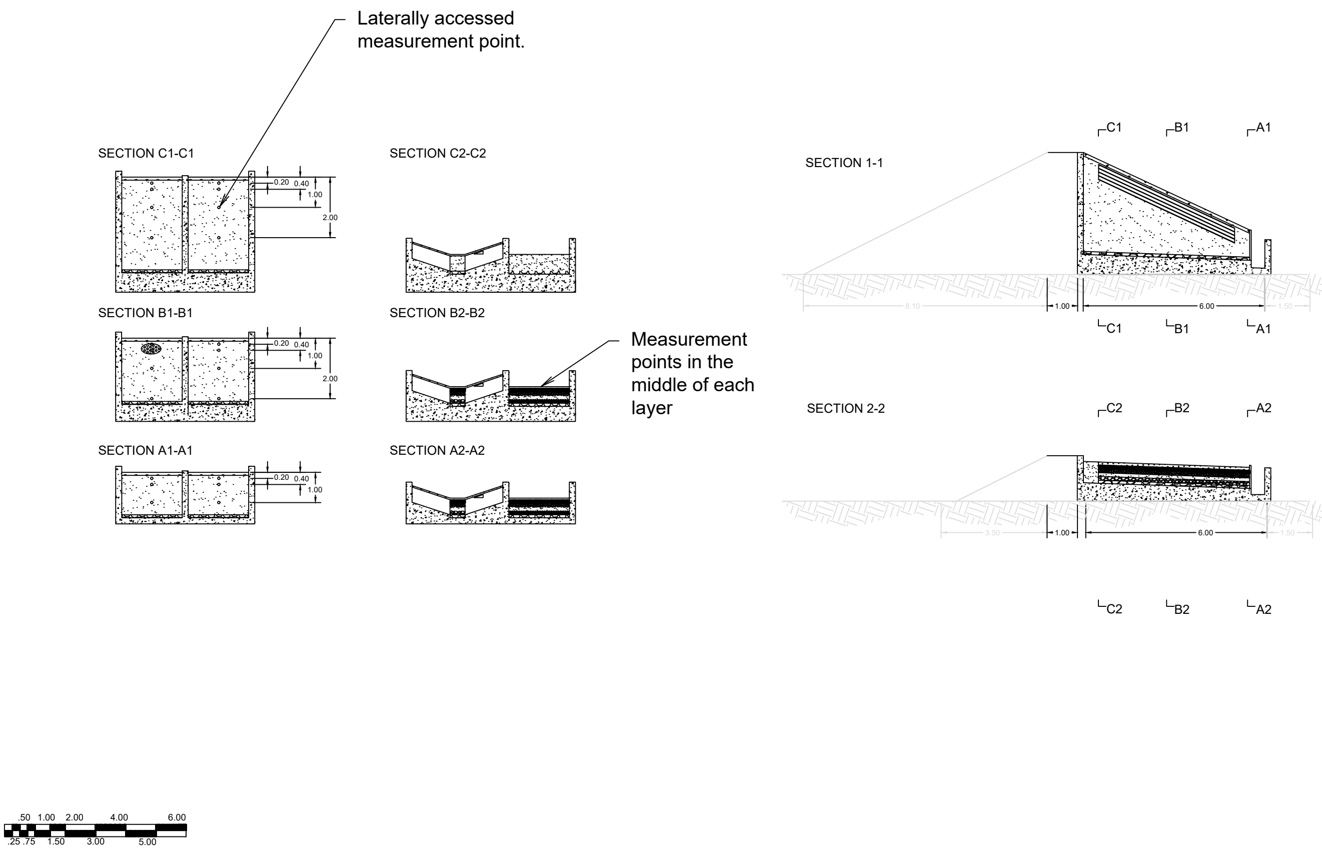


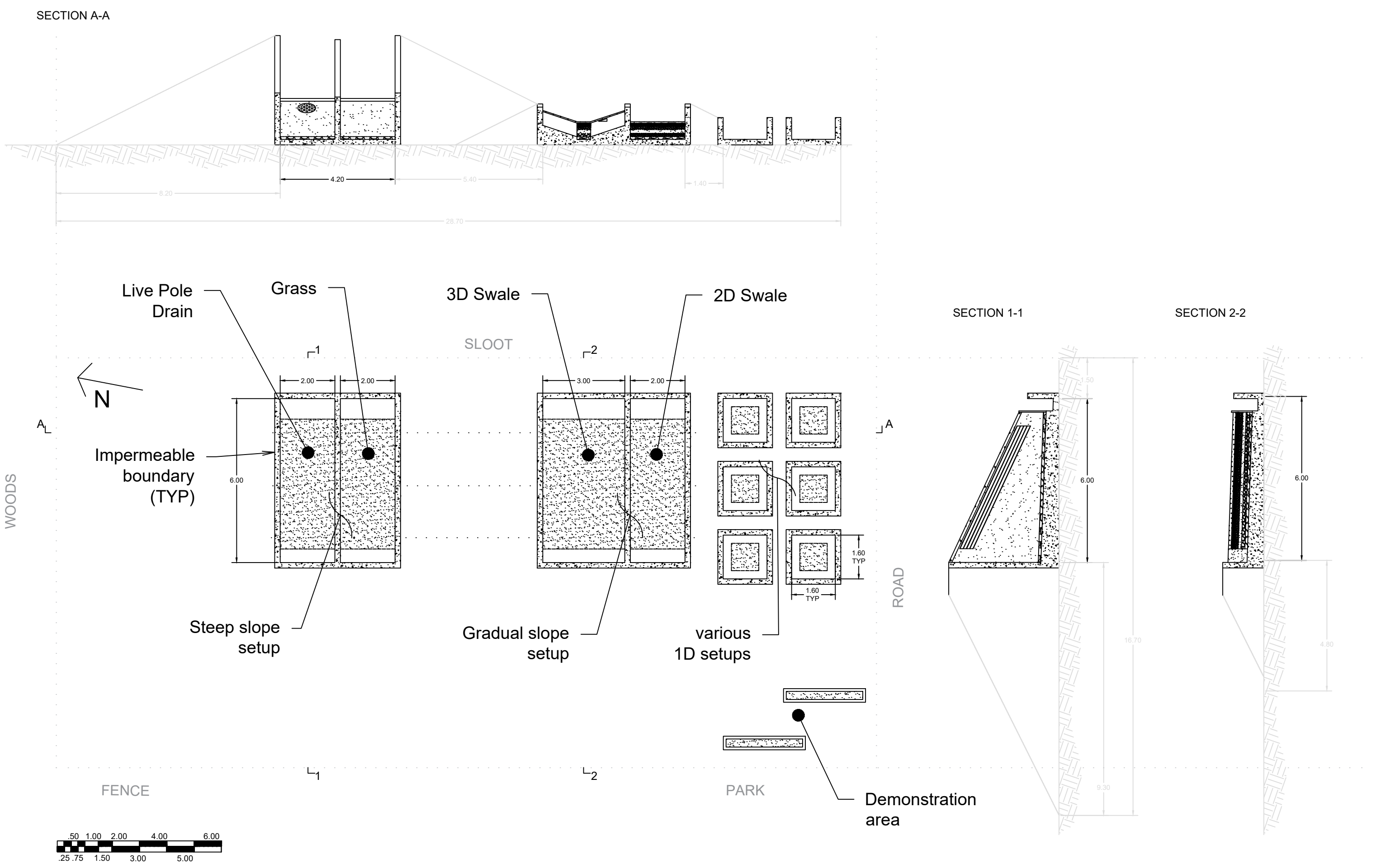


INSTRUMENTATION NOTES:

- Install each set of sensors at top, middle and bottom of slope
- Install sensors from the side where possible.

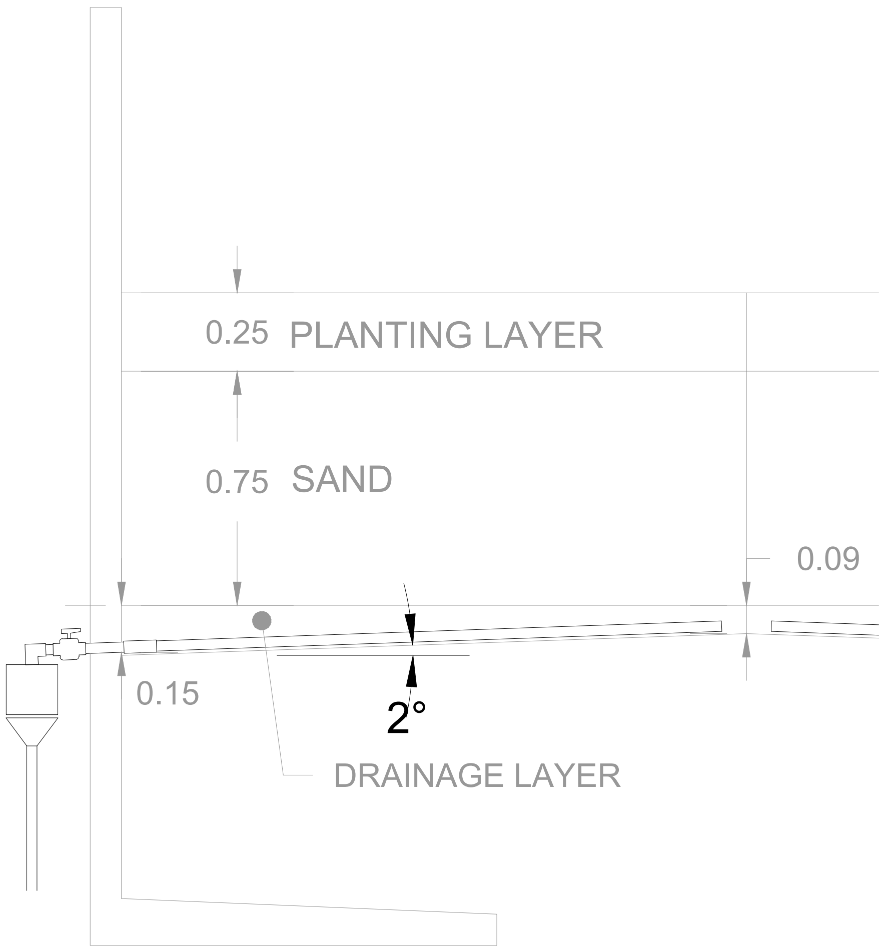

N
SLOOT
WOODS
ROAD
FENCE
Impermeable boundary (TYP)
Steep slope setup
Gradual slope setup
Mosquitos 2
Mosquitos 1
Tree root zone storage capacity
Biochar filtration
Live Pole Drain
Grass
3D Swale
2D Swale
2.00
2.00
3.00
2.00
6.00
1.60 TYP
1.60 TYP
Sand box
Demonstration area
.50 1.00 2.00 4.00 6.00
.25 .75 1.50 3.00 5.00


Laterally accessed measurement point.
SECTION C1-C1
SECTION C2-C2
SECTION B1-B1
SECTION B2-B2
Measurement points in the middle of each layer
SECTION A1-A1
SECTION A2-A2
0.20
0.40
1.00
2.00
SECTION 1-1
C1
B1
A1
1.00
6.00
SECTION 2-2
C2
B2
A2
1.00
6.00
.50 1.00 2.00 4.00 6.00
.25 .75 1.50 3.00 5.00



SECTION A-A
4.20
SECTION 1-1
SECTION 2-2
Live Pole Drain
Grass
3D Swale
2D Swale
SLOOT
N
WOODS
Impermeable boundary (TYP)
2.00
2.00
3.00
2.00
6.00
1.60 TYP
1.60 TYP
Steep slope setup
Gradual slope setup
various 1D setups
ROAD
FENCE
PARK
Demonstration area
.50 1.00 2.00 4.00 6.00
.25 .75 1.50 3.00 5.00

Design Details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SAND
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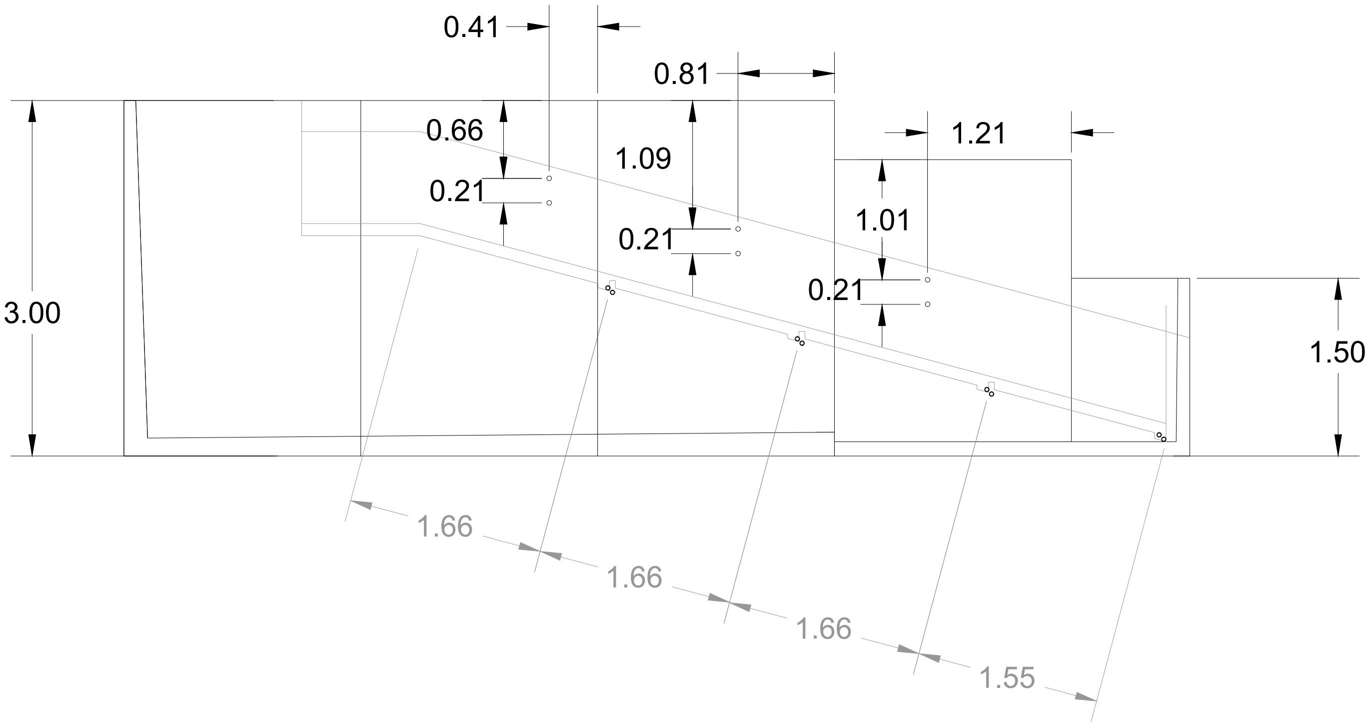
2°
DRAINAGE LAYER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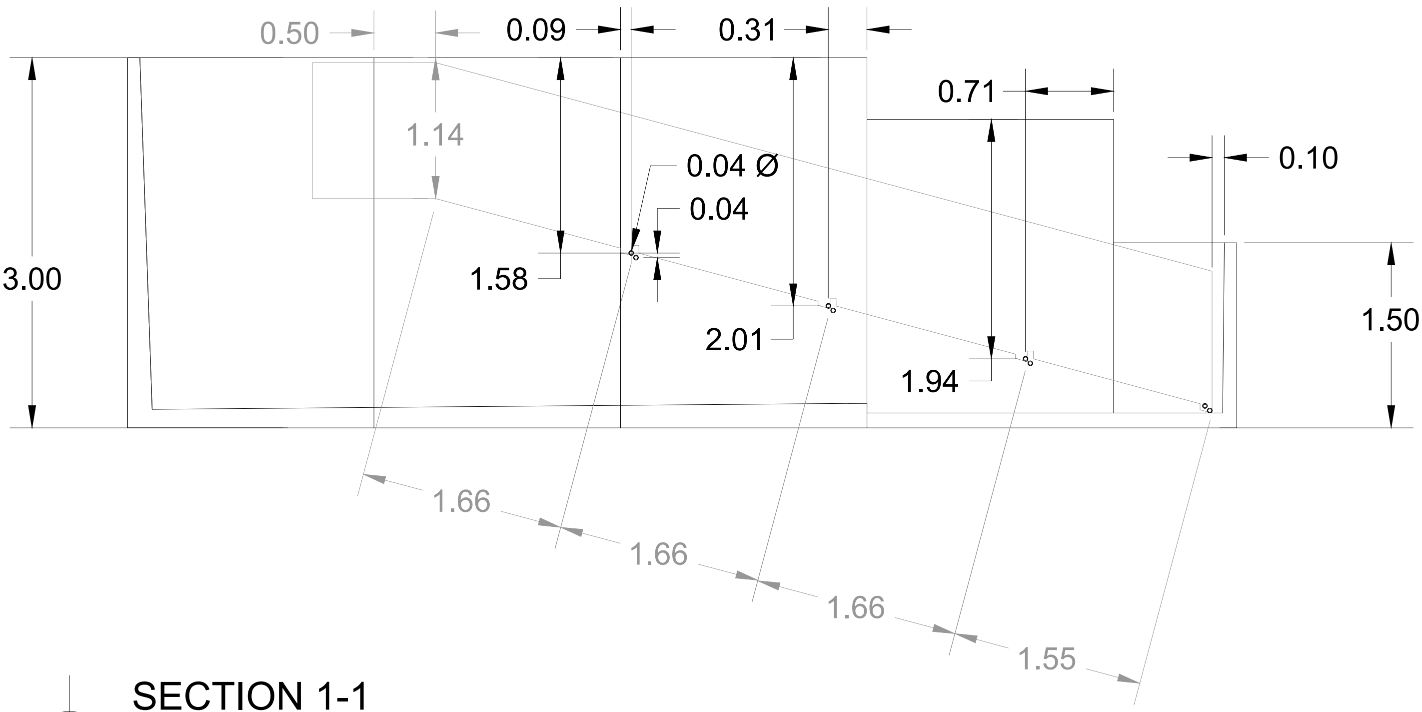
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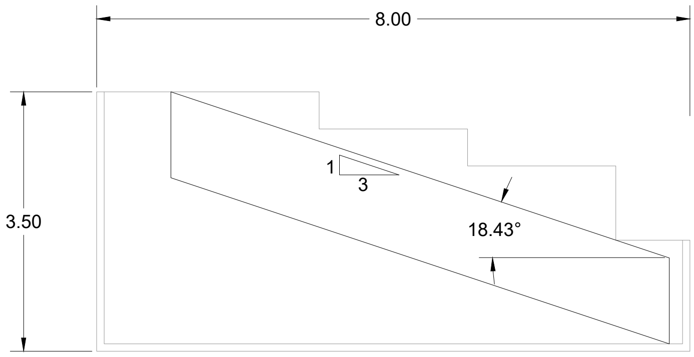
SECTION 1-1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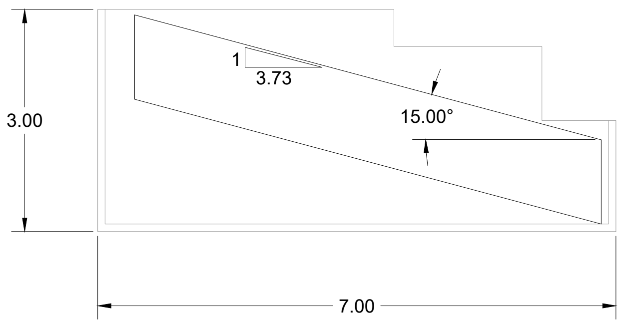
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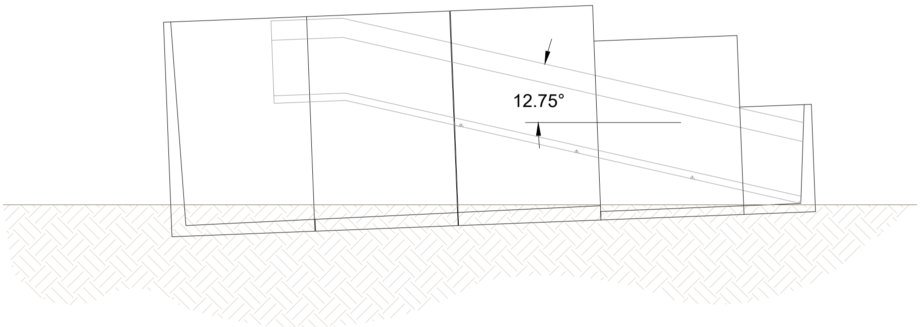
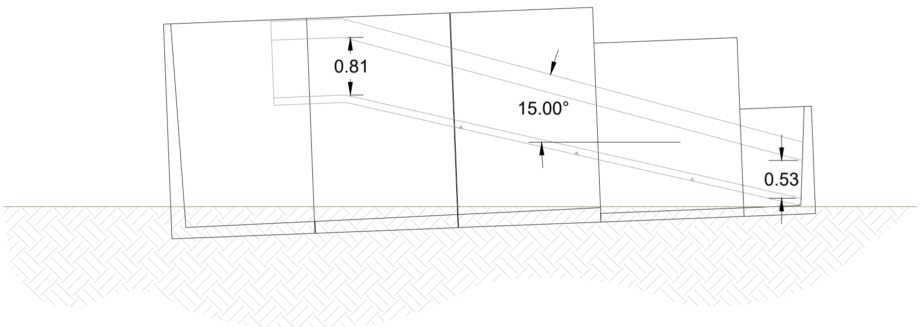
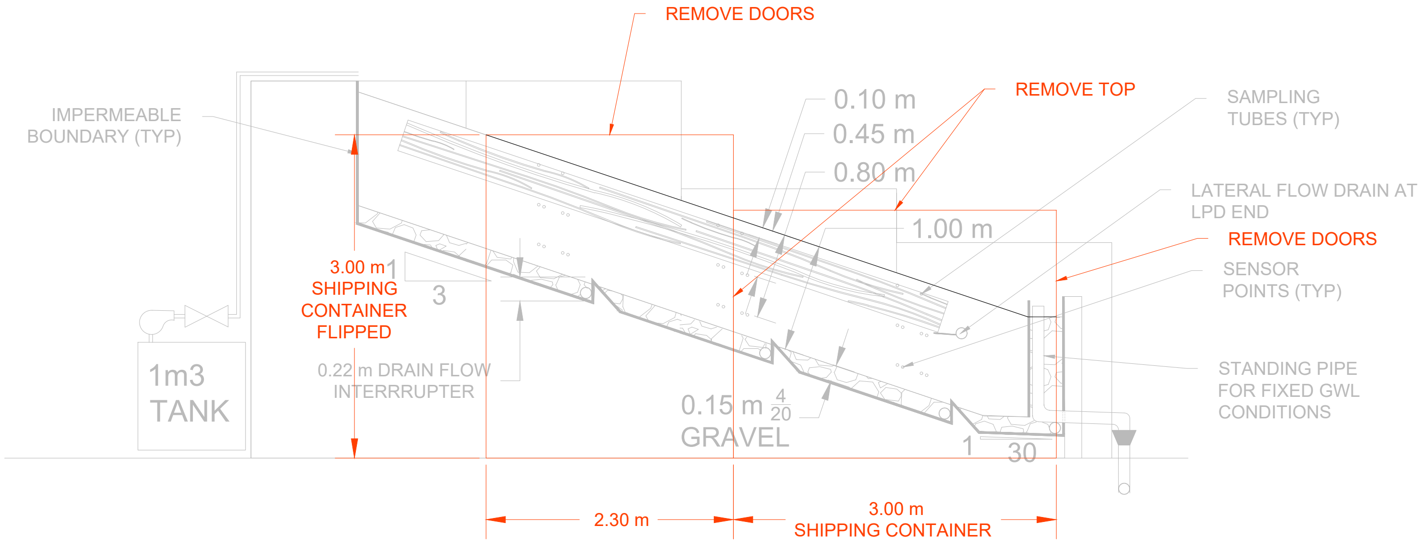
7.00

Settling



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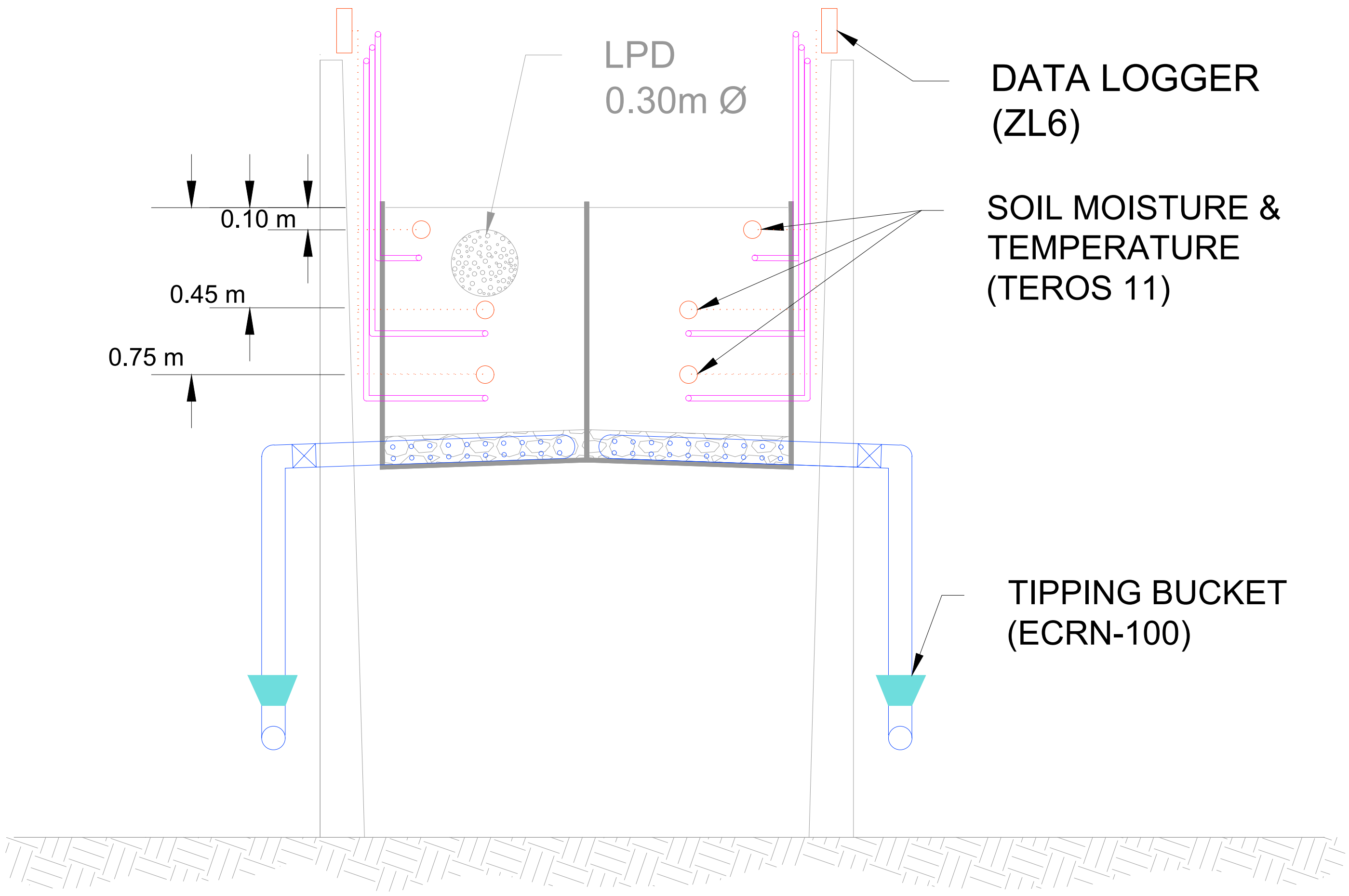
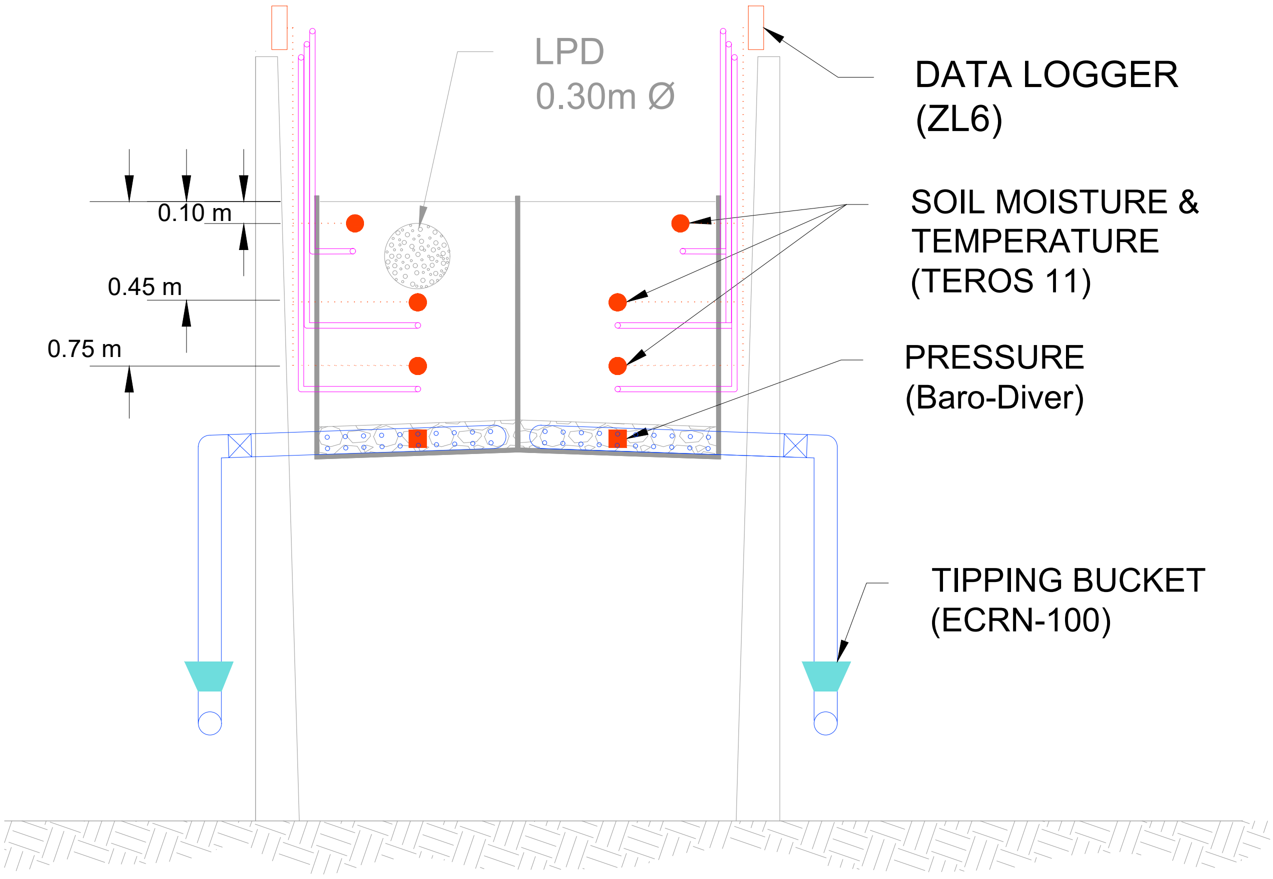
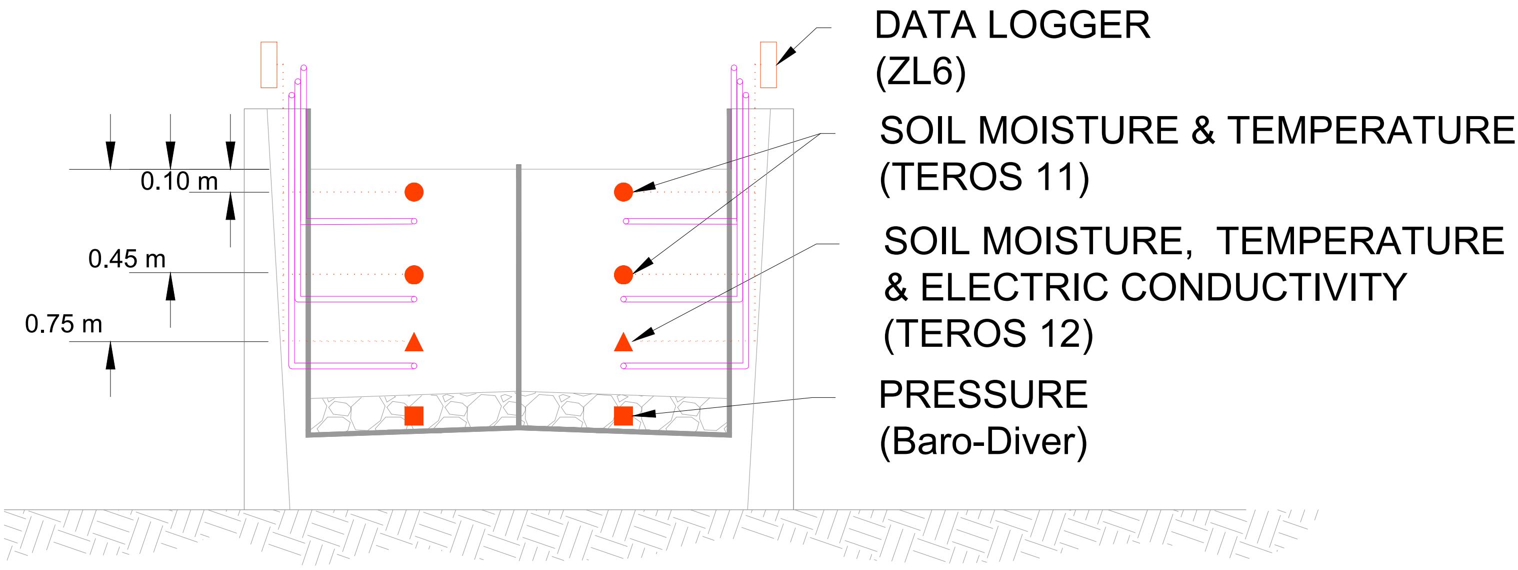
REMOVE TOP
SAMPLING
TUBES (TYP)
IMPERMEABLE
BOUNDARY (TYP)
0.10 m
0.45 m
0.80 m
1.00 m
LATERAL FLOW DRAIN AT
LPD END
REMOVE DOORS
SENSOR
POINTS (TYP)
3.00 m
SHIPPING
CONTAINER
FLIPPED
1
3
0.22 m DRAIN FLOW
INTERRRUPTER
1m3
TANK
0.15 m
4
20
GRAVEL
STANDING PIPE
FOR FIXED GWL
CONDITIONS
1
30
2.30 m
3.00 m
SHIPPING CONTAINER

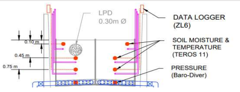
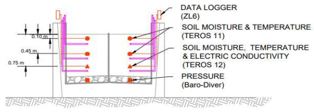
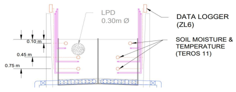
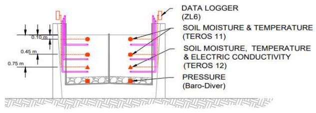
Smart sensors


LPD
0.30m Ø
DATA LOGGER
(ZL6)
SOIL MOISTURE &
TEMPERATURE
(TEROS 11)
0.10 m
0.45 m
0.75 m
TIPPING BUCKET
(ECRN-100)


LPD
0.30m Ø
DATA LOGGER
(ZL6)
SOIL MOISTURE &
TEMPERATURE
(TEROS 11)
PRESSURE
(Baro-Diver)
TIPPING BUCKET
(ECRN-100)
0.10 m
0.45 m
0.75 m



DATA LOGGER
(ZL6)
SOIL MOISTURE & TEMPERATURE
(TEROS 11)
SOIL MOISTURE, TEMPERATURE
& ELECTRIC CONDUCTIVITY
(TEROS 12)
PRESSURE
(Baro-Diver)
0.10 m
0.45 m
0.75 m

ITEM NO.	ITEM	QTY	UNIT	UNIT PRICE	TOTAL	NOTE
SENSORS - Three measuring x-sections						
INS1	Weather Station	1	ea	€ 0.00	€ 0.00	From Delft Meet program, no cost
ZENTRA	Cloud standard plan, 12-month, METER	1	ea	€ 199.00	€ 199.00	
Baro-Diver	Pressure and temp diver	1	ea	€ 439.00	€ 439.00	For atmospheric pressure
STEEP SETUP					**€ 10,574.00**	
TEROS11	Soil Mositure and Temp Sensor, METER	18	ea	€ 244.00	€ 4,392.00	 x 3
Baro-Diver	Pressure and temp diver	2	ea	€ 439.00	€ 878.00	
ZL6	Six-Port Data logger, METER	4	ea	€ 816.00	€ 3,264.00	
ECRN-100	Tipping bucket	6	ea	€ 340.00	€ 2,040.00	
FLAT SETUP					**€ 11,240.00**	
TEROS11	Soil Mositure and Temp Sensor, METER	12	ea	€ 244.00	€ 2,928.00	 x 3
TEROS12	Soil Moisture, Temp and EC, METER	6	ea	€ 289.00	€ 1,734.00	
TEROS54	Soil moisture 4 depths, METER	0	ea	€ 890.00	€ 0.00	
Baro-Diver	Pressure and temp diver	6	ea	€ 439.00	€ 2,634.00	
ECRN-100	Tipping bucket	2	ea	€ 340.00	€ 680.00	
ZL6	Six-Port Data logger, METER	4	ea	€ 816.00	€ 3,264.00	
Total Sensors					**€ 22,452.00**	
SENSORS - Two measuring x-sections						
INS1	Weather Station	1	ea	€ 0.00	€ 0.00	From Delft Meet program, no cost
ZENTRA	Cloud standard plan, 12-month, METER	1	ea	€ 199.00	€ 199.00	
Baro-Diver	Pressure and temp diver	1	ea	€ 439.00	€ 439.00	For atmospheric pressure
STEEP SETUP					**€ 5,240.00**	
TEROS11	Soil Mositure and Temp Sensor, METER	12	ea	€ 244.00	€ 2,928.00	 x 2
ZL6	Six-Port Data logger, METER	2	ea	€ 816.00	€ 1,632.00	
ECRN-100	Tipping bucket	2	ea	€ 340.00	€ 680.00	
FLAT SETUP					**€ 7,114.00**	
TEROS11	Soil Mositure and Temp Sensor, METER	8	ea	€ 244.00	€ 1,952.00	 x 2
TEROS12	Soil Moisture, Temp and EC, METER	4	ea	€ 289.00	€ 1,156.00	
TEROS54	Soil moisture 4 depths, METER	0	ea	€ 890.00	€ 0.00	
Baro-Diver	Pressure and temp diver	2	ea	€ 439.00	€ 878.00	
ECRN-100	Tipping bucket	2	ea	€ 340.00	€ 680.00	
ZL6	Six-Port Data logger, METER	3	ea	€ 816.00	€ 2,448.00	
Total Sensors					**€ 12,992.00**	

Live Pole Drain Specification

Live fascine specification for Live Pole Drain

A live fascine is a long bundle of woody vegetation such as small branches and twigs that can sprout. For live pole drains, the twigs and branches of a fascine should be oriented in the same direction, in order to insure buds are facing down-slope when installed.

Materials

- Live native willow twigs
- Jute Twine
- Live willow stakes to fix LPD to slope

Fascine specifications

- Diameter 30 cm
- Twigs must be live
- Average twig diameter of 2 cm, max diameter 3 cm
- Twigs must be oriented with tips facing in the same direction
- Tie bundle with jute twine every 1 m, or as necessary to hold fascine together

Figure 1. Live Pole Drain (Polster, 2003)

References

Live Fascines, Riparian Habitat Restoration https://riparianhabitatrestoration.ca/575/livefascines.htm

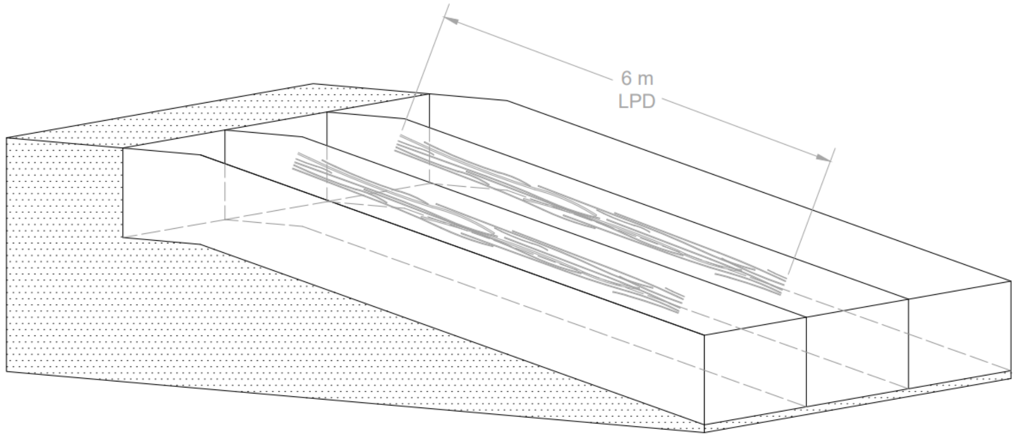
Live Pole Drains, LARIMIT https://www.larimit.com/mitigation_measures/1028/

Polster, D. F. (2003). Soil bioengineering for slope stabilization and site restoration. *Mining and the Environment*, *3*, 25-28. https://botanicgardens.uw.edu/wp-content/uploads/sites/7/2013/12/SoilBioengineeringForSlopeStabilizationAndSiteRestoration.pdf

Fascines and stakes required for TU Delft experimental live pole drain (LPD) setup

We are studying the hydrological behaviour of LPDs on an artificial slope, see images below. For this, we require:

- Two fascines of 6 m total length each. These may be built as a single fascine of full 6 m length, or made up of two or three bundles of 3 m or 2 m length, respectively.
- 12 stakes of diameter 3 to 5 cm, and length 50 cm.



Swale Design

Some relevant swale design guidelines from CIRIA

Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. (2007). *The SUDS manual* (Vol. 697). London: Ciria.

Input Parameters		
swale width	0.65	
swale length	5.4	
slope	2%	
mannigns n, below grass	0.35	Reconmended in CIRIA p318
mannings n, above grass		depends on flow depth see fig 17.7

Calculation	**Design guide**	
Mannings Eq	section 24.11.11	
Infiltration design calc	section 25.6	n/a
No infiltration design	section 24.8	
peak flow control design	section 17.4.3	n/a
exceedance flow design		n/a
Underdrain	section 18.8.2	

Materials	**Material**	**Design guide**
Vegetation	turf	best practices chp. 29
Erosion control while vegetation establishes	straw	
Planting	Teelgrond	
Filter	Drainage sand	Min d50=250um
Drain	4/20 gravel	

Design requiremnets				
Check	**max**	**min**	**rec'd**	**design**
Width	2	0.5		0.65
Longitudinal slope	6%	0.50%		2%
Side slope	33%		25%	
Depth	0.6			
Max flow velocity [m/s]	1			
Vegetation height [mm]	150	75		
Design event flow depth [mm]				
Design event flow velocity [m/s]				
Residence time [min]		9		
Underdrain flow capacity [l/s/ha]		2		
Flow depth < vegetation height				
Design event – 1:1 year event, for road typically 15 minute event				

Maintenance	Chapter 32
mowing	
removing litter and debris	
Water Quality	
Removal efficiencies of swales	Chapter 26, annex 3
Biodiversity	
Biodiversity guidelines	Chapter 6

Construction Time Line

Calendar of Construction Activities

Involving:
Dennis, Jan and Stevenof van der Ent contracting (completed heavy work, incl. when no names are mentioned)
Linnaea Cahill, MSc student (present thorughout, incl. when no names are mentioned)
(JP) Jean-Paul of the Green Village and Flood Proof Holland
Thom Bogaard, project lead
Job van der Werf, Water Management Department
Bokuretsion Estifanos, Waterlab
Fernanda Berlitz, visitng PhD stsarting in Jan 2024

08/05/2023	Mon	Site walk
15/06/2023	Thu	Site clearead by van der Ent contracting, supervised by Jean-Paul
23/06/2023	Fri	Site walk and layingout footprints with Thom, Job, Jean-Paul
02/10/2023	Mon	Structural elements delivered
17/10/2023	Tue	Structural elements delivered, flat setup structure partially erected by van der Ent contracting, supervised by Jean Paul and Linnaea. Mistake in material delivery and installation. New elements ordered to arrive later in the week
18/10/2023	Wed	Collecting drainage materials from gamma, hornbach and the water lab storage. Foundation sand of large setup installed
19/10/2023	Thu	
20/10/2023	Fri	
21/10/2023	Sat	
22/10/2023	Sun	
23/10/2023	Mon	Erection of flat structure by van der Ent
24/10/2023	Tue	Start of erection of steep structure. Noticed there are two extra 3 x 2 m elements. Deciding what to do based on price difference. keep elements, make setup longer
25/10/2023	Wed	No work on site, JP hears back from concrete elements, decision to keep extra elements
26/10/2023	Thu	No work on site due to traffic, Dennis didn't make it
27/10/2023	Fri	Setup is sinkign into the ground, decision to improve base with "repak", i.e. crushed concrete debris. "Bauwvolgorde" document sent to Dennis
28/10/2023	Sat	
29/10/2023	Sun	
30/10/2023	Mon	Improvement of the 'grote bak' foundation
31/10/2023	Tue	Re-erection of structure in progress. Visit TGV to see available materials. Frans and Jan on site. Discuss boring with Jan
01/11/2023	Wed	Deciding on sand type with Jan's book
02/11/2023	Thu	Drilling started by Jan
03/11/2023	Fri	
04/11/2023	Sat	
05/11/2023	Sun	
06/11/2023	Mon	No work, Jan was sick
07/11/2023	Tue	70 2x2 m Stelcon plates delivered
08/11/2023	Wed	
09/11/2023	Thu	Installing spanning wires to keep the setup aligned by Jan, Plastic orered from Joosten Kuntstoffen.
10/11/2023	Fri	Drilling continues, fillign steep setup with sandy ground as base fill
11/11/2023	Sat	
12/11/2023	Sun	
13/11/2023	Mon	Drilling finalized
14/11/2023	Tue	Base fill on steep setup finalized, worteldoek ready to install. Sent Jan dimensions for dividers
15/11/2023	Wed	LDPE will be delivered, no digger on site
16/11/2023	Thu	Dividers installed by Jan
17/11/2023	Fri	Drainage layer plastic and pipes installation, big setup
18/11/2023	Sat	
19/11/2023	Sun	
20/11/2023	Mon	Drainage layer plastic and pipes installation, big setup
21/11/2023	Tue	Gravel installed, big setup. Site visit by Ekaterina, PhD candidate interested in research there?
22/11/2023	Wed	
23/11/2023	Thu	Jan & Steven at TGV - no work at FPH
24/11/2023	Fri	Jan & Steven at TGV - no work at FPH
25/11/2023	Sat	
26/11/2023	Sun	
27/11/2023	Mon	No work due to rain
28/11/2023	Tue	Fill setup with sand
29/11/2023	Wed	
30/11/2023	Thu	
01/12/2023	Fri	
02/12/2023	Sat	
03/12/2023	Sun	
04/12/2023	Mon	Install sensors Linnaea + Thom - note Structure is settling,
05/12/2023	Tue	Borrowing pump from Water lab, for experiemnts Linnaea and Bokure torubleshooting pumps
06/12/2023	Wed	
07/12/2023	Thu	Field experiemnts, falling head and applying large volume of water at top of slope.
08/12/2023	Fri	Pump tube breaks, no further experiments, Jan installs braces to keep structure straight.
09/12/2023	Sat	

10/12/2023	Sun	
11/12/2023	Mon	
12/12/2023	Tue	
13/12/2023	Wed	
14/12/2023	Thu	Site check, structure settling measured
15/12/2023	Fri	
16/12/2023	Sat	
17/12/2023	Sun	
18/12/2023	Mon	
19/12/2023	Tue	
20/12/2023	Wed	
		Christmas holidays
11/01/2024	Thu	
12/01/2024	Fri	Site check, structure settling measured. Presenting setup to Dies Natalis tour of FPH, Linnaea and Fernanda.
13/01/2024	Sat	
14/01/2024	Sun	
15/01/2024	Mon	
16/01/2024	Tue	
17/01/2024	Wed	
18/01/2024	Thu	
19/01/2024	Fri	
20/01/2024	Sat	
21/01/2024	Sun	
22/01/2024	Mon	LPD materials delivered on site by van Aalsburg, received by Linnaea, however most stakes are not live
23/01/2024	Tue	
24/01/2024	Wed	Tree trimming at FPH, Jean-Paul and Linnaea request tree trimmers to set aside some live poles for LPDs
25/01/2024	Thu	Arranging LPD materials into bundles, Linnaea and Fernanda, Jan and helper fix sand layer and move planting soil.
26/01/2024	Fri	Reinstallign sensors in sand and installing LPDs (Linnaea and Fernanda), Jan and helper install planting soil

Proposed Monitoring Activities

Parameter	Measurement method	(commercial name)	Measurement frequency	Measuremnt location	Source	Notes
Vegetation Parameters						
Allometry	Measure and correlate		seasonally	field	Muukkonen, 2006	
Leaf Area Index (LAI)	SLA per Wolf, 1972, with non destructive adaptation based on Allometric relationships		seasonally	field + lab	Wolf, 1972	
Canopy crown area (Ac)	Photos		seasonally	field		
Mean above ground biomass	Extrapolate from SLA with Allometric relationships		seasonally	field + lab	Muukkonen, 2006	
Diameter at breast height (DBH)	Measuring tape		yearly	field + lab		Not necessary for a few years
Photosynthetic and transpiration rate	CO2 Flux chamber		portocol TBD	portocol TBD		
Pull-out capacity/resistance	destructive, methodology TBD		portocol TBD	portocol TBD		
Root biomass	destructive, methodology TBD, estimation based on RSR		portocol TBD	portocol TBD		
Root length and Volume	destructive, methodology TBD		portocol TBD	portocol TBD		
Root length density (RLD)	destructive, methodology TBD		portocol TBD	portocol TBD		
Root tensile strength	destructive, methodology TBD		portocol TBD	portocol TBD		
Root Cellulose content	destructive, methodology TBD		portocol TBD	portocol TBD		
Soil Parameters						
Soil sample hydraulic conductivity	ISO standard		yearly	Lab		
In-situ soil permeability	Falling head test		yearly	Field		
Soil Dry bulk density	ISO standard		yearly	Lab		Drying oven available from Hydraulics lab
Soil shear strength	ISO standard		yearly	Lab	See Benschop, 2022	Triaxial test availabel from Geoscience Lab
Soil internal friction angle	ISO standard		yearly	Lab		
Soil organic matter content	ISO standard		yearly	Lab	Tabatabai, 1986	
Soil drained cohesion	ISO standard		yearly	Lab		
Soil cohesion	ISO standard		yearly	Lab		
Soil biodiversity	custom protocol		seasonally	Field		
Soil State						
Soil Matric suction (ua-uw)	Field Tensiometer (Irrometer)	TEROS21	Data logger 15-minutes	Field		
Soil (volumetric) moisture content (Θ)	Moisture sensor	TEROS11 and TEROS 12	Data logger 15-minutes	Field		
Electric conductivity	EC sensor	TEROS12	Data logger 15-minutes	Field		
Temperature	Temperature sensor	TEROS11 and TEROS 12	Data logger 15-minutes	Field		
Ground water level	Pressure sensor	TD diver	Data logger 15-minutes	Field		
Fluxes						
Stemflow	install gutter around larger stems.			Field	(Gonzalez-Ollauri and Mickovski, 2017)	Not necessary for a few years
Throughfall	capture throughfall in gutters or rain gauges			Field	(Gonzalez-Ollauri and Mickovski, 2017)	Note necessary for a few years
Lateral and percolation out-flows	Tipping bucket	ECRN100	Data logger 15-minutes	Field		
Precipitation	Weather Station	Alecto, Delft Meet Regen program	Data logger 15-minutes	Field		
Evaporation	Estimation, with weather station data				Penman, 1948; Monteith, 1965	

D Appendix: Lab Protocols

D.1 Bulk Density, Soil Moisture and Porosity

Materials:
- Analytical balance of resolution +-0.001g,
- Drying oven at 105C,
- Trays,
- Undisturbed soil samples

Method:
1. Find volume of undisturbed sample (V1),
2. weigh trays (MC),
3. add wet soil sample and weigh (M1),
4. dry samples in oven set to 105C for 24 hours,
5. weigh dry samples (M2).

Calculation:
- Bulk density (ρ) = ((M2+MC) - MC) / V1
- Soil moisture (θ) =((M1+MC)-(M2+MC))/((M2+MC)-MC) x100
- Porosity (∅) = 1 - (bulk density / particle density), assume constant Particle density = 2.65

D.2 Particle Size Analysis Protocol - Wet Sieve

Figure 28: Wet sieve analysis

D.3 Particle Size Analysis Protocol - Dry Sieve

Materials:
- Drying Oven
- Analytical scale
- Sieve analysis equipment (sieves and shaker)
- Aluminium Trays

Safety measures: Always use glove and tongs to place and remove samples oven.

Method:
1. Oven dry sample at 105C for 24 hours
2. Weigh a dry soil sample which should be at least 500gr.

3. Record the weight of the sieves and the pan that will be utilized during the analysis. Each sieve should be thoroughly cleaned up before the test.
4. Assemble the sieves in ascending order, placing those with the larger openings on top. Therefore, the No. 4 sieve should be on top and the No. 200 sieve on the bottom of the stack.
5. Place the soil sample into the top sieve and place a cap/lid over it.
6. Place the stack in a mechanical shaker and shake for 10 minutes
7. Remove the sieve stack from the shaker and measure the weight of each sieve and that of the pan placed at the bottom of the stack.

Figure 29: Dry sieve setup

D.4 Soil texture by feel method

Ribbon test: Place soil ball between thumb and forefinger and gently push it with your thumb, squeezing upward. Try to form a ribbon uniformly 1/8 thick, allowing it to emerge and extend over the forefinger until it breaks under its own weight. note length and texture.

D.5 Organic Matter Content by Weight Loss on Ignition Protocol

Materials:
- Drying oven
- Muffle furnace
- Aluminium trays
- Analytical scale

Safety measures: Wear appropriate PPE when operating the muffle furnace: glasses, lab coat, N95 mask. Always use glove and tongs to place and remove samples from furnace.

Method:
1. Oven dry sample at 125C for 24 hours
2. Record the weights of trays (MC)
3. Weigh dry soil samples which should be at least 10gr (M1+MC)
4. Pre-heat Muffle furnace to 400C
5. Place samples in oven with glove and tongs, note location of each sample in the oven as permanent marker will disappear on ignition.
6. Samples in oven for 2 hours at 400C
7. Remove samples from oven and allow to cool
8. Weigh samples (M2+MC)

Calculation:
- Organic matter (OM%) = ((M1+MC)-(M2+MC))/((M2+MC)-MC) x100

D.6 Calibration of Soil Moisture Sensors (METER TEROS11 and 12)

Materials:
- 4 litres of soil sample
- Drying oven
- > 4 litre container / bucket
- Analytical scale
- Volumetric beaker
- Large tray/container for air drying and mixing soil
- 2mm sieve
- Trays

Method:
1. See instructions video from METER: `https://www.youtube.com/watch?v=eq_2VhcXxfI`
2. Collect representative soil sample, around 4 litres.
3. Air dry sample in large tray
4. Sieve soil through 2mm sieve
5. Select container large enough to
6. Layer soil in bucket to achieve a similar bulk density to the in-situ soil
7. Reserve a sample of soil and weigh to determine water content.
8. Insert soil moisture sensor, fully covered in soil and take a reading.
9. Remove soil from bucket, add 7ml of water per 100ml of soil and mix well
10. Repeat steps 5 to 8 five or six times to create calibration points.
11. Oven dry reserved samples at 105C for 24 hours to determine water content.
12. Use spreadsheet at meter.ly/soil-specific-calibration to record data

D.7 Non-standard Quick infiltration test

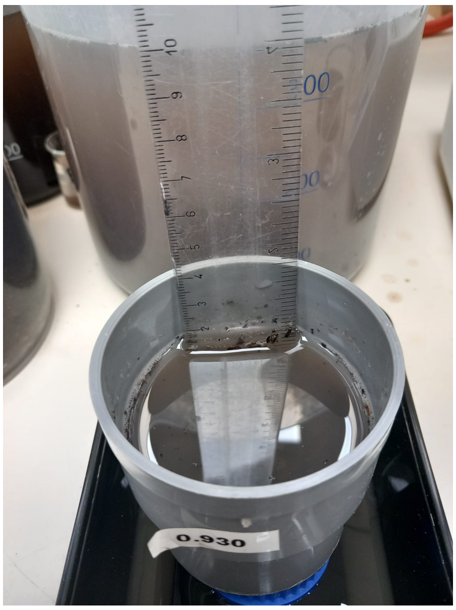


Figure 30: Lab setup for quick infiltration test

2. Quick Infiltration Test
a. Materials
- Cilinder with permeable bottom
- Tray to place cylinder during infiltration test
- Volumetric beaker
- Pipette
- Stopwatch

- Analytical scale
- Weight – for compacting soil

b. Methods
- Weigh empty cylinder (M0)
- Measure cylinder dimensions diameter and depth/length of soil (Dc, Ls)
- Weigh tray (M1)
- Add soil to cylinder with permeable bottom in 4 layers of 1 cm. Note cylinder diameter
- Compact each layer by dropping a flat circular compaction weight of X g and a radius of X cm from a height of X cm. This generates a compaction force of X kN. Repeat 7 times.
- Weigh soil in cylinder (M2)
- Place soil cylinder in tray
- Measure 200 ml of water in a volumetric beaker (V1)
- Add water to soil at a consistent rate using the pipette until it begins to drain from the bottom.
- Note volume of water remaining in the beaker (V2)
- Weigh tray with soil and cylinder (M3)
- Remove saturated soil cylinder and weigh tray again (M4)
- Place saturated soil cylinder in tray.
- Add 3 cm of water to cylinder
- Time water infiltration
c. Calculation
- Soil volume (VS) = pi * $(Dc/2)\hat{2}$ * Ls
- Water retained by soil (V3) = V1 – V2
- Water retention [cm3/cm3] = VS / V3

D.8 Non-standard Quick runoff test

Figure 31: Lab setup for quick runoff test

D.9 Soil Water Retention Curves

SWRC protocol attached. For the GCU setup, the protocol was followed exactly, for the Delft setup, instead of calculating soil moisture from mass, a soil moisture sensor was included in the setup.

(a) (b)

Figure 32: SWRCs, (a) Lab setup for SWRCs at TU Delft, (b) Lab setup for SWRCs at GCU.

D.10 Leaf Area Index

LAI protocol attached.

Figure 33: Leaf Area Index, 100 leaves measured

Water retention function – drying and wetting paths

Materials

- Aluminum cylinder with two monitoring ports
- Plastic lid
- T5 Tensiometers
- CR1000 DataLogger
- Analytical scale
- Water
- Soil

Protocol

DRYING PATH

Steps

a. Final gravimetric moisture content
b. Mass of water at the end of experiment
c. Mass of water at the experiment start
d. Initial gravimetric moisture content
e. Soil moisture content update
f. Retrieve matric suction values from logger file
g. Soil water characteristic curve fit

a) *Final gravimetric moisture content*:

Once the evaporation test has finished, the gravimetric moisture content from a soil subsample or the entire soil column must be determined. To do so, weigh the mass of wet soil (m1) on an empty container of known mass (mc). Place the sample in the oven at 100 C until constant mass (i.e. ca.24 h). Weigh the soil sample+container (m2+mc). Determine the gravimetric moisture content as:

$\theta(\%)=((m1+mc)-(m2+mc))/((m2+mc)-mc) \times 100$

b) Mass of water at the end the experiment:

Multiply the final volumetric moisture content (estimated in 1) by the soil mass in the cylinder (measured at the beginning of the experiment).

c) Mass of water at the experiment start:

Add the mass of water lost throughout the experiment (i.e. scale mass reading at t=0 – scale mass reading at the end of experiment) to the mass of water calculated in 2)

d) Initial gravimetric moisture content:

Divide the mass of water at the experiment start (i.e. calculated in 3) by the mass of soil in the cylinder (measured at the beginning of the experiment). Compare this value with the soil porosity. Remember that soil porosity is calculated as:

∅=1- (bulk density)/(particle density)

Where the particle density is normally assumed to be 2.65 and the bulk density is estimated as: mass of soil/total volume of soil (or cylinder)

e) *Soil moisture update over the series of time steps (see sample spreadsheet)*

Carry out this step using excel or any other spreadsheet. Please, make sure you start the table at the top-left corner of the sheet. Allocate each variable to each column as follows: (i) date/time; (ii) scale reading (i.e. mass; g) ; (iii) water loss ; (iv) moisture content; (v) water mass (g) ; (vi) soil mass (g). Firstly, estimate water mass loss in (iii) by calculating the difference between time steps in (ii). Do this for the whole time series. Then, introduce the initial mass of water in (v) as calculated in 3) and restate the water loss per time step calculated in (iii). Use the values obtained in (v) to estimate the moisture content per time step. This is done by dividing the mass of water at a given time step by the soil mass.

f) Retrieve matric suction values from data logger file

Open the data logger file in excel or any other spreadsheet. Copy the matric suction values from the two tensiometers that “exactly” match in terms of “date and time” with the records taken throughout the evaporation experiment. Paste these values on the spreadsheet created in 5)

g) Soil water characteristic curve fit

Crete SWCC plot lines by assigning values iteratively to α and n (α: inverse of air entry pressure, kPa-1; n: pore –size distribution parameter) in the following equation:

θ(ua-uw)= θr+(θs-θr)x(1/ 〖〖(1+α(ua-uw)〗^n)〗^(1-1/n))

where θr is generally the moisture content at the end of the experiment (calculated in 1), θs is generally the moisture content at the start of the experiment (calculated in 3), and (ua-uw) is the matric suction (kPa). The values given to θr and θs can be adjusted to obtain a better curve fit.
Plot the point cloud obtained throughout the evaporation test and adjust visually the fit between line and points. Estimate the coefficient of determination by fitting the objective function between predictions and observations.

The curve can be fitted for each sensor but it is recommended to use the average between the two or just the top sensor, as the bottom one is subject to capillarity interferences.

WETTING PATH

Follow steps 1 to 6

Step 1: place the soil sample into a perforated aluminum cylinder of known dimensions by compacting the soil slightly into three distinct layers. Weight the initial mass of soil sample available and then the final mass of soil left. The difference will tell the amount of soil in the cylinder and will allow determining the bulk density within the cylinder.
Step 2: prepare a known volume of distilled water (e.g. 250 ml) in a beaker.
Step 3: Add a collar to the top of the cylinder and attach with duck tape. Ideally, the collar should have the same diameter as the testing cylinder. This collar will facilitate the formation of ponding on the soil surface and will prevent the formation of runoff (i.e. all the added water will eventually infiltrate).
Step 4: Insert the tensiometers by the perforated holes in the cylinder. To prevent damaging the sensors, it is advisable to drill the holes first in the soil column. To do so, cover the top of the soil column with a lid to prevent the soil in the column to scape the cylinder. Then, use a sharp stick or drill to make the corresponding holes.
Step 5: Write down the exact time at which the experiment starts. Start the stopwatch and add known volumes of water with a Pasteur pipette. Add new amounts once the previous water added has infiltrated completely. Take note of the amount of water added and the time at which this has been added. Also, take note of when ponding is formed and when percolation occurs. First adds are difficult to monitor, as they occur too quickly. It may be advisable to add and annotate the amounts added and then start annotating the times of the water adds when ponding has formed.
Step 6: Finish the test when the whole soil column is saturated.
Step 7: Remove the sensors from the cylinder and take a sample for moisture content determination.
Step 8: Measure the volume of water left in the beaker for comparison with the total amount of water added during the test.
Step 9: Carry out the required calculations. These involve calculating the moisture content in the soil column at any given time by considering the mass of water added with respect to the mass of soil. For this, it is critical that the soil sample is completely dry at the beginning of the experiment. Extract the matric suction values from the logger file and select the values matching the water adds. These times have to be inferred by adding the testing time elapsed with respect to the starting time annotated at the beginning of the experiment. Create a spreadsheet containing the matric suctions and soil moisture content. Draw and fit the SWCC as for the drying path. Compare both SWCCs (i.e. drying vs. wetting) and discuss in the light of soil hysteresis.

Leaf Area Index (LAI) and dry biomass

Materials

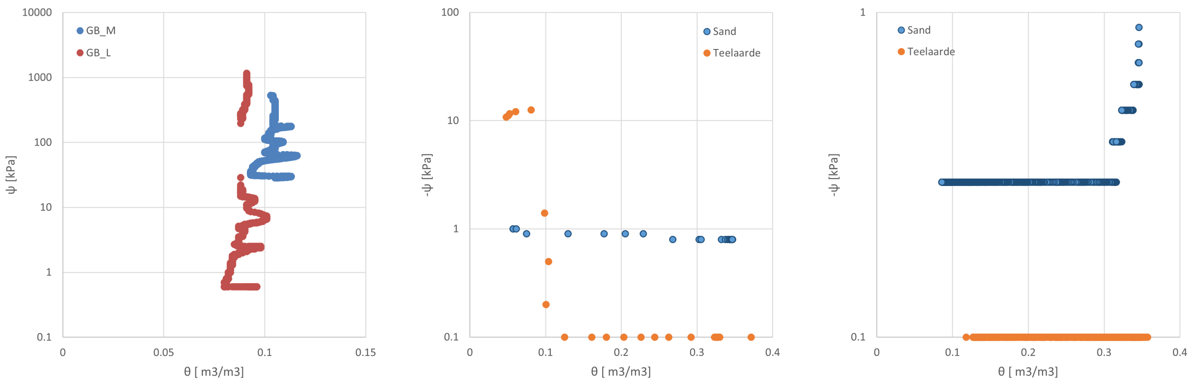
- Scanner
- Aluminum trays
- Oven
- Analytical scale

Protocol

1) Pick a sample of 100 fresh, green leaves randomly
2) Clean the leaves with tap water to remove any dirt and dust
3) Air dry the leaves for 2 hours
4) Proceed to scan the leaves using a regular A4 scanner
5) Weight the fresh, green leaves on the digital scale
6) Oven dry the leaves at 60 C for 24 hours
7) Measure the dry leaves' mass
8) Calculate the total leaf area using Black Spot freeware
9) Calculate the specific leaf area (SLA) by calculating the ratio of the area of the 100 leaves to the total dry mass
10) Quantify the dry mass of all the leaves in the sample branch
11) Calculate LAI by multiplying the total dry mass by SLA
12) Extrapolate LAI on the basis of the total number of branches in the tree and divide by the total crown projected area

E Appendix: Field and Lab Data collected and analysis details

E.1 SWRC



(a) (b) (c)

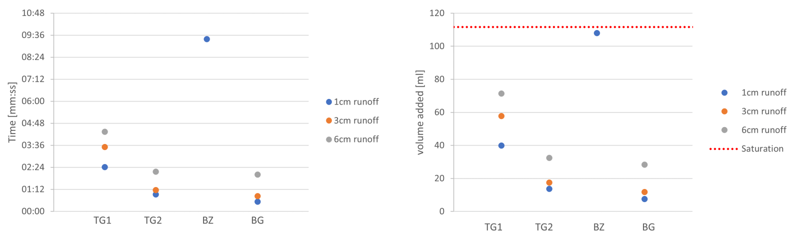
Figure 34: Soil moisture vs matric suction in (a) sand layer in field setup of 15-day duration (b) wetting lab setup of 2-hour duration (c) drying lab setup of 30-day duration.

E.2 Quick infiltration test

(a) (b)

Figure 35: Results of quick infiltration test for Teelgrond (TG), Bomen zand (BZ), and Bomen grond (BG): (a) infiltration rate (b) retained water.

E.3 Quick runoff test



(a) (b)

Figure 36: Results of quick runoff test for Teelgrond (TG), Bomen zand (BZ), and Bomen grond (BG): (a) time to reach runoff distance (b) added volume of water to reach runoff distance.

E.4 Wet sieve test

E.5 Soil moisture sensor calibration

METER

Soil ID:	Drainage Zand
Soil Volume (cm^3)	4000
Container Weight (g)	346.3
Dry Soil Weight (g)	6035.2
Bulk Density (g cm^{-3})	1.51
Sensor Model	TEROS 11

Soil + Container Weights		**wet wt**	**water wt**	***w***	**q**	**Sensor Measurements**	
						Sensor 1	**Sensor 2**
Points	**g**	**g**	**g**	**g g-1**	**m^3 m^{-3}**	**RAW**	**RAW**
Air dry	6466.54	6120.3	85.08	0.0141	0.0213	1931.866667	3.353333333
Point 2	6746.54	6400.3	365.08	0.0605	0.0913	2035.7	5.466666667
Point 3	7026.54	6680.3	645.08	0.1069	0.1613	2103.833333	6.706666667
Point 4	7306.54	6960.3	925.08	0.1533	0.2313	2273.366667	9.146666667
Point 5	7586.54	7240.3	1205.08	0.1997	0.3013	2545.166667	13.44666667

Gravimetric Water Content Calculations of Air Dry Sample		
	Values	**Units**
Wet Soil + Tin	25.7	g
Dry Soil + Tin	25.38	g
Tin Weight	2.36	g
Gravimetric WC, *w*	0.013900956	g g^{-1}

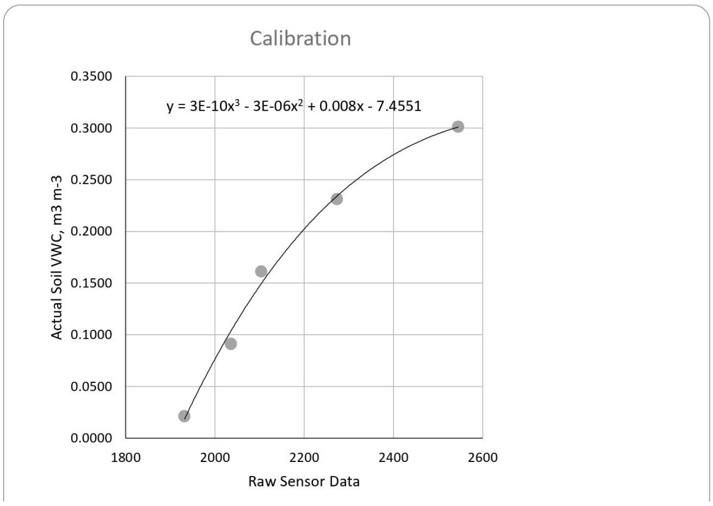
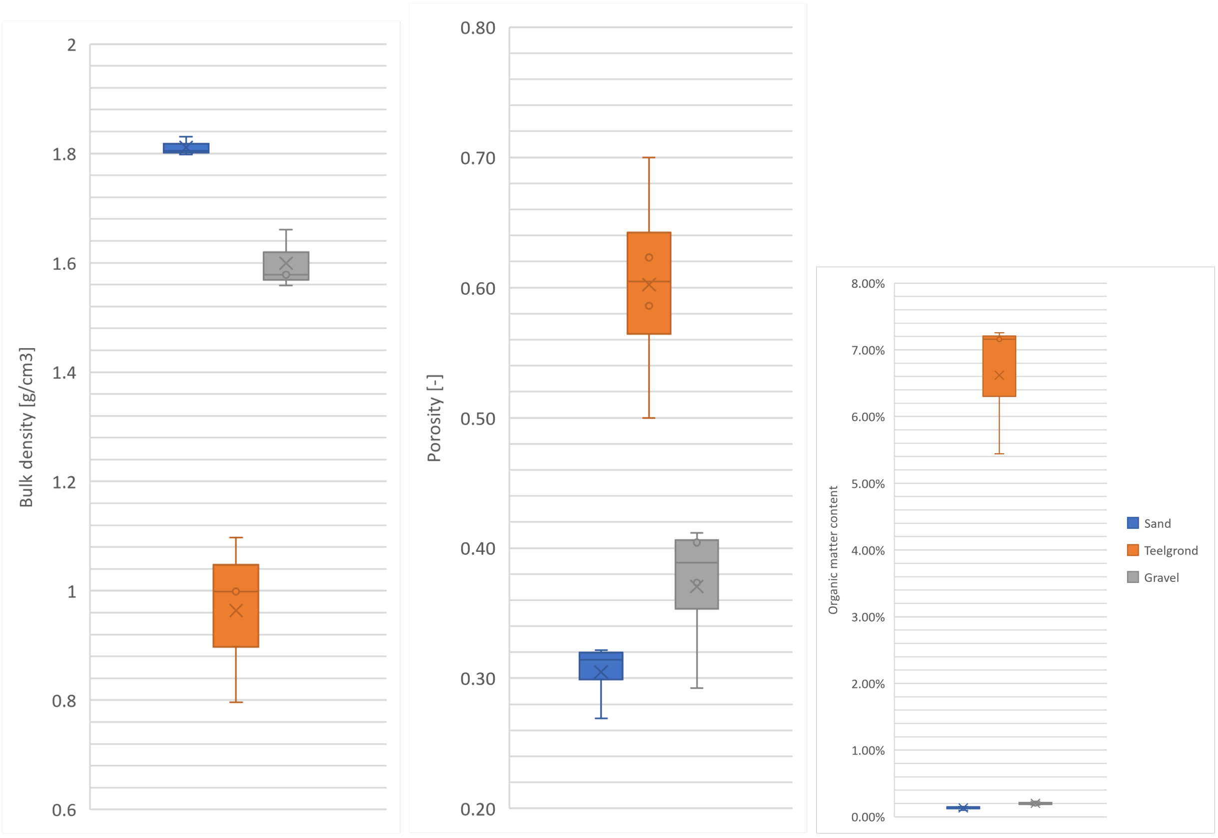


Figure 37: Soil Moisture calibration per METER instruments protocol

E.6 General soil properties - final steep slope setup materials



(a) (b) (c)

Figure 38: Soil properties of sand, gravel, and planting soil (i.e. teelgrond) (a) Bulk density (b) Porosity (c) Organic matter content

E.7 Dry sieve test

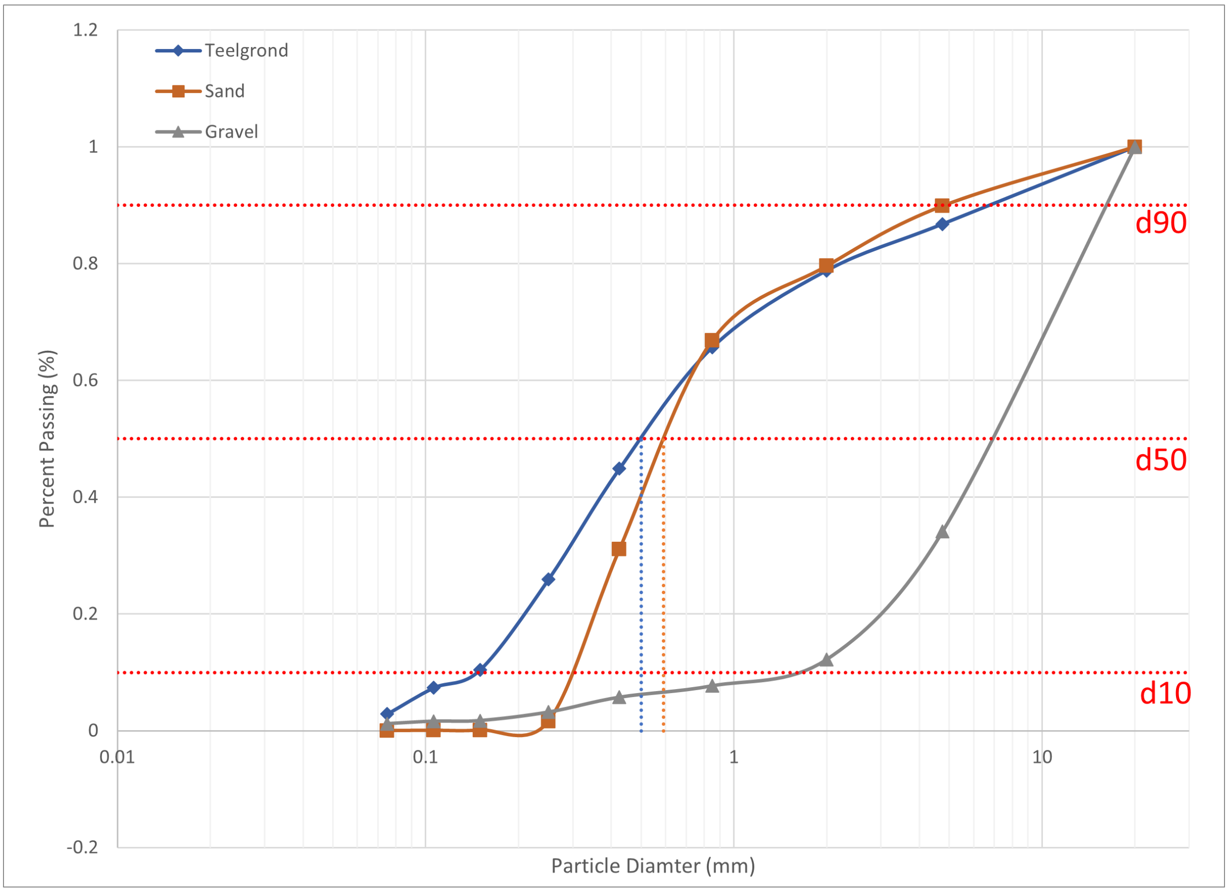


Figure 39: Grain size distribution, dry sieve

E.8 Inverse Auger test for k_{sat} approximation in field

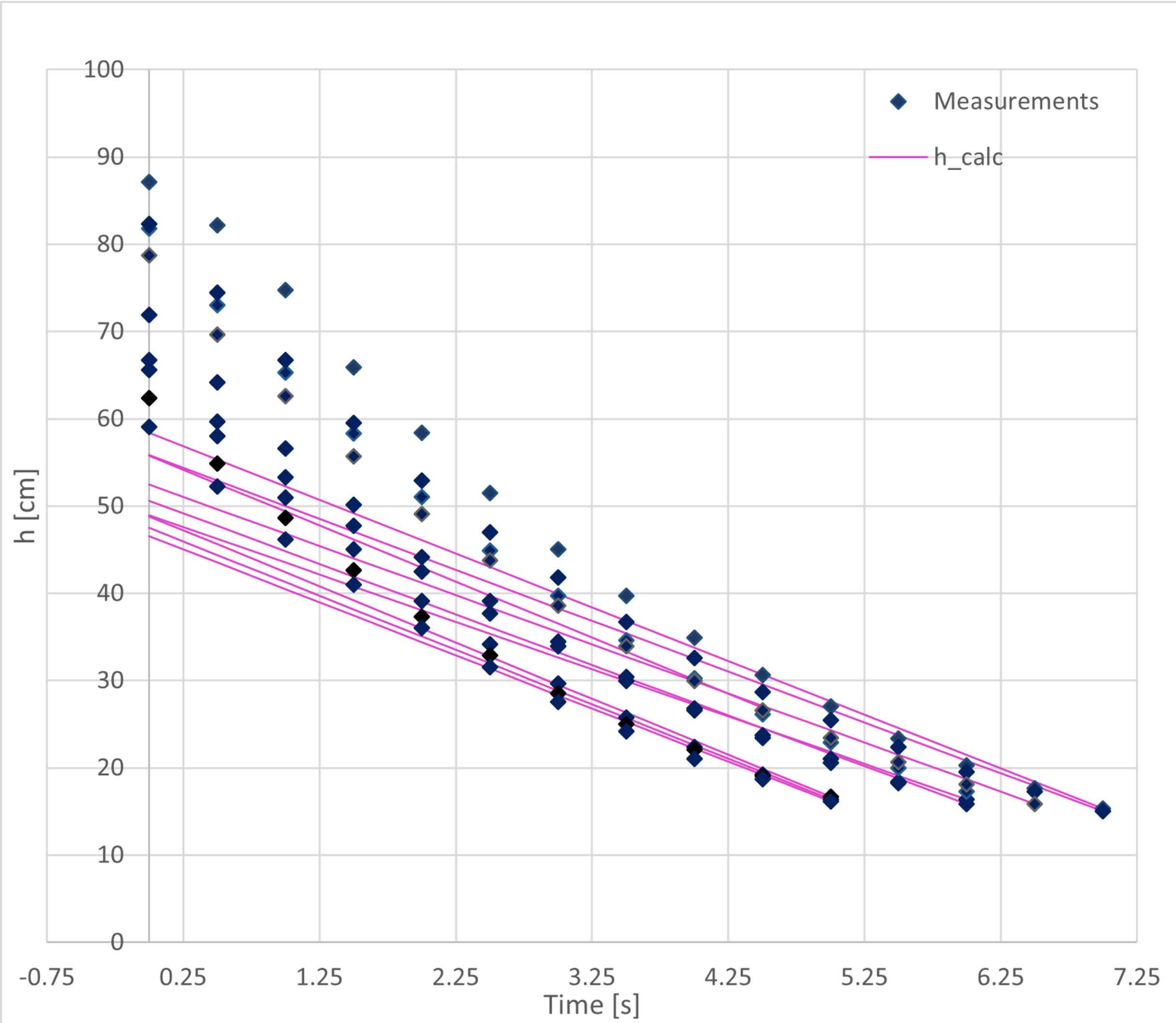


Figure 40: Inverse auger test, k_{sat} calculated as a function of the slope of the falling head curve

F Appendix: Field Protocols

F.1 Plant growth protocol

The following allometric relationships for saplings are recommended for non-destructive SLA and extrapolation, to be measured on a statistically representative sample of plants:

- A. Maximum and median leaf width and length to sapling length.
- B. Number of leaves to sapling length, for saplings with no branches
- C. Branches to shoot length
- D. Number of leaves to branch length
- E. Branches to diameter at breast height for poles.

Use A to calculate individual leaf area per Verwijst & Wen, 1996, and leaf area per shoot length. Use B to extrapolate area to all saplings. Use C and D for saplings with branches. Use E for poles.
Verwijst, T., & Wen, D. Z. (1996). Leaf allometry of Salix viminalis during the first growing season. Tree Physiology, 16(7), 655-660.

F.2 Soil Biodiversity

In addition to the hydrological modelling parameters, we would like to collect data on the ecological function of the setups. Due to the scale of the two setups 30m2/each, I think it would be interesting to look into soil macrofauna diversity.
Some protocols from literature and monitoring initiatives around the Netherlands and the EU (see below), however, before making a decision on what to follow, it would be best to check if there is any ongoing research or monitoring at the TU.

Protocols in consideration

- Soil Macrofauna, Microarthropods, Nematodes, Earthworms, Enchytraeids (ISO, 2006a, 2006b, 2007a, 2007b, 2008)
- IBS-bf: Soil Biodiversity Index of the protocol “Biodiversity Friend” (Caoduro et al, 2014)
- Soil DNA barcoding (Martin-Laurent et al, 2001) (would be a recommendation for future research, not for me to get into) Initiatives checked to find protocols
- EcoFINDERS (Follows ISO and OECD protocols)
- Netherlands Soil Monitoring Network, Biological Indicator for Soil Quality (BiSQ) by RIVM. No sites in Zuid-Holland? (Rutgers et al 2009)
- OPTV Protocole (France) = Earthworm observatory
- Biodiversa+ (collaboration between European and international partners)
- ESDAC (Europe)
- FAO (UN) GEO BON (Global) Partners in Delft are IHE and Deltares, Wageningen is also involved.

Caoduro, G., Battiston, R., Giachino, P. M., Guidolin, L., & Lazzarin, G. (2014). Biodiversity indices for the assessment of air, water and soil quality of the “Biodiversity Friend” certification in temperate areas. Biodiversity Journal, 5(1), 69-86.
Du Preez, G., Daneel, M., De Goede, R., Du Toit, M. J., Ferris, H., Fourie, H., ... & Schmidt, J. H. (2022). Nematode-based indices in soil ecology: Application, utility, and future directions. Soil Biology and Biochemistry, 169, 108640.
Gardi, C., Montanarella, L., Arrouays, D., Bispo, A., Lemanceau, P., Jolivet, C., ... & Menta, C. (2009). Soil biodiversity monitoring in Europe: ongoing activities and challenges. European Journal of Soil Science, 60(5), 807-819.
ISO 2006a. Soil Quality–Sampling of Soil Invertebrates Part 1: HandSorting and Formalin Extraction of Earthworms. ISO 23611-1, Geneva.
ISO 2006b. Soil Quality–Sampling of Soil Invertebrates Part 2: Sampling and Extraction of Microarthropods

(Collembola and Acarina). ISO 23611-2, Geneva.
ISO 2007a. Soil Quality–Sampling of Soil Invertebrates Part 3: Sampling and Soil Extraction of Enchytraeids. ISO 23611-3, Geneva.
ISO 2007b. Soil Quality–Sampling of Soil Invertebrates Part 4: Sampling, Extraction and Identification of Free-Living Stages of Nematodes. ISO 23611-4, Geneva.
ISO 2008. Soil Quality–Sampling of Soil Invertebrates Part 5: Sampling and Extraction of Soil Macrofauna. Draft ISO 23611-5, Geneva.
Martin-Laurent, F., Philippot, L., Hallet, S., Chaussod, R., Germon, J.C., Soulas, G. et al. 2001. DNA extraction from soils: old bias for new microbial diversity analysis methods. Applied & Environmental Microbiology, 67, 2354–2359
Winding, A., Singh, B. K., Bach, E., Brown, G., Zhang, J., Cooper, M., ... & Lindo, Z. (2020). State of Knowledge of Soil Biodiversity: Status, Challenges, and Potentialities.

G Appendix: Catterline Fieldwork

Contents:

- Tree Metrics
- Additional Sensor Data from LPD21 and LPD23
- Allometry, SLA and LAI
- LPD growth metrics visualization code
- Rainfall and Throughfall partitioning
- Lateral Flow Experiments
- Soil Samples for lab analysis and in-situ soil data

Tree metrics

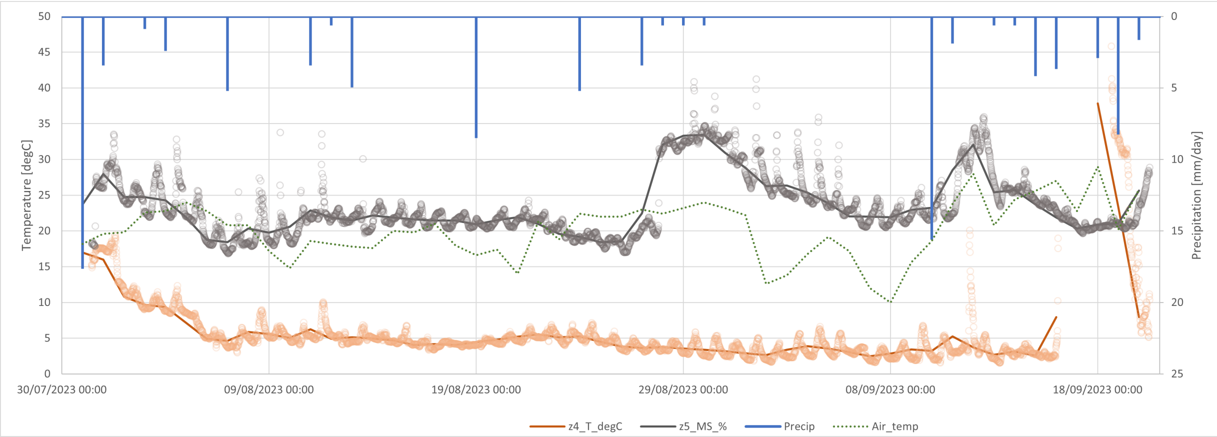
Data was collected toward a long-term data set of tree metrics in Catterline. 11 of 34 trees on which data is were monitored. See Figure 41

Figure 41: Catterline Bay with monitored tree locations.

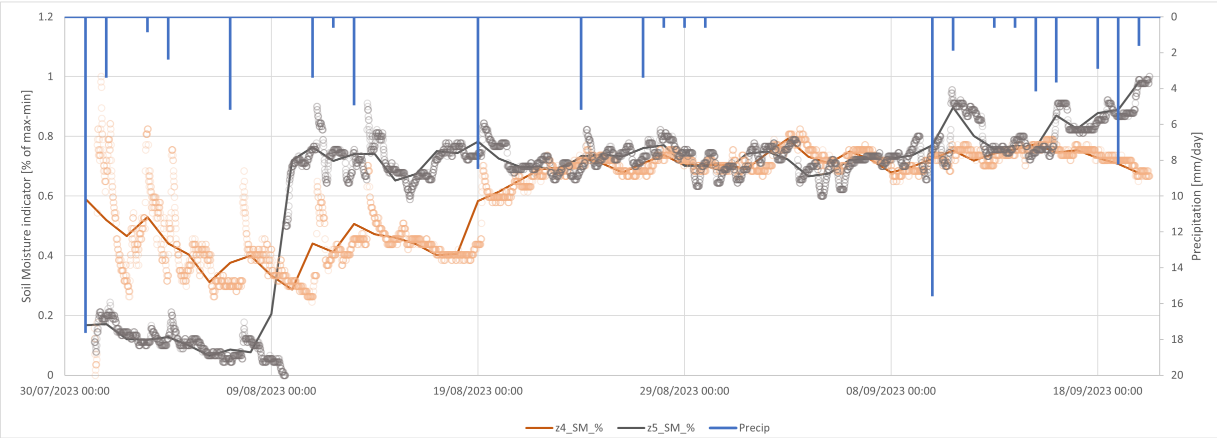
Table 10: Traits of 11 trees at study site. Species; DBH: diameter at breast height (m); Ht: tree height (m); A_{crown}: Projected crown area; #P: number of primary branches; #S: number of secondary branches; SL_{BH}: stem lean from vertical (°); SL_{base}: stem lean from vertical at base; Br_{min}: minimum branch insertion angle (°); Br_{max}: maximum branch insertion angle (°); Br_{av}: average branch insertion angle (°); CD: Canopy Density

ID	**Species**	**DBH**	**Ht**	A_{crown}	**#P**	**#S**	SL_{BH}	SL_{base}	Br_{min}	Br_{max}	Br_{av}	**CD**
5	Salix viminalis	14.6	5.8	10.46	0	8	0	60	25	35	32	-
9	-	1.3	2.1	0.87	30	8	30	30	30	45	40	-
12	Salix caprea	7.8	4.1	6.16	18	8	18	18	25	66	50	-
13	-	0.0	0.5	n/a	5	3	5	5	n/a	n/a	n/a	-
15	Betula sp.	2.9	2.2	2.84	35	10	35	60	25	65	45	83
16	Betula sp.	2.5	3.4	3.14	40	8	40	35	40	80	55	81
18	Salix caprea	4.8	4.7	5.5	40	4	40	40	40	60	50	42
19	Salix caprea	3.2	3.9	5.5	15	6	15	15	15	40	26	98
28	Crataegus sp.	3.5	2.6	3.5	75	8	75	45	50	100	73	90
27A	Salix caprea	6.4	3.2	6.6	25	14	25	85	45	110	68	93
27B	Salix caprea	6.0	4.2	5.7	30	11	30	25	20	80	53	87.52
Min		0.0	0.5	0.9	0.0	3.0	0.0	0	15.0	35.0	26.0	42
Max		14.6	5.8	10.5	75.0	14.0	75.0	0	50.0	110.0	73	98
Avg		4.8	3.3	5.0	28.5	8.0	28.5	0	31	68	49	82

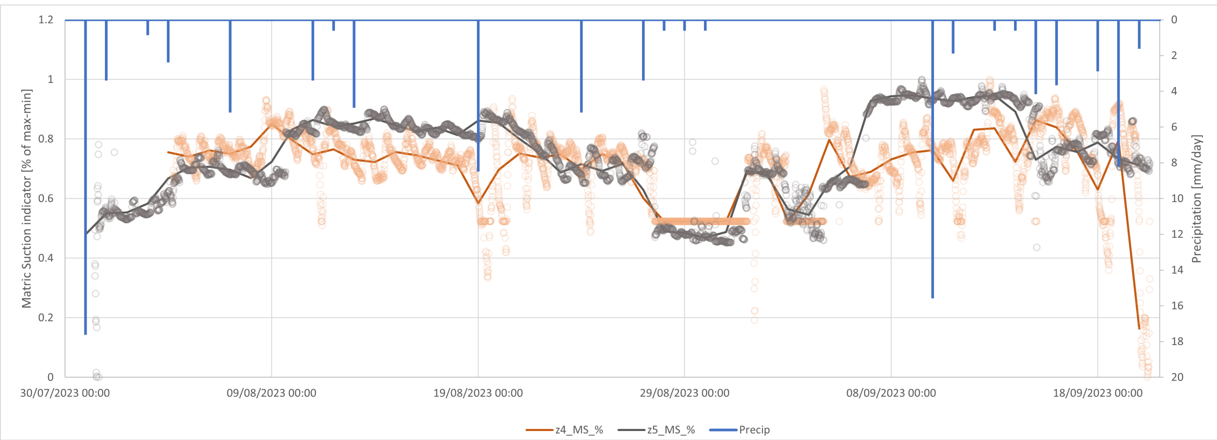
Additional sensor data from LPD23 and LPD21



(a)

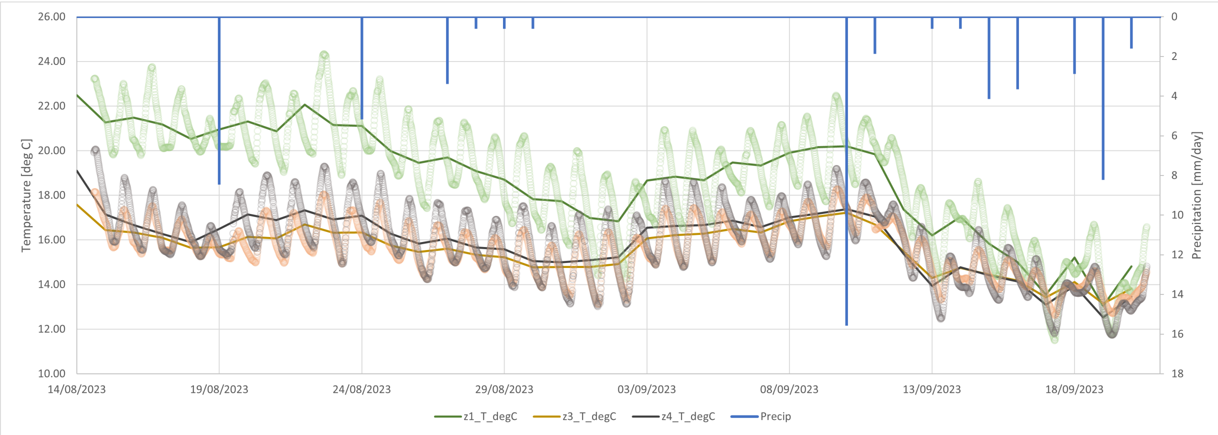


(b)

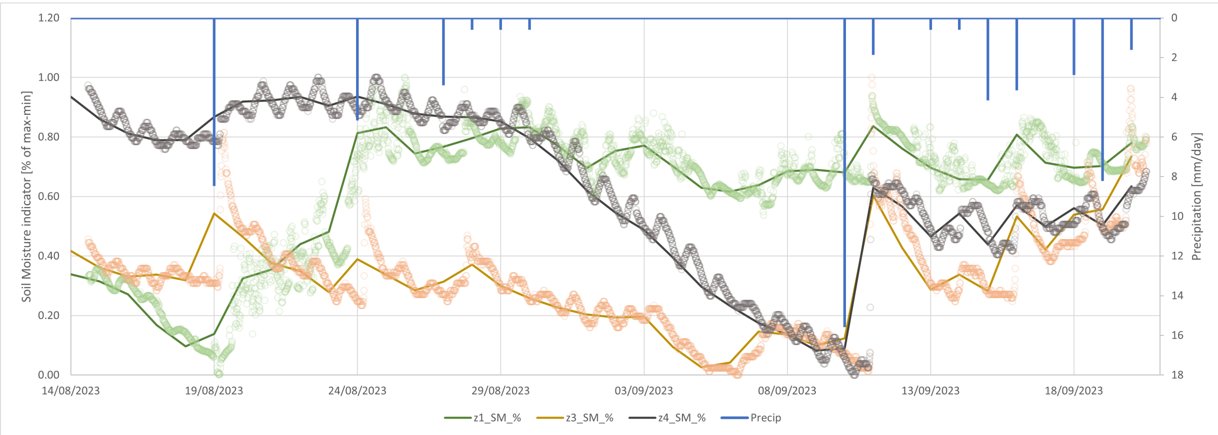


(c)

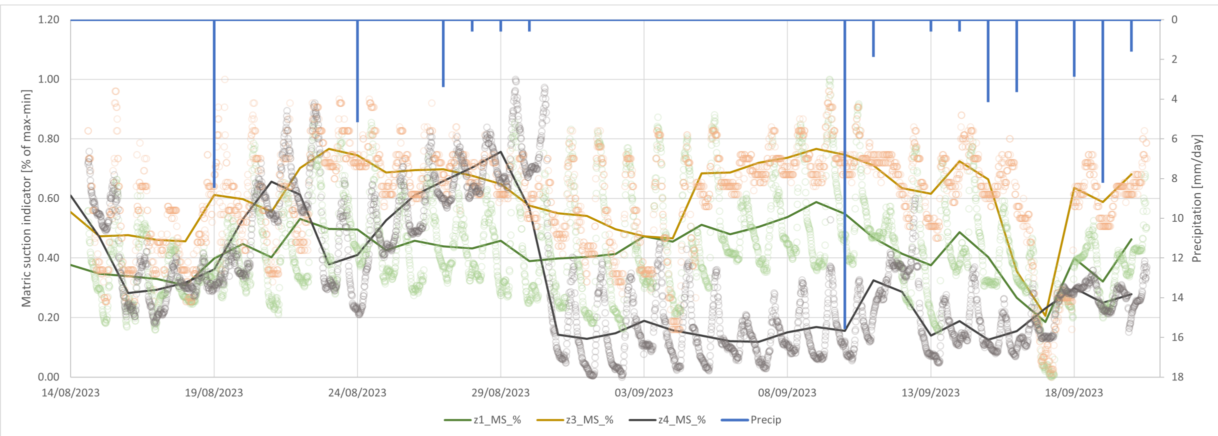
Figure 42: Observations of (a) Soil temperature, (b) Soil Moisture, and (c) Matric suction, in middle (orange) and toe (gray) of LPD21 from August 1st to September 20 of LPD21



(a)



(b)



(c)

Figure 43: Observations of (a) Soil temperature, (b) Soil Moisture, and (c) Matric suction, in top (green), middle (orange) and toe (gray) of LPD23 from August 14st to September 20

Allometry, SLA and LAI

Specific Leaf Area Calculation

Table 1. Leaves and branch for SLA and LAI sample

Branch number	Branch length (cm)	Leaves	Shoots	Diameter	Stem tray (g)	+Stems (g)	Leaf tray (g)	+Leaves (g)	+Dry stems (g)	+Dry leaves (g)	Stems wet (g)	Leaves wet (g)	Stems dry (g)	Leaves dry (g)	g/ea leaf wet	g/cm stem length dry	g/ea leaf dry	Stem moisture content (%)	Leaf moisture content (%)
1	127	57	6	1	2.027	45.62	2.003	22.832	23.986	10.305	43.593	20.829	21.959	8.302	0.365421053	0.34	0.145649123	49.62723373	60.14210956
2	114	73	9	1	2.021	39.868	2.045	32.343	21.207	14.851	37.847	30.298	19.186	12.806	0.415041096	0.33	0.175424658	49.30641795	57.73318371
3	88	47	0	0.7	2.024	18.062	2.059	17.81	10.495	9.164	16.038	15.751	8.471	7.105	0.33512766	0.18	0.151170213	47.18169348	54.8917529
4	42	22	0	0.3	2.026	4.569	2.024	5.282	3.34	3.665	2.543	3.258	1.314	1.641	0.148090909	0.06	0.074590909	48.32874558	49.63167587
5	28	20	0	0.4	2.028	4.194	2.09	4.377	2.956	3	2.166	2.287	0.928	0.91	0.11435	0.08	0.0455	57.15604801	60.20988194
6	37	25	0	0.35	2.027	5.629	2.062	5.245	3.733	3.371	3.602	3.183	1.706	1.309	0.12732	0.10	0.05236	52.63742365	58.8752749
7	30	24	0	0.15	2.013	4.566	2.053	4.838	3.187	3.188	2.553	2.785	1.174	1.135	0.116041667	0.09	0.047291667	54.01488445	59.2459605
8	12	15	0	0.2			4.466	5.454				0.988			0.065866667				
9	8.5	13	0	0.2			3.489	4.091				0.602			0.046307692				
10	6.5	14	0	0.2			2.948	3.489				0.541			0.038642857				
11	9.5	18	0	0.2			2.59	2.948				0.358			0.019888889				
12	4.5	9	0	0.1			2.315	2.59				0.275			0.030555556				
13	18.5	13	0	0.3			3.241	4.466				1.225			0.094230769				
14	14	19	0	0.2			2.004	3.241				1.237			0.065105263				
15	4	6	0	0.12			2.025	2.315				0.29			0.048333333				
16	4.5	12	0	0.2			2.669	3.012				0.343			0.028583333				
17	4.5	12	0	0.2			2.327	2.669				0.342			0.0285				
18	3.5	7	0	0.2			2.179	2.327				0.148			0.021142857				
19	3.5	8	0	0.2			2.035	2.179				0.144			0.018				
19, 18, 17, 16	16.00	39.00	0	0.20	2.028	2.254	2.035	3.012	2.113	2.445	0.226	0.977	0.085	0.41	0.025051282	0.01	0.010512821	62.38938053	58.03480041
15, 12, 11, 10 , 9	33.00	60.00	0	0.16	2.03	2.54	2.025	4.091	2.228	2.914	0.51	2.066	0.198	0.889	0.034433333	0.02	0.014816667	61.17647059	56.96999032
14, 13, 8	44.50	47.00	0	0.23	2.032	3.702	2.004	5.454	2.756	3.465	1.67	3.45	0.724	1.461	0.073404255	0.04	0.031085106	56.64670659	57.65217391
Total branches		414.00	15.00								110.75	84.88	55.75	35.97	0.11	0.12	0.07	53.85	57.34
100-leaf sample	n/a	100	0	n/a	n/a	n/a	2.021	25.979		13.511	n/a	23.958		11.49	0.23958		0.1149		52.04107188

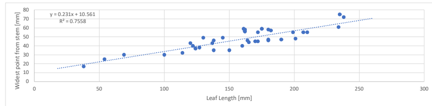
Table 2. Leaf area

Area = length * widths * factor of = 0.74 for Salix viminalis (Verwijst & Wen, 1996)

No	Width [mm]	Length [mm]	Middle (measured) [mm]	Middle %	Middle (calc'd) [mm]	Area (calc'd) Ellipse and triangle [cm2]	Area (calc'd) Wolf [cm2]
1	4	18			14.72	0.528	0.533
2	7	36			18.88	1.637	1.865
3	6.5	35			18.65	1.483	1.684
4	6	36			18.88	1.403	1.598
5	7	40			19.80	1.796	2.072
6	8	38	17	0.447368421	19.34	1.962	2.250
7	7	46			21.19	2.033	2.383
8	9	54			23.04	3.022	3.596
9	8	47			21.42	2.369	2.782
10	5	52			22.58	1.622	1.924
11	4	48			21.65	1.207	1.421
12	7	54	25	0.462962963	23.04	2.350	2.797
13	5	52			22.58	1.622	1.924
14	6	50			22.11	1.879	2.220
15	8	49			21.88	2.460	2.901
16	9	70			26.73	3.837	4.662
17	10	69	30	0.434782609	26.50	4.206	5.106
18	10	94			32.28	5.621	6.956
19	11	100	30	0.3	33.67	6.557	8.140
20	6	113			36.67	4.018	5.017
21	8	119			38.06	5.629	7.045
22	6	121			38.52	4.290	5.372
23	10	150	35	0.233333333	45.22	8.791	11.100
24	10	114	32	0.280701754	36.90	6.753	8.436
25	8	110			35.98	5.221	6.512
26	9	111			36.21	5.925	7.393
27	6	122	40	0.327868852	38.75	4.324	5.417
28	11	120			38.29	7.802	9.768
29	8	120			38.29	5.674	7.104
30	11	124	37	0.298387097	39.21	8.051	10.094
31	8	128			40.14	6.036	7.578
32	10	120	43	0.358333333	38.29	7.093	8.880
33	8	127	38	0.299212598	39.90	5.991	7.518
34	9	130			40.60	6.893	8.658
35	8	132			41.06	6.217	7.814
36	9	137	43	0.313868613	42.21	7.249	9.124
37	8	135			41.75	6.353	7.992
38	11	141			43.14	9.109	11.477
39	9	138	35	0.253623188	42.45	7.300	9.191
40	9	142			43.37	7.504	9.457
41	10	130			40.60	7.659	9.620
42	12	130	49	0.376923077	40.60	9.190	11.544
43	7	127			39.90	5.242	6.579
44	11	135			41.75	8.736	10.989
45	10	138	46	0.333333333	42.45	8.111	10.212
46	12	148			44.76	10.413	13.142
47	11	145			44.06	9.358	11.803
48	10	145	49	0.337931034	44.06	8.508	10.730
49	10	155			46.37	9.073	11.470
50	11	161	59	0.366459627	47.76	10.354	13.105
51	8	150			45.22	7.032	8.880
52	14	162	58	0.358024691	47.99	13.258	16.783
53	10	155			46.37	9.073	11.470
54	16	168			49.38	15.695	19.891
55	11	170	45	0.264705882	49.84	10.915	13.838
56	17	164	46	0.280487805	48.45	16.291	20.631
57	11	167			49.15	10.728	13.594
58	13	175	59	0.337142857	50.99	13.267	16.835
59	14	160	40	0.25	47.53	13.099	16.576
60	10	162	56	0.345679012	47.99	9.470	11.988
61	11	165	44	0.266666667	48.68	10.603	13.431

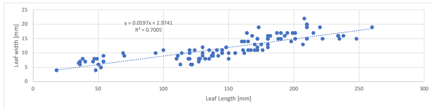
Table 3. Relationship between metrics

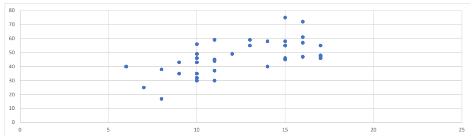
X	Y	RSQ	LINEST	
Width	Length	0.700506205	11.73904593	8.756638772
Width	Middle	0.389415658		
Width	Middle %	0.247237718		
Length	Middle	0.755831242	0.231048118	10.56123453
Length	Middle %	0.427694327		

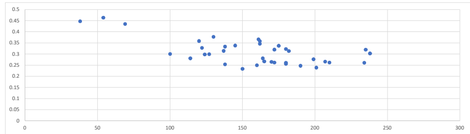


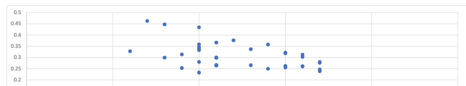
Specific Leaf Area	
Total area [m2]	1.401
Total mass [g]	11.49
SLA [m2/g]	0.122

Leaf moisture content pretty constant	
average leaf moisture content	57.3386804









62	12	180			52.15	12.586	15.984
63	14	165			48.68	13.495	17.094
64	16	182	57	0.313186813	52.61	16.962	21.549
65	15	172	55	0.319767442	50.30	15.053	19.092
66	15	172	45	0.261627907	50.30	15.053	19.092
67	11	176			51.23	11.288	14.326
68	15	190			54.46	16.581	21.090
69	12	172			50.30	12.043	15.274
70	16	180	47	0.261111111	52.15	16.781	21.312
71	13	180			52.15	13.635	17.316
72	13	170			49.84	12.899	16.354
73	17	195			55.62	19.273	24.531
74	15	180	46	0.255555556	52.15	15.733	19.980
75	15	180	58	0.322222222	52.15	15.733	19.980
76	11	172			50.30	11.039	14.001
77	15	180			52.15	15.733	19.980
78	17	187			53.77	18.504	23.525
79	14	198			56.31	16.110	20.513
80	15	188			54.00	16.412	20.868
81	17	201	48	0.23880597	57.00	19.851	25.286
82	17	199	55	0.27638191	56.54	19.658	25.034
83	19	210			59.08	23.154	29.526
84	16	193			55.15	17.959	22.851
85	17	190	47	0.247368421	54.46	18.792	23.902
86	19	173			50.53	19.175	24.324
87	15	201			57.00	17.515	22.311
88	15	210	55	0.261904762	59.08	18.279	23.310
89	19	260			70.63	28.530	36.556
90	17	215			60.24	21.198	27.047
91	13	207	55	0.265700483	58.39	15.621	19.913
92	15	235	75	0.319148936	64.86	20.402	26.085
93	20	210			59.08	24.372	31.080
94	15	222			61.85	19.298	24.642
95	16	238	72	0.302521008	65.55	22.033	28.179
96	15	248			67.86	21.505	27.528
97	16	234			64.63	21.671	27.706
98	19	220			61.39	24.229	30.932
99	16	234	61	0.260683761	64.63	21.671	27.706
100	22	208			58.62	26.561	33.862
Total						1106.281	1400.513

Allometric Realtionships and LPD growth Metrics

Table 1. Leaves per shoot			
Location	LPD23		
Count leaves per shoot of growth in LPD, selected randomly			
rsq	0.552503855		
m, b	0.253850103	14.29722793	
Shoot length	**Leaves**	**Shoots**	**L+S**
20	19	0	19
25	18	0	18
30	22	0	22
35	25	0	25
40	24	0	24
40	30	0	30
50	26	0	26
50	20	0	20
55	29	2	31
60	26	0	26
70	31	0	31
70	14	12	26
70	36	7	43
80	35	6	41
95	20	13	33

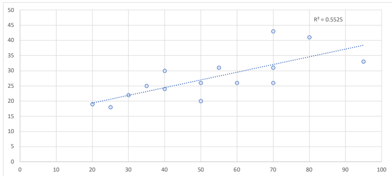


Table 2. Leaves per branch in sample for SLA		
Location	SLA sample from LPD21 and other willows willow	
rsq	0.792101264	
m,b	2.737265372	-47.18397935
Branch length	**# Leaves**	**Diameter**
3.5	7	0.2
3.5	8	0.2
4	6	0.12
4.5	9	0.1
4.5	12	0.2
4.5	12	0.2
6.5	14	0.2
8.5	13	0.2
9.5	18	0.2
12	15	0.2
14	19	0.2
18.5	13	0.3
28	20	0.4
30	24	0.15
37	25	0.35
42	22	0.3
88	47	0.7
114	73	1
127	57	1
300	995	2.55

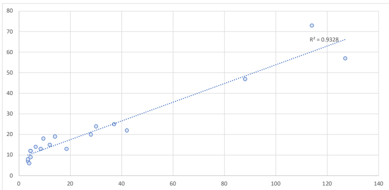
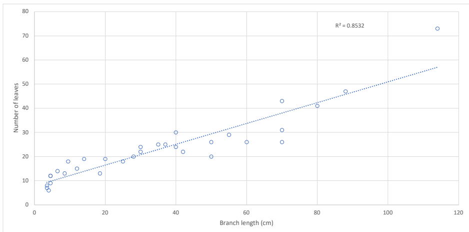


Table 3. CombinedLPD23 and SLA sample		
rsq	0.818437897	
m, b x-y	0.399936209	8.517514686
m,b y-x	2.046421102	-10.70437116
Shoot length (cm)	**Number of leaves**	
3.5	7	
3.5	8	
4	6	
4.5	9	
4.5	12	
4.5	12	
6.5	14	
8.5	13	
9.5	18	
12	15	
14	19	
18.5	13	
28	20	
30	24	
37	25	
42	22	
88	47	
114	73	
20	19	
25	18	
30	22	
35	25	
40	24	
40	30	
50	26	



50	20	
55	29	
60	26	
70	31	
70	26	
70	43	
80	41	
95	33	

Table 4. From Eefje and Fernanda's lab setup destructive analysis daat

rsq	**0.801613586**	
m, b	0.066475168	4.481639792
Height_st_mm	Height_mm	Leaves
153	165	13
274	327	26
425	472	47
459	506	45
270	306	24
135	152	18
486	530	54
577	625	61
120	138	9
199	225	22
114	91	11
124	136	6
365	420	33
560	615	59
125	134	15
95	100	15
81	105	14
330	375	28
399	444	30
157	181	13
313	336	26
525	545	52
490	536	38
360	404	28
355	395	35
411	455	36
270	305	23
336	392	31
181	211	18
322	371	29
320	365	27
207	223	23
359	397	28
111	141	11
315	372	29
148	192	13
272	318	24
559	602	45
208	254	29
589	620	50
585	601	51
384	519	38
110	127	12
75	88	13
299	330	30
47	65	14
283	352	23
290	336	21
207	236	15
577	589	47
111	136	3
324	385	30
292	357	29
89	108	17
389	444	28
158	183	17
519	586	55
275	308	25
365	433	27
476	501	49
478	525	45
140	166	12
235	283	24
23	40	5
357	387	34
596	628	50
620	679	49
164	200	21
660	681	59
175	190	14
584	622	52
512	556	42
150	185	20
753	783	58
208	230	20

120	137	10
468	501	49
544	582	48
402	464	34
381	407	32
626	662	41
900	925	44
528	571	24
642	688	39
751	737	36
477	517	37
n/a	60	0
499	529	28
408	441	24
648	679	53
358	406	33
725	766	46

Table 5. Diameter vs Number of primary branches. LPD 21

rsq	0.730350002	
m, b	9.893438107	-3.56745182
circumferece	diameter	primary branches
6	1.91	12
4	1.27	8
6	1.91	15
4	1.27	14
5	1.59	18
5	1.59	6
10.5	3.34	30
8	2.55	25
6	1.91	13
7	2.23	17

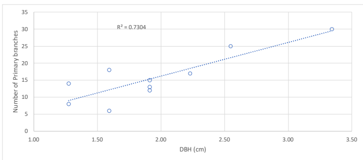


Table 6. Total count of leaves on a typical pole of basket willow from LPD21

Pole diameter	2.55			
Primary branches	27			
Secondary banches	10			
Leaves per branch +-5	**Branch count**	**Total leaves**	**Branch length etimate (cm)**	**Weighted average branch length**
5	8	40	5	40
15	2	30	31	61.39263305
25	11	275	51	562.7658029
35	10	350	72	716.2473855
45	4	180	92	368.3557983
55	1	55	113	112.5531606
65	1	65	133	133.0173716
Total		995	70.87729491	53.90086897

Table 7. Branch length and total mass of leaves, for SLA sample

m, b	0.085795	-0.110609226
rsq	0.978196685	
avergae moisture	57.23139398	
Branch length (cm)	Leaves wet (g)	
127	20.829	
114	30.298	
88	15.751	
42	3.258	
28	2.287	
37	3.183	
30	2.785	
12	0.988	
8.5	0.602	
6.5	0.541	
9.5	0.358	
4.5	0.275	
18.5	1.225	
14	1.237	
4	0.29	
4.5	0.343	
4.5	0.342	
3.5	0.148	
3.5	0.144	

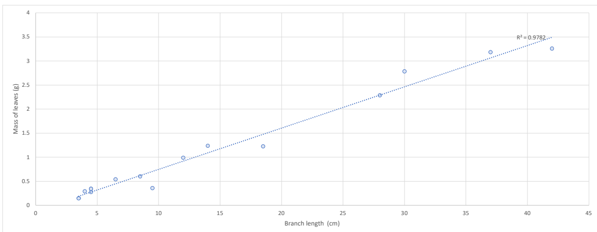


Table 8. LPD 23 Growth metrics

LPD width [m]	1					
SLA	0.121889721					
x	y	# branches	branch length	wet weight, each	dry wieght, each	total dry weight
0	0	6	25	2.14	0.92	5.50
0.5	0	7	40	3.43	1.47	10.27
1	-0.25	1	70	6.01	2.57	2.57

1	-0.25	4.5	40	3.43	1.47	6.60
1	-0.25	4.5	40	3.43	1.47	6.60
1.25	0	4	15	1.29	0.55	2.20
1.75	0.25	4	80	6.86	2.94	11.74
1.75	-0.25	4	30	2.57	1.10	4.40
2.25	0.3	4	80	6.86	2.94	11.74
2.75	0.25	4	30	2.57	1.10	4.40
2.75	0.25	1	110	9.44	4.04	4.04
3.25	-0.25	6	50	4.29	1.83	11.01
3.5	0.25	8	60	5.15	2.20	17.61
3.75	0.3	4	50	4.29	1.83	7.34
4	0	3	10	0.86	0.37	1.10
4.6	0.25	1	20	1.72	0.73	0.73
5	0.25	12	60	5.15	2.20	26.42
5.75	0	2	20	1.72	0.73	1.47
5	0	12	60	5.15	2.20	26.42
6.25	0	1	20	1.72	0.73	0.73
6.6	-0.25	1	50	4.29	1.83	1.83
6.6	-0.25	3	20	1.72	0.73	2.20
7	0	5	20	1.72	0.73	3.67
8	0	4	35	3.00	1.28	5.14
8.2	0	8	55	4.72	2.02	16.15

LPD23	Meter 1	Meter 2	Meter 3	Meter 4	Meter 5	Meter 6	Meter 7	Meter 7.5	Meter 8.5	Average
Total [g/m2]	25.0	25.0	20.2	37.1	27.2	27.9	4.8	7.3	21.3	21.7
LAI	3.0	3.0	2.5	4.5	3.3	3.4	0.6	0.9	2.6	2.6

Table 9. LPD21 Growth Metrics

SLA	0.12											
canopy width	3											
								FROM TABLE 5	FROM TABLE 6 AVG	FROM TABLE 7	FROM TABLE 7 MOISTURE CONTE	* #BRANCHES * # POLES
x	y	# poles	polecircumference	pole angle	height [m]	notes	pole diameter	primary branches	primary branch length	wet weight, each	dry wieght, each	total dry weight
0.5	-0.25	1	7	10	4		2.2	18.5	53.9	4.5	2.6	47.73148797
0.75	-0.25	1	7	30	4		2.2	18.5	53.9	4.5	2.6	47.73148797
0	0.25	1	6	60	4		1.9	15.3	53.9	4.5	2.6	39.59615131
0.75	0.25	1	6	30	4		1.9	15.3	53.9	4.5	2.6	39.59615131
0.8	0	1	6	10	3		1.9	15.3	53.9	4.5	2.6	39.59615131
0.5	0	1	5	10	3		1.6	12.2	53.9	4.5	2.6	31.46081464
0.8	0.25	1	5	10	3		1.6	12.2	53.9	4.5	2.6	31.46081464
0.3	-0.2	1	5	15	3		1.6	12.2	53.9	4.5	2.6	31.46081464
0.4	0.2	1	5	10	3		1.6	12.2	53.9	4.5	2.6	31.46081464
0.2	0.25	2	4	10	3		1.3	9.0	53.9	4.5	2.6	46.65095595
1.3	0	2	6	0	0.6	pruned	1.9	15.3	53.9	4.5	2.6	79.19230261
1.6	0.25	1	4	10	3		1.3	9.0	53.9	4.5	2.6	23.32547797
1.7	0	1	6	10	3		1.9	15.3	53.9	4.5	2.6	39.59615131
1.75	0.25	1	5	10	3		1.6	12.2	53.9	4.5	2.6	31.46081464
1.75	0	1	4	10	3		1.3	9.0	53.9	4.5	2.6	23.32547797
1.75	-0.25	1	4	10	3		1.3	9.0	53.9	4.5	2.6	23.32547797
2	0	1	4	10	3		1.3	9.0	53.9	4.5	2.6	23.32547797
2	-0.25	1	6	10	3		1.9	15.3	53.9	4.5	2.6	39.59615131
2.2	0.3	1	4	10	3		1.3	9.0	53.9	4.5	2.6	23.32547797
2.6	0.25	1	2	10	2.5		0.6	2.7	53.9	4.5	2.6	7.054804643
2.75	-0.2	1	4	10	3		1.3	9.0	53.9	4.5	2.6	23.32547797
3	-0.25	1	6	10	3		1.9	15.3	53.9	4.5	2.6	39.59615131
3	0	2	2	0	2.5		0.6	2.7	53.9	4.5	2.6	14.10960929
3.5	0	1	4	10	3		1.3	9.0	53.9	4.5	2.6	23.32547797
3.6	0	1	5	10	3		1.6	12.2	53.9	4.5	2.6	31.46081464
3.65	0.25	1	3	10	2.75		1.0	5.9	53.9	4.5	2.6	15.19014131
3.8	-0.2	1	6	10	3		1.9	15.3	53.9	4.5	2.6	39.59615131
5.15	-0.25	1	7.5	10	2	other tree	2.4	20.1	53.9	4.5	2.6	51.79915631
5.3	0	2	5	10	3		1.6	12.2	53.9	4.5	2.6	62.92162928
5.75	0	1	5	10	3		1.6	12.2	53.9	4.5	2.6	31.46081464
5.75	0	1	7	10	3.5		2.2	18.5	53.9	4.5	2.6	47.73148797
5.75	0.25	1	7	10	3.5		2.2	18.5	53.9	4.5	2.6	47.73148797
6.5	0.25	1	3	10	2.5		1.0	5.9	53.9	4.5	2.6	15.19014131
7.3	0	1	5	10	3		1.6	12.2	53.9	4.5	2.6	31.46081464
7.75	0.25	1	10.5	10	3	(14 branches over 3 CIRC)	3.3	29.5	53.9	4.5	2.6	76.2051663

LPD21	Meter 1	Meter 2	Meter 3	Meter 4	Meter 5	Meter 6	Meter 7	Average
Total [g/m2]	386.7	220.2	279.9	0.0	241.6	15.2	107.7	
LAI	15.7	8.9	11.4	0.0	9.8	0.6	4.4	7.3

Table 10. LPD22 Growth Metrics - top part

LPD width	1										
SLA	0.12										
LPD22 - upper staked area	15 / 28 stakes alive										
x	y	alpha_a	alpha_b	l	cnt_v	hmax	diameter base	diameter @ 110	cnt_h	notes	stake
2	0	30	45	180	2	160	2	n/a	3		n
3	0	5	95, 100	160	6	150	1.4, 1.8	n/a	2		n
4	0	25	110	2	5	170	2	n/a	1 + 3 mini		n
5	0	35	75	130, 90	8, 2	200, 240	2.5, 1.9	n/a	2		n
6	0	50	25	0	n/a	250	2.3	1.8	1 (v)		n
7	0	25	75	70	0, 1	10	0.7	n/a	2		n
8.8	0	n/a	115	130	0	20	1, 0.9, 0.9	n/a	3		n
10	0	n/a	25	n/a	n/a	300	1.5	1.1	2 (v)		n
11	0	n/a	20	n/a	n/a	250	1.5, 1.2, 0.9	1, 0.9, 0.6	3 (v)		n
13	-0.5	20	20	n/a	n/a	120	0.7	n/a	1 (v)	13-A	y
13	0	n/a	20	n/a	n/a	200	1.7, 0.9	1.4, n/a	2 (v)	13-B	n
13.8	-0.75	15	15	n/a	n/a	155	0.9, 0.8	n/a	2 (v)	other willow	y
14.5	n/a	5	n/a	n/a	n/a	300	1.6, 1.8	1.3, 1.4	11 (v)	other willow	n

15.5	-0.8	n/a	15	n/a	n/a	190	1.2	n/a	8 (v)	other willow	n
15.5	0.7	5	5	n/a	n/a	180	1.2	n/a	1 (v)	15-16-A	y
15.6	0.5	10	5	n/a	n/a	180	1.3	n/a	2 (v)	15-16-B	y
15.9	0.8	10	10	n/a	n/a	100	0.7	n/a	1 (v)	15-16-C	y
16.25	0.75	30	5	n/a	n/a	3	2.9	1.9	3 (v)	15-16-D	y

LPD22 Growth Metrics - lower part					
LPD width	1	SLA	0		
x	y	cnt_v	hmax	stake	notes
3	b	1	160	y	
4	m	1	70	y	
5	t	1	170	y	
6	b	1	90	y	stump, other tree
6.6	b	3	100, 180, 200	y	
7	b	1	210	y	
7	t	2	180, 180	y	
7.2	b	1	300	y	
7.5	m	1	300	y	
7.7	b	1	170	y	other, pruned
8	t	4	200, 150, 150, 150	y	
8.5	t	1	150	y	
9	b	1	170	y	other
10	b	1	190	y	
10.5	t	4	300, 170, 170, 170	y	
11	b	1	100	y	
11.5	b	1	70	y	
11.5	t	2	200, 100	y	
12	t	1	270		

LPD growth metrics visualization Python

In [46]:
```
#pip install adjustText
```

In [47]:
```
#Libraries
import numpy as np
import pandas as pd
from adjustText import adjust_text
import matplotlib.pyplot as plt
```

In [1]:
```
"""
This function generates a plot of the locations and diameters of vegetation.
The shape of the LPD must be input manually within the function.
"""
#filename = 'LPD23_growth.csv'
filename = 'legend.csv'
plotLPD(filename)
```

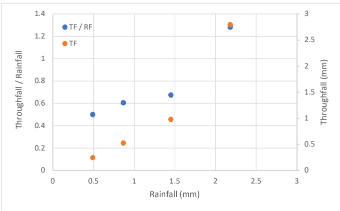
In [307…
```
def plotLPD(filename):

    df = pd.read_csv(filename)
    #df['label'] = df['dia'].astype(str) + df['type'].astype(str)+ '        '
    color_map = {'S': '#53b874', 'P': 'darkgreen', 'St': '#769109', 'StS': '#97c251', 'StP': '#888a38', 'StB': '#6a7d45', 'StS-BW': '#b36
    df['color'] = df['type'].map(color_map)
    #create scatter plot of x vs. y
    fig, ax = plt.subplots(figsize=(15, 15))

    df.plot(kind='scatter', x='y', y='x', ax=ax, s=[2000 * dia for dia in df['dia']], c=df['color'], alpha=0.45, zorder=2)


    # label each point in scatter plot
#     texts = []
#     for idx, row in df.iterrows():
#          texts.append(ax.text(row['y'], row['x'], row['label']))

    # adjust overlapping labels
    adjust_text(texts)


    # calculate y-axis limits with 5% buffer
#     y_min = df['x'].min()
#     y_max = df['x'].max()
#     y_range = y_max - y_min
#     y_buffer = 0.5 * y_range



    ax.set_aspect('equal')

     # LPD21
#     ax.plot([0, 0], [0, 10.00], color='lightgray', linewidth=50, zorder=1)
#     ax.plot([0, -.85],[10.00, 11.60],  color='lightgray', linewidth=30, zorder=1)
#     ax.plot( [0, .85], [10.00, 11.70], color='lightgray', linewidth=30, zorder=1)
#     ax.set_xlim( -2, 2)

    #LPD22
#     ax.plot( [0, 0],[0, 12.00], color='lightgray', linewidth=50, zorder=1)
#     ax.plot( [0, -.875],[12.00, 17.00], color='lightgray', linewidth=40, zorder=1)
#     ax.plot( [0, .875],[12.00, 17.00], color='lightgray', linewidth=40, zorder=1)
#     # set y-axis limits with buffer
#     ax.set_xlim( -2, 2)

    #LPD23
    ax.plot( [0, 0],[0, 7.50], color='lightgray', linewidth=70, zorder=1)
    ax.plot( [0, -1],[7.5, 8.5], color='lightgray', linewidth=40, zorder=1)
    ax.plot( [0, -5],[4.00, 4.50], color='lightgray', linewidth=40, zorder=1)
    #set y-axis limits with buffer
    ax.set_xlim( -6, 0.5)

    ax.set_ylim(-0.25, 18)
    ax.tick_params(axis='both', direction='in')
    ax.set_yticks([])
    #plt.yticks(range(0, int(max(df['x']))+2, 1))
    ax.spines['top'].set_visible(False)
    ax.spines['right'].set_visible(False)
    ax.spines['left'].set_visible(False)
    ax.set_xlabel('[m]')
    #ax.set_ylabel('[m]')

    # show the plot
    #plt.tight_layout()
    plt.show()

    return()
```

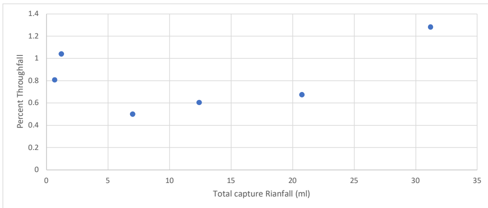
In [ ]:
```
```

Rainfall and Throughfall Partitioning

Rainfall and throughfall results													
Guage area	143.1388153												
Gauge ID	**E**	**N**	**Site**	**Slope angle**	**Slope aspect**	**Canopy Density**	**Notes**	**22/09/2023 13:30**	**23/09/2023 12:10**	**24/09/2023 11:00**	**25/09/2023 09:30**	**26/09/2023 09:05**	**27/09/2023 08:00**
RF1	-2.216730267	56.8944405	LPD23	30	bay	0		18	10	40	16	1	1
RF2			LPD23	30	bay	0		23	nan	32	10	1	nan
RF3			LPD21-Left	45	bay	0		20	5	10	8	1	1
RF4			LPD21-Right	50	bay	0		22	6	30	12	2	0.5
RF5			Cottage	0	n/a	0		nan	nan	44	16	1	0.1
TF1	-2.215609811	56.89556383	LPD21	30	bay	56.73		10	3	24	4	1	0.5
TF2	-2.215609811	56.89556383	LPD21	30	bay	41.79		28	5	38	8	1	0.1
TF3	-2.215609811	56.89556383	LPD21	20	bay	81.67		4	3	46	8	0	0.5
TF4	-2.215609811	56.89556383	LPD21	15	bay	90.35		14	3	52	10	3	1
Mean RF								20.75	7	31.2	12.4	1.2	0.65
Mean TH								14	3.5	40	7.5	1.25	0.525
%TH								0.674698795	0.5	1.282051282	0.60483871	1.041666667	0.807692308

RF	1.449641731	0.489035765	2.179702266	0.866291926
TF	0.97807153	0.244517882	2.794490084	0.523966891
TF / RF	0.674698795	0.5	1.282051282	0.60483871
RF-TH	0.471570202	0.244517882	-0.614787819	0.342325035





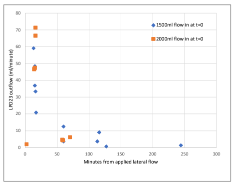
Measured	
Calculated	

Lateral Flow Experiments

Lateral Flow Results

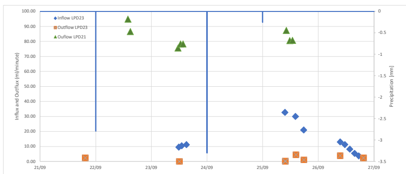
Base flow											
Date		Start	End	Volume 1 (ml)	Volume 2 (ml)	Volume 3 (ml)	Notes	Time	Rate vol1	Rate vol2	total
	21/09/2023 19:30	21/09/2023 19:30	22/09/2023 14:30	2650			Initial setup	1140	2.324561404	0	2.324561404
	23/09/2023 12:05	23/09/2023 12:05	23/09/2023 17:05	0			Settling/drying of mud around gutter	300	0	0	0
25/09/2023	25/09/2023	09:45	14:21		full			276	0		0
25/09/2023	25/09/2023	09:45	17:47	150				482	0.31120332	0	0.31120332
25/09/2023	25/09/2023	14:21	17:47		912			206	0	4.427184466	4.427184466
	25/09/2023 17:47	25/09/2023 17:47	26/09/2023 09:25	1000	full			938	1.066098081		1.066098081
26/09/2023	26/09/2023	09:25	11:28	0	472			123	0	3.837398374	3.837398374
	26/09/2023	26/09/2023 19:30	27/09/2023 08:38	130	1670	full		788	0.164974619	2.11928934	2.284263959

Experiments															
Date	Start	End	Volume 2 (ml)	Volume 3 (ml)	Inflow at start (ml)	Inflow time	Outflow start	Outflow slow	Outflow normal		Time from inflow	Time	Vol2 rate	Vol3 rate	Total vol
26/09/2023	11:28	11:45	354	nan	1500	11:28	nan				17	17	20.82352941		20.82352941
26/09/2023	11:49	13:35	72	nan	0	11:28					127	106	0.679245283		0.679245283
26/09/2023	13:36	15:32	158	nan	0	11:28					244	116	1.362068966		1.362068966
26/09/2023	15:33	15:52	534	nan	1500	15:36	15:39	15:42	15:48	00:03:00	16	16	33.375		33.375
26/09/2023	15:54	17:29	350	nan	0	15:36					113	95	3.684210526		3.684210526
26/09/2023	17:30	17:49	554	nan	1500	17:34	17:37	17:42		00:03:00	15	15	36.93333333		36.93333333
26/09/2023	17:51	19:30	505	394	0	17:34					116	99	5.101010101	3.97979798	9.080808081
27/09/2023	08:38	09:01	500	226	1500	08:46	08:49	08:52		00:03:00	15	15	33.33333333	15.06666667	48.4
27/09/2023	09:03	09:46	152	386	0	08:46					60	43	3.534883721	8.976744186	12.51162791
27/09/2023	09:46	10:02	548	220	1500	09:49	09:52			00:03:00	13	13	42.15384615	16.92307692	59.07692308
27/09/2023	10:03	10:49	70	100	0	09:49					60	46	1.52173913	2.173913043	3.695652174
27/09/2023	10:50	11:07	604	108	2000	10:52	10:53:40			00:01:40	15	15	40.26666667	7.2	47.46666667
27/09/2023	11:09	11:50	140	50	0	10:52					58	41	3.414634146	1.219512195	4.634146341
27/09/2023	11:52	12:07	608	45	2000	11:53	11:55:40			00:02:40	14	14	43.42857143	3.214285714	46.64285714
27/09/2023	12:09	12:52	178	10	0	11:53					59	43	4.139534884	0.23255814	4.372093023
27/09/2023	12:57	13:12	590	480	2000	12:56	12:58:40			00:02:40	16	15	39.33333333	32	71.33333333
27/09/2023	13:12	14:06	260	74	0	12:56					70	54	4.814814815	1.37037037	6.185185185
27/09/2023	14:06	14:25	955	110	2000	14:09	14:11:41			00:02:41	16	16	59.6875	6.875	66.5625
											2				2



Outflow from LPD21					
Date	Start	End	Volume (ml)	Time (minutes)	Rate (ml/minute)
21/09/2023	12:48	15:15	Full	147	
22/09/2023	13:54	14:54	5690	60	94.83333333
22/09/2023	14:56	15:56	5200	60	86.66666667
23/09/2023	11:29	12:29	4540	60	75.66666667
23/09/2023	12:33	13:37	5010	64	78.28125
23/09/2023	13:39	15:42	9640	123	78.37398374
25/09/2023	10:10	11:37	7600	87	87.35632184
25/09/2023	11:40	12:46	5320	66	80.60606061
25/09/2023	12:51	14:01	5650	70	80.71428571

Inflow LPD23							
Date	datetime	Start	End	Volume (ml)	Time (minutes)	Rate (mm/minute)	Average daily
23/09/2023	11:51:00	11:51	12:59	650	68	9.56	
23/09/2023	23/09/2023	13:02	15:00	1230	118	10.42	
23/09/2023	23/09/2023	15:05	17:50	1850	165	11.21	10.39822452
25/09/2023	25/09/2023	09:34	10:00	850	26	32.69	
25/09/2023	25/09/2023	14:08	14:38	900	30	30.00	
25/09/2023	25/09/2023	17:42	18:46	1340	64	20.94	27.87660256
26/09/2023	26/09/2023	09:26	11:24	1530	118	12.97	
26/09/2023	26/09/2023	11:26	13:31	1410	125	11.28	
26/09/2023	26/09/2023	13:34	15:30	950	116	8.19	
26/09/2023	26/09/2023	15:36	17:26	590	110	5.36	
26/09/2023	26/09/2023	17:26	19:26	446	120	3.72	8.30321198



Soil Samples for Lab Analysis

Soil Samples and Field Results

Additional fieldwork. Field vane shear test (ASTM D4767).						
ID	**Site**	**Location**	**Vane**	**Give (kPa)**	**Rotate (kPa)**	**Soil Moisture**
VST_1	LPD23	Crib wall, low tier	33mm	>30	>30	40.5
VST_2	LPD23	Crib wall, low tier	33mm	23	27	41.8
VST_3	LPD23	Crib wall, low tier	33mm	24	>30	41.4
VST_4	LPD23	Crib wall, low tier	33mm	>30	>30	42.4
VST_5	LPD23	UnderLPD, udisturbed fail face, no visible seepage	33mm	27	22	49.6
VST_6	LPD23	UnderLPD, udisturbed fail face, visible seepage	33mm	6	6.5	61
VST_7	LPD23	UnderLPD, undisturbed fail face, visible seepage	33mm	8	10	69.2
VST_8	LPD23	On LPD 100cm from toe	33mm	8	10	50.2
VST_9	LPD23	On LPD 100cm from toe	33mm	18	19	45.6
VST_10	LPD23	Under LPD, eroded mud	33mm	2	4	too wet
VST_11	LPD23	Crib wall, low tier	19mm	56	58	41.8
VST_12	LPD23	Crib wall, low tier	19mm	58	45	42.4
VST_13	LPD23	UnderLPD, udisturbed fail face, no visible seepage	19mm	22	22	49.6
VST_14	LPD23	UnderLPD, udisturbed fail face, visible seepage	19mm	2	4	61
VST_15	LPD23	Failure face above crib wall, 60cm depth	19mm	10	12	48
VST_16	LPD23	Failure face above crib wall, 20cm depth	19mm	25	28	34.6
VST_17	LPD21	350cm from toe	33mm	19	19	85
VST_18	LPD21	700cm from toe	33mm	6	6	too wet
VST_19	LPD21	900cm from toe	33mm	16	17	75.8
VST_20	LPD21	2m left of middle of 450cm above toe	33mm	15	22	59.2
VST_21	LPD21	2m left of middle of 800cm above toe	33mm	9	10.5	42.6

Field notes. Soil sample locations				
ID	**Site**	**Location**	**Soil Moisture**	**Notes**
USOL_LPD23_1	LPD23	150cm from toe	36.6	clumped soil from recent LPD construction
USOL_LPD23_2	LPD23	470cm from toe	39.8	clumped soil from recent LPD construction
USOL_LPD23_3	LPD23	320cm from toe	34.3	clumped soil from recent LPD construction
USOL_LPD23_4	LPD23	70cm above 3rd post down from upper right corner	43.2	undisturbed soil
DSOL_LPD23_1	LPD23	Failure face above crib wall, 60cm depth	42.3	undisturbed soil
DSOL_LPD23_2	LPD23	Failure face above crib wall, 20cm depth	38.9	undisturbed soil
USOL_LPD21_1	LPD21	150cm above toe	Too wet	soft mud, evidence of ponding (moss/algae layer)
USOL_LPD21_2	LPD21	520cm above toe	Too wet	soft mud, evidence of ponding (moss/algae layer)
USOL_LPD21_3	LPD21	1000cm above toe	61.6	Leaf litter
USOL_LPD21_4	LPD21	2m left of middle of 450cm above toe	-	Grassy patch
DSOL_LPD21_1	LPD21	2m left of middle of 450cm above toe	-	Grassy patch

Field notes. Soil Macrofauna							
Location	**Worms**	**Earwigs**	**Larvae shells**	**Centipede**	**Millipede**	**Snail shells**	**Total organisms**
Clear in LPD 23 area	5	1	2	1	0	0	9
Willow stand past first crib wall	12	2	5	0	16	8	43

Field notes. Soil Moisture with hand-held sensor				
ID	Site	Location (cm from toe)	Average	Std dev
LPD21_HH2_SMA	LPD21	450	24.2	0
LPD21_HH2_SMB	LPD21	850	41.5	0
LPD21_Temp	LPD21	450	15	0
LPD21_150_SM1	LPD21	100	63.9	21.07178208
LPD21_150_SM2	LPD21	200	73.2	3.959797975
LPD21_150_SM3	LPD21	300	87.5	17.67766953
LPD21_150_SM4	LPD21	400	70.95	8.697413409
LPD21_150_SM5	LPD21	500	100	0
LPD21_150_SM6	LPD21	600	100	0
LPD21_150_SM7	LPD21	700	79.8	2.545584412
LPD21_150_SM8	LPD21	800	67.2	3.111269837
LPD21_150_SM9	LPD21	900	65.35	1.202081528
LPD21_150_SM10	LPD21	1000	59.9	1.838477631
LPD23_HH2_SMA	LPD23	600	15.62941176	1.053425784
LPD23_HH2_SMB	LPD23	400	25.32941176	1.402571168
LPD23_Temp	LPD23	600	13.91176471	0.441421501
LPD23_150_SM1	LPD23	100	44.1	8.940693485
LPD23_150_SM2	LPD23	200	47.3125	1.785450457
LPD23_150_SM3	LPD23	300	44.6625	2.708720485
LPD23_150_SM4	LPD23	400	37.8375	5.069368797
LPD23_150_SM5	LPD23	500	45.94375	3.085659033
LPD23_150_SM6	LPD23	600	34.35625	4.131015815
LPD23_150_SM7	LPD23	700	43.875	5.177837386

soil moisture cont…

Day	21/09/2023	21/09/2023	21/09/2023	23/09/2023	23/09/2023	23/09/2023	23/09/2023	24/09/2023
Hour		12	15	11	12	15	17	11
LPD21_HH2_SMA			24.2					
LPD21_HH2_SMB			41.5					
LPD21_Temp	15	15	15					
LPD21_150_SM1		78.8	49					
LPD21_150_SM2		70.4	76					
LPD21_150_SM3		100	75					
LPD21_150_SM4		64.8	77.1					
LPD21_150_SM5		100	100					
LPD21_150_SM6		100	100					
LPD21_150_SM7		81.6	78					
LPD21_150_SM8		65	69.4					
LPD21_150_SM9		66.2	64.5					
LPD21_150_SM10		61.2	58.6					
LPD23_HH2_SMA				18.1	17.3	17.1	15	16.5
LPD23_HH2_SMB				25.9	25.8	25.9	25.8	28.5
LPD23_Temp				13	14	14	14	14
LPD23_150_SM1					18.9	29.8	40.6	42.5
LPD23_150_SM2					47	45.6	44	47
LPD23_150_SM3					45.6	42	43.6	46.8
LPD23_150_SM4					27.4	32	37	37.7
LPD23_150_SM5					48.6	42.6	43.6	51.2
LPD23_150_SM6					38	32.5	26.2	41.4
LPD23_150_SM7					53	45.4	47.6	49

soil moisture cont...

Day	25/09/2023	25/09/2023	25/09/2023	26/09/2023	26/09/2023	26/09/2023	26/09/2023	26/09/2023
Hour	9	14	17	9	11	13	15	17
LPD21_HH2_SMA								
LPD21_HH2_SMB								
LPD21_Temp								
LPD21_150_SM1								
LPD21_150_SM2								
LPD21_150_SM3								
LPD21_150_SM4								
LPD21_150_SM5								
LPD21_150_SM6								
LPD21_150_SM7								
LPD21_150_SM8								
LPD21_150_SM9								
LPD21_150_SM10								
LPD23_HH2_SMA	15.4	15.8	15.6	14.9	14.7	15.4	15.3	15.7
LPD23_HH2_SMB	25.4	25.8	22.9	25.8	26.2	26.5	23.1	23.4
LPD23_Temp	14	15	14	14	14	14	14	14
LPD23_150_SM1	46.2	46	53.2	52.4	49	46.4	46.1	49.4
LPD23_150_SM2	49	48.8	47	46.9	48.9	50.4	46.4	47.6
LPD23_150_SM3	48.6	46.8	45.8	46.8	42.1	39.8	44.9	44.7
LPD23_150_SM4	42.3	30.8	43	44	39.4	41.1	44.9	41.8
LPD23_150_SM5	51.3	50.8	45	45.3	46.6	43	46.4	46.6
LPD23_150_SM6	38.2	38.9	36	29.4	38.2	35.2	35.7	31.8
LPD23_150_SM7	32.6	48	35.5	47	46.3	41.6	41.6	43.1

soil moisture cont...

Day	27/09/2023	27/09/2023	27/09/2023	27/09/2023
Hour	8	10	10	11
LPD21_HH2_SMA				
LPD21_HH2_SMB				
LPD21_Temp				
LPD21_150_SM1				
LPD21_150_SM2				
LPD21_150_SM3				
LPD21_150_SM4				
LPD21_150_SM5				
LPD21_150_SM6				
LPD21_150_SM7				
LPD21_150_SM8				
LPD21_150_SM9				
LPD21_150_SM10				
LPD23_HH2_SMA	14.5	14.2	15.2	15
LPD23_HH2_SMB	23.6	25.5	25.5	25
LPD23_Temp	13	13.5	14	14
LPD23_150_SM1	50.2	49.2	37.5	48.2
LPD23_150_SM2	47.6	48.2	48.8	43.8
LPD23_150_SM3	42.5	49.2	40.8	44.6
LPD23_150_SM4	34.6	35.7	34.4	39.3
LPD23_150_SM5	43	44.7	44.4	42
LPD23_150_SM6	35	32	31.7	29.5
LPD23_150_SM7	47	43	39.2	42.1

H Appendix: Hydrus model

Contents:

- Finite element model setup for complete LPD cross-section
- Hydrus Modelling for Conceptual Model Assumption Validation

Finite element model setup for complete LPD cross-section

The model matches the geometry of the LPD experimental setup. It includes the locations of impermeable boundaries, drains, soil layers, and LPD locations. The location of sensors in the LPD are taken as observation points to compare model results to observed data.

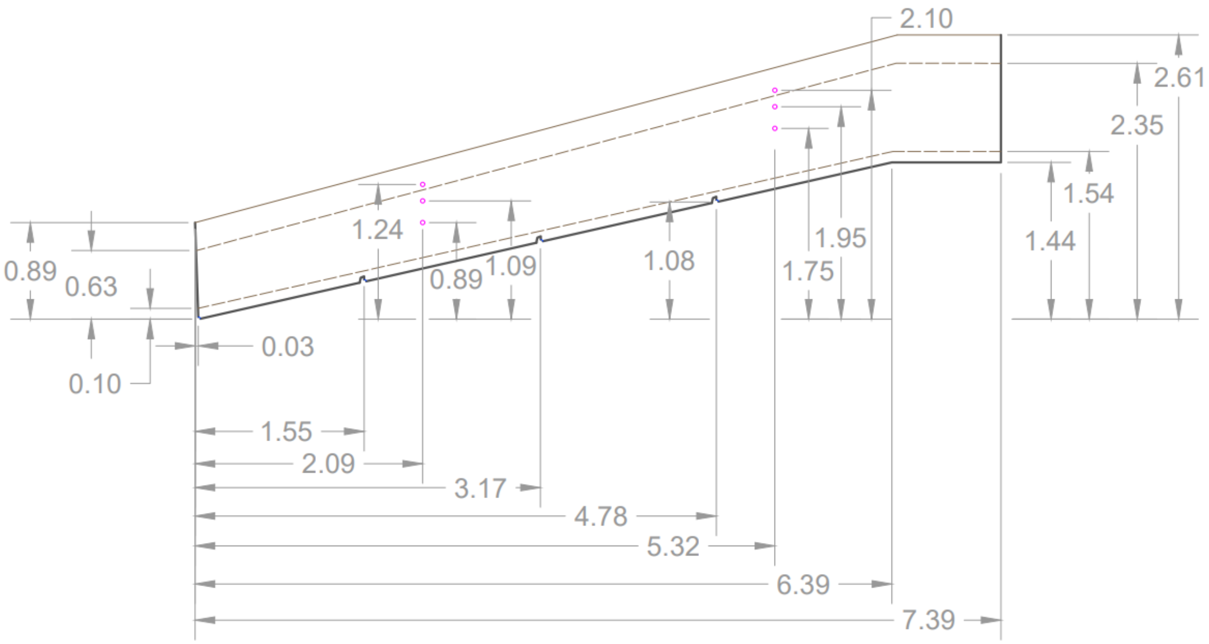


Figure 44: Hydrus model input geometry

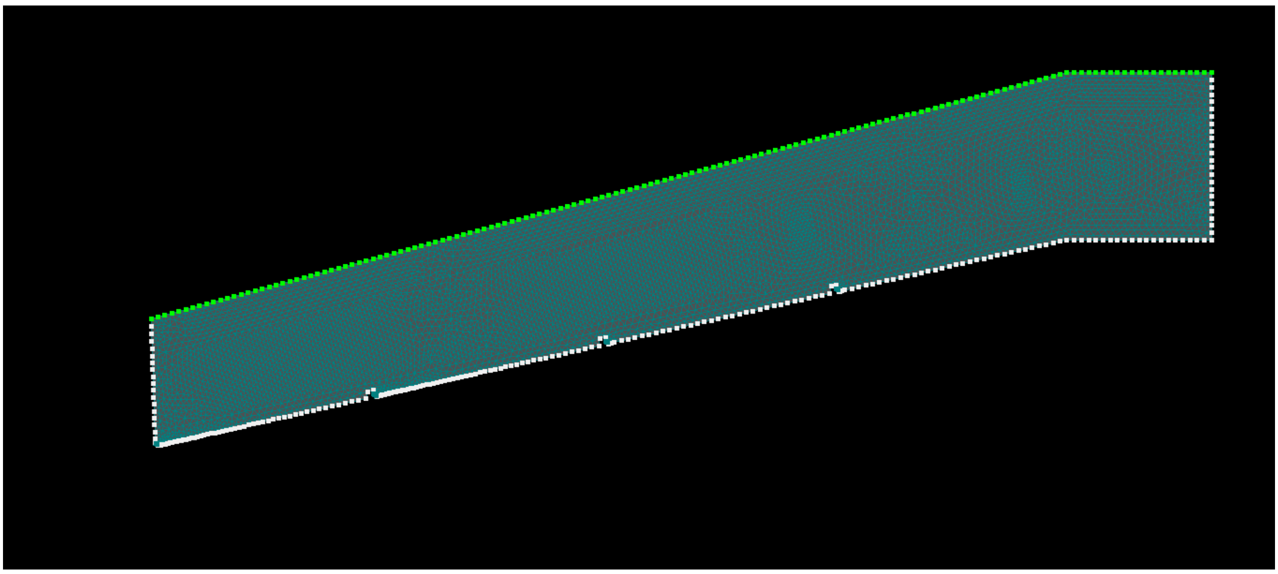


Figure 45: Hydrus model layout

Hydrus Modelling

for Conceptual Model Assumption Validation

1. Validation of assumption that flow in the unsaturated soil matrix is one-dimensional. This justifies decision for a lumped conceptual model with only lateral flow in LPD macropores. See activity 1.

2. Quantification of water content conditions necessary for seepage to occur from soil to LPD macropores. See activity 2.

3. Validation and quantification of assumption that capillary boundary between soil types governs initiation of percolation flux. See activity 3.

0. Model settings.

All three activities are setup with Hydrus defaults besides the following settings:

- Time units are set to hours, initial timestep = 0.01, min timestep = 0.001, max timestep = 1.
- Water content tolerance is set to 0.01.
- van Genuchten – Maulem model is selected with air-entry value of -2cm
- The properties of materials 'Sand' and 'Sandy Clay Loam' are selected from Hydrus' soil catalog

Mat	Name	Qr [-]	Qs [-]	Alpha [1/cm]	n [-]	Ks [cm/hour]	l [-]
1	Sand	0,045	0,43	0,145	2,68	29,7	0,5
2	Sandy Clay Loam	0,1	0,39	0,059	1,48	1,31	0,5

Settings on geometry, initial conditions and boundary conditions are indicated individually for each of the activities in this report.

1. Model of the experimental control setup longitudinal cross-section geometry (2D).

The objective of this activity is to determine whether there is a significant movement of water along the slope, or if it only infiltrates vertically.

a. Model setup

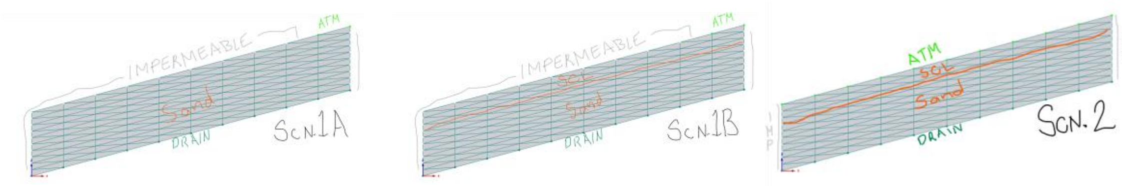
Geometry: 6.5 meter by 1 meter at a 15 degree slope. Boundary conditions: free drainage on the bottom, impermeable on the sides, top boundary condition varies by case.

b. Scenarios and Model Runs

The layout of each scenario is shown in figure 1.1.
Scenario 1: Atmospheric boundary condition only near the top of the slope.

- Scenario 1A: entire cross-section is sand, Three model runs for this scenario with 1mm/h precipitation were run, each with a different initial pressure head; Scn1Ai: -100cm, Scn1Aii: -50cm and Scn1Aiii: -10cm.
- Scenario 1B: the top 30cm of the cross-section are sandy clay loam, and the remainder is sand, Three model runs for this scenario with 10mm/h precipitation were run, each with a different initial pressure head; Scn1Bi: -100cm, Scn1Bii: -50cm and Scn1Biii:-10cm. An additional run with initial pressure head of -100cm and precipitation rate of 100mm/h (Scn1Biv) was also run.

Scenario 2: Atmospheric boundary conditions along the entire top boundary. The top 30 cm of the cross section are sandy clay loam, and the remainder is sand. Initial conditions of -100 cm pressure head. Four model runs are completed with different precipitation rates; Scn2A: 10 mm/h,



(a) **(b)** **(c)**

Figure 1.1. Model setup for each scenario. Not to scale.

c. Results

The results of Scenario 1 (figure 1.2) show that water mostly flows in one dimension; downwards. In the model runs starting with a pressure heads over -100cm (Scn1Aii, Scn1Aiii, Scn1Bii, Scn1Biii) showed draining of water from the initial condition, before eventually reaching a steady state similar to the scenarios that started at h=-100cm (Scn1Ai, Scn1Bi).
For the Scenario 2 model runs, the time and maximum pressure in the Sandy Clay Loam when water content began to increase in the sand were recorded in Table 1.1 and shown in Figure 1.4. While there may be some indication toward the behaviour of the capillary boundary between the two soil types in this scenario, not enough model runs were made to provide a clear result. Based on the findings from Scenario 1, this question should be easily answered in a 1D model (see Activity 3).

Table 1.1 Summary of results from model runs of Scenario 2.

Scn.	Precip. [mm/hr]	Infiltration from SCL to Sand (t_{inf}) [hr]	Cumulative Precip @ t_{inf} [mm]	Maximum pressure in SCL [cm]
2A	10	8.75	87.5	-1.3
2B	20	6.00	120.0	3.8
2C	30	5.50	165.0	3.7
2D	50	5.25	265.0	3.9

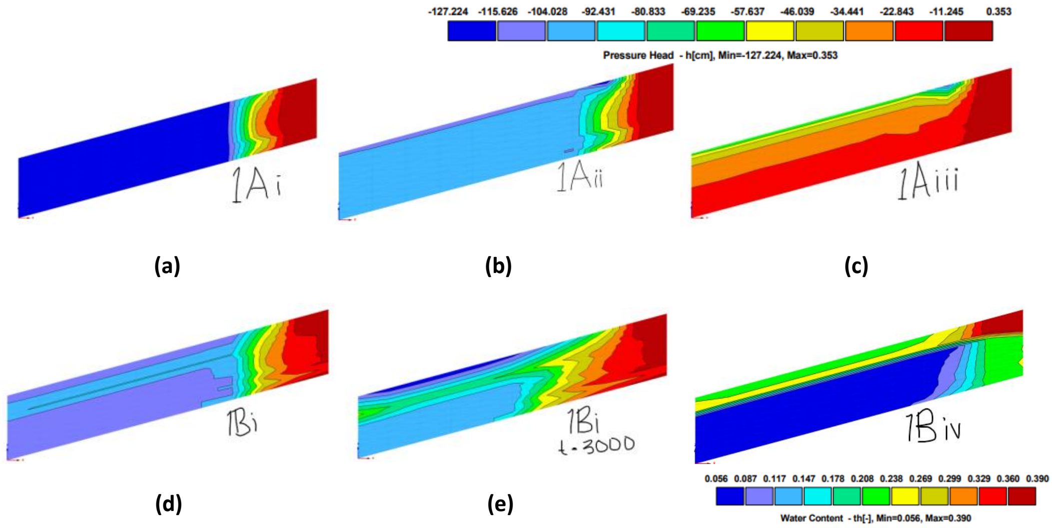


Figure 1.2. Results for pressure head in 1A scenarios at t=60hrs (a) Init h=-100, (b) Init h=-50, (c) Init h=-10, Results for pressure head in 1B Scenarios Init=-100 (d) Init=-100 t=60hrs, (e) Init=-100 t=60hrs; and 1Biv water content (f) Init=-100 t=3000

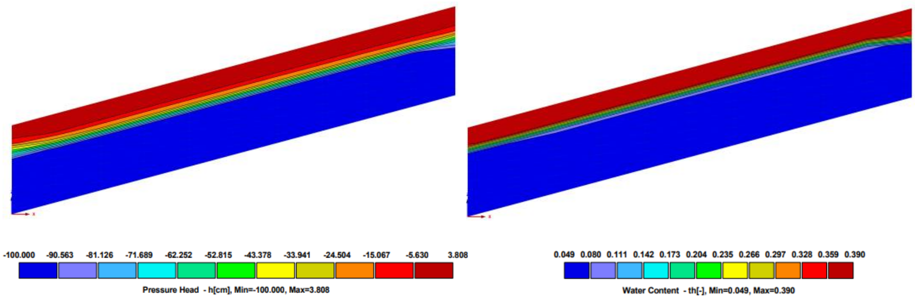


Figure 1.3. Results Scenario 2B at t=6hrs (a) pressure head, and (b) water content.

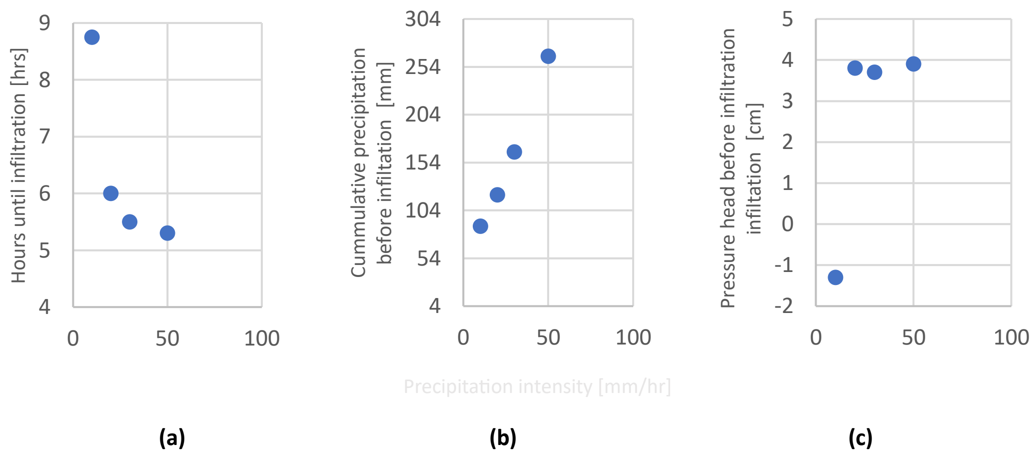


Figure 1.4. Results Scenario 2B varying precipitation intensity on (a) hours until infiltration to sand layer, (b) cumulative precipitation before infiltration, (c) maximum pressure head in SCL before infiltration.

2. Model of the Live Pole Drain experimental setup transverse cross-section (2D)

The purpose of this activity is to find the precipitation intensity at which there is surface runoff and/or seepage from the top layer of the soil in the experimental setup. Two scenarios with varying precipitation were set up to answer this question.

a. Scenarios

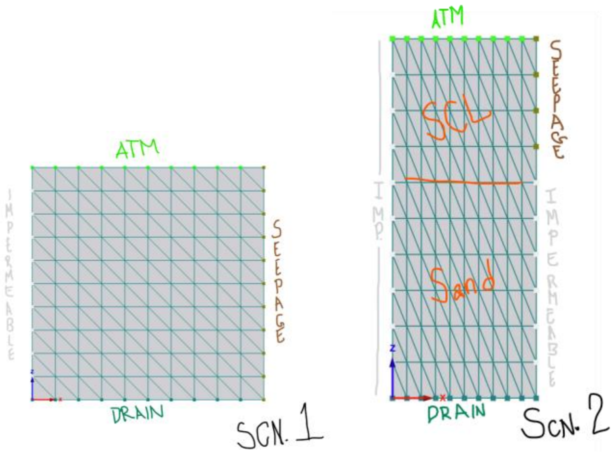


Figure 2.1. Model setup. Not to Scale.

Scenario 1. Only Sandy Clay Loam, 40 by 40 cm, with a seepage face on one side, impermeable boundary on the other, free drainage bottom, and atmosphere top. Initial conditions pressure = -100cm. Scn1A. Precip = 5 mm/h, Scn1B. Precip = 10 mm/h, Scn1C. Precip = 11 mm/h, 1D. Precip = 15 mm/h, Scn1E. Precip = 20 mm/h

Scenario 2. Two layers, 60 cm of Sand under 40 cm of Sandy Clay Loam, only Sandy Slay Loam layer has a seepage face on one side, the other side is impermeable, as well as both sides of the sand; the bottom boundary has free drainage, and the top is an atmospheric boundary. Scn2A. Precip = 5 mm/h, Scn2B. Precip = 10 mm/h, Scn2C. Precip = 20 mm/h

a. Results

For each model run, the time steps in which infiltration, runoff and seepage begin are recorded (Table 2.1), For Scenario 1, seepage begins before runoff, at a precipitation rate of 11 mm/hr; both seepage and infiltration reach their maximum rates in for a precipitation rate of 15 mm/hr. For Scenario 2, seepage never occurs.

Table 2.1 Summary of results from model runs.

Scn.	Precip. [mm/hr]	Infiltration start [hr]	Runoff start [hr]	Seepage start [hr]	Infiltration rate [cm2/hr]	Runoff rate [cm2/hr]	Seepage rate [cm2/hr]	Cumulative Precip @ t_{inf} [mm]	Cumulative Precip @ t_{seep}[mm]
1A	1	27.0	n/a	n/a	4	0	0	20	n/a
1B	5	13.0	n/a	n/a	20	0	0	65	n/a
1C	10	7.0	n/a	n/a	40	0	0	70	n/a
1D	11	6.5	n/a	11.00	45	0	0.15	70	120
1E	15	4.7	2.5	4.00	50	5	2.00	70	60
1F	20	3.5	0	4.00	50	22	2.00	70	60
2A	10	15.0	n/a	n/a	40	0	0	150	n/a
2B	15	12.0	2.5	n/a	50	5	0	180	n/a
2C	20	12.0	1.0	n/a	50	20	0	240	n/a

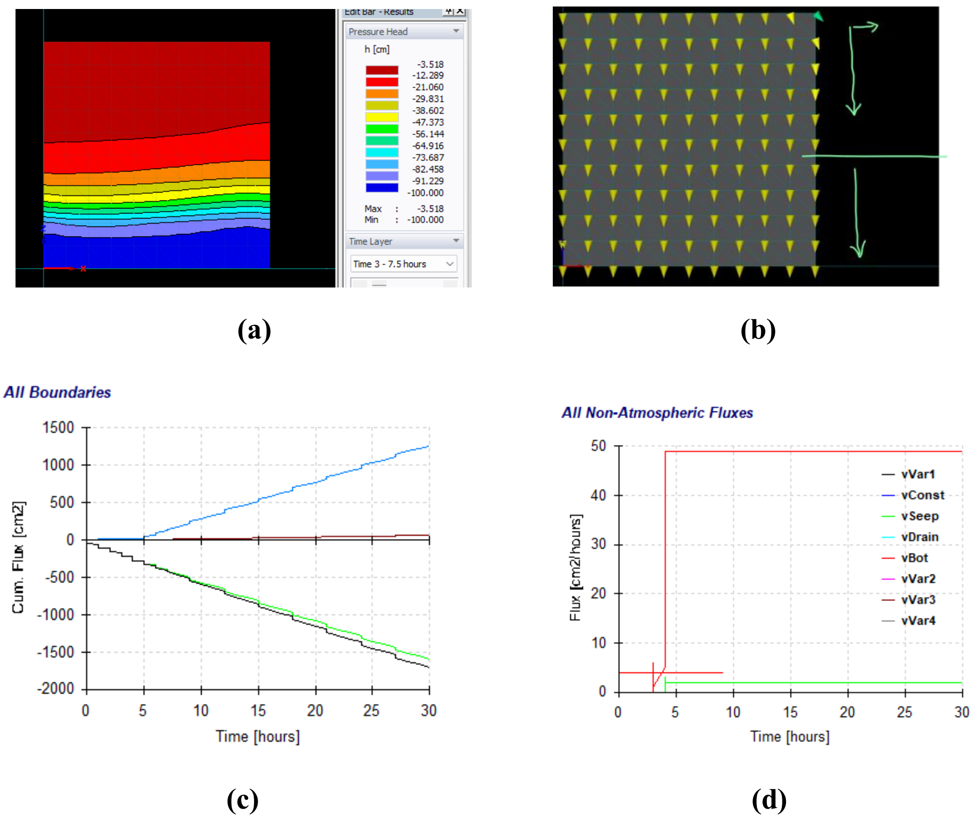


Figure 2.2. Example results from Scenario 1 Model (a) pressure head slightly higher on the seepage face side of the x-sect. (b) flow vectors showing a horizontal component in the upper part of the x-sect on the seepage boundary. (c) cumulative fluxes over all boundaries; blue: bottom flux, brown: seepage, green: precipitation-runoff, black: precipitation. (d) hourly fluxes; red: bottom flux, and green: seepage flux.

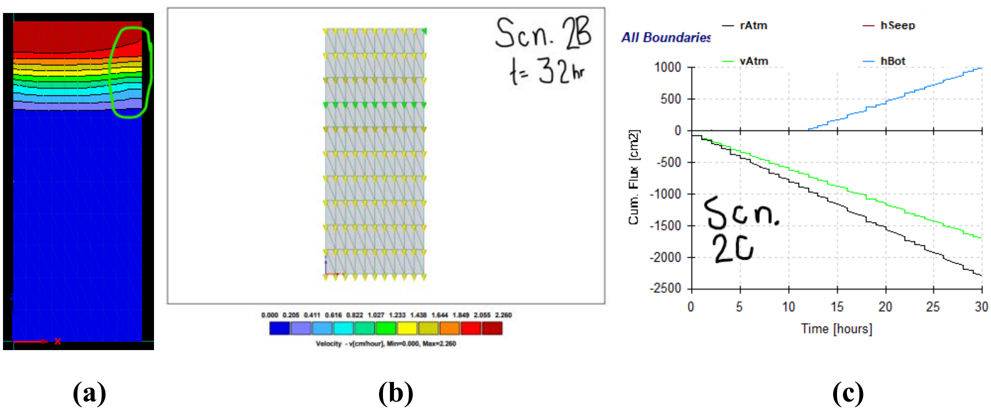


Figure 2.3. Example results from Scenario 2 Model. (a) skewed head toward seepage face, (b) skewed flow velocity vectors toward seepage face, with slower velocities at interface between soil materials (c) cumulative fluxes over all boundaries; blue: bottom flux, green: precipitation-runoff, black: precipitation.

3. Model of soilcolumn with two type soil (1D)

The objective of this activity is to check whether capillary boundary effects are detectable in a soil column of two materials, the method and visualization of results follows an approach by Mancarella and Simeone (2012).

Mancarella, D., & Simeone, V. (2012). Capillary barrier effects in unsaturated layered soils, with special reference to the pyroclastic veneer of the Pizzo d'Alvano, Campania, Italy. *Bulletin of Engineering Geology and the Environment*, *71*, 791-801.

a. Model setup

100cm soil column

Material 1 = Sand, bottom 60 cm (Node 42 to 101)

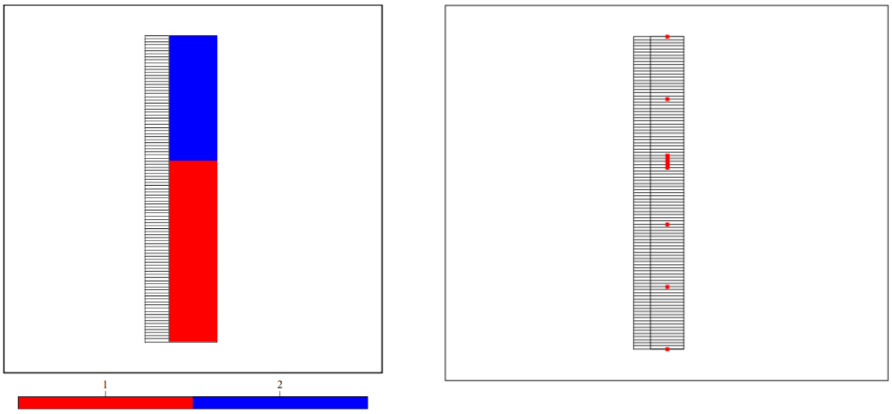
Material 2 = Sandy Clay Loam, 40 cm (Node 1 to 41)

Top boundary condition = Atmospheric

Bottom boundary condition = free drainage

Print times = 0, 50, 100, 500, 1000, 1001, 1002, 1003, 1004, 1005, 1006 , 1010, 1015, 1020, 1025

Observation Nodes = 1, 21, 39, 40, 41, 42, 43, 44, 61, 81, 101



(a) (b)

Figure 3.1. Model setup (a) Material distribution, (b) Observation nodes.

b. Drying – Initial scenario to check model function and outputs.

i Run-specific inputs:

Atmospheric flux = 0, Run time = 1025 hours, Initial conditions h=-100cm. This scenario was run with sand in the upper layer and SCL in the lower layer.

ii Results:

From the observation nodes, water content converges to field capacity = 0.2 for M2 (N1-5) and 0.05 for M1 (N6-10). Pressure head starts all =-100, then moves toward equilibrium (for a run of 18000 hours, the head at the lower boundary increases.)

From the profile information, we can see that Water content, starts uniform in both layers, at T1 it starts decreasign in the top and increasing in the bottom of the top layer, at T2 it starts increasing slightly in the sand.

Hydraulic conductivity, and hydraulic capacity, proportional to water content.

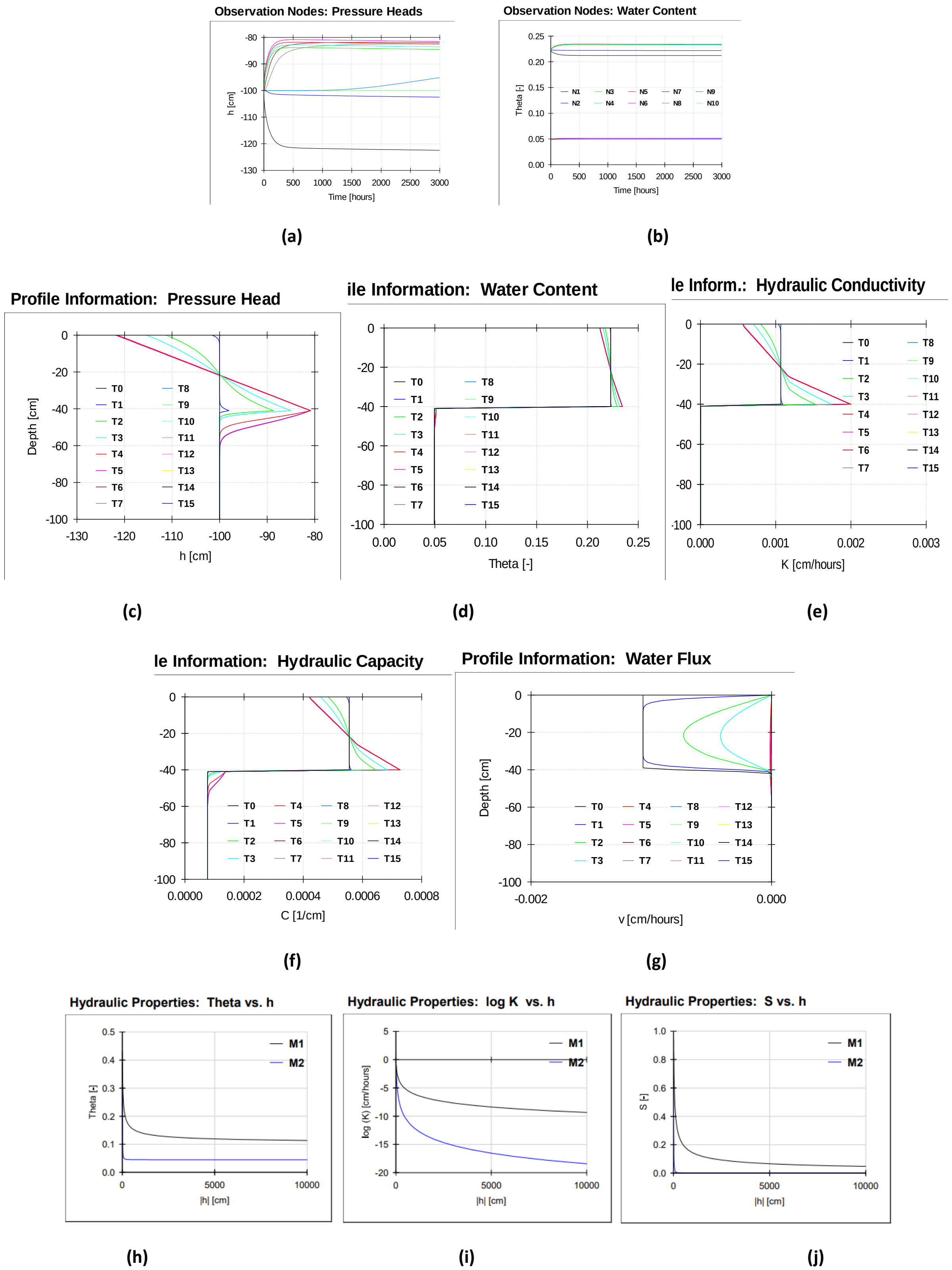


Figure 3.2. Example Hydrus 1D outputs, for dryign scenario. (a-b) Observation node results, (c-g) Profile information at prrint times, (h-j) Hydraulic properties.

iii Scenarios and Model Runs

The model is run with

Initial WC [-] / P [mm/h]	0.11	0.20
2	Th11P02	Th20P02
5	Th11P05	Th20P05
10	Th11P10	Th20P10
20	Th11P20	Th20P20

iv Results.

The expected results, based on Mancarella and Simeone (2012) are shown in figure 3.3, where delays are visible between the moment when water content starts to increase above the interface, and when it starts to increase at the bottom of the profile.

To better see what is happening at the interface, I include an additional node directly below the interface. The results (figure 3.4) show a similar pattern to Mancarella's, however no increased delay is visible between the nodes above and below the interface.

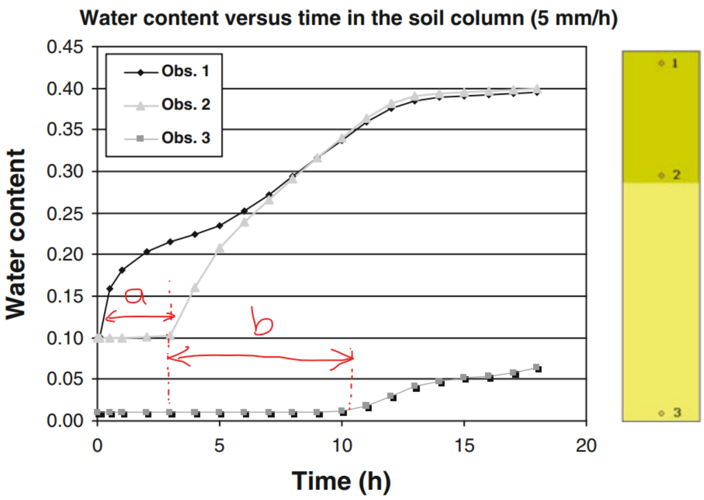


Figure 3.3. Results from similar study (Mancarella and Simeone, 2012). Adapted to indicate the delay before increasing water content above the interface (a) and near the bottom of the profile (b).

Table 3.2. Results from model runs. Times and cumulative precipitation when wetting front reaches each observation node

Scn.	Initial Water Content. [-]	Precip. [mm/hr]	Above interface WC increase [hr]	Below interface WC increase [hr]	Bottom WC increase [hr]	Cumulative Precip @ t_{AI} [cm2/hr]	Cumulative Precip @ t_{BI} [mm]	Cumulative Precip @ t_{inf}[mm]
Th11P02	0.11	2	40	42	65	80	84	130
Th11P05	0.11	5	18	19	31	90	95	155
Th11P10	0.11	10	10	10	17	100	100	170
Th11P20	0.11	20	6	6	11	120	120	220
Th20P02	0.20	2	18	22	42	36	44	84
Th20P05	0.20	5	11	11	21	55	55	105
Th20P10	0.20	10	6	6	12	60	60	120
Th20P10	0.20	20	4	4	8	80	80	160

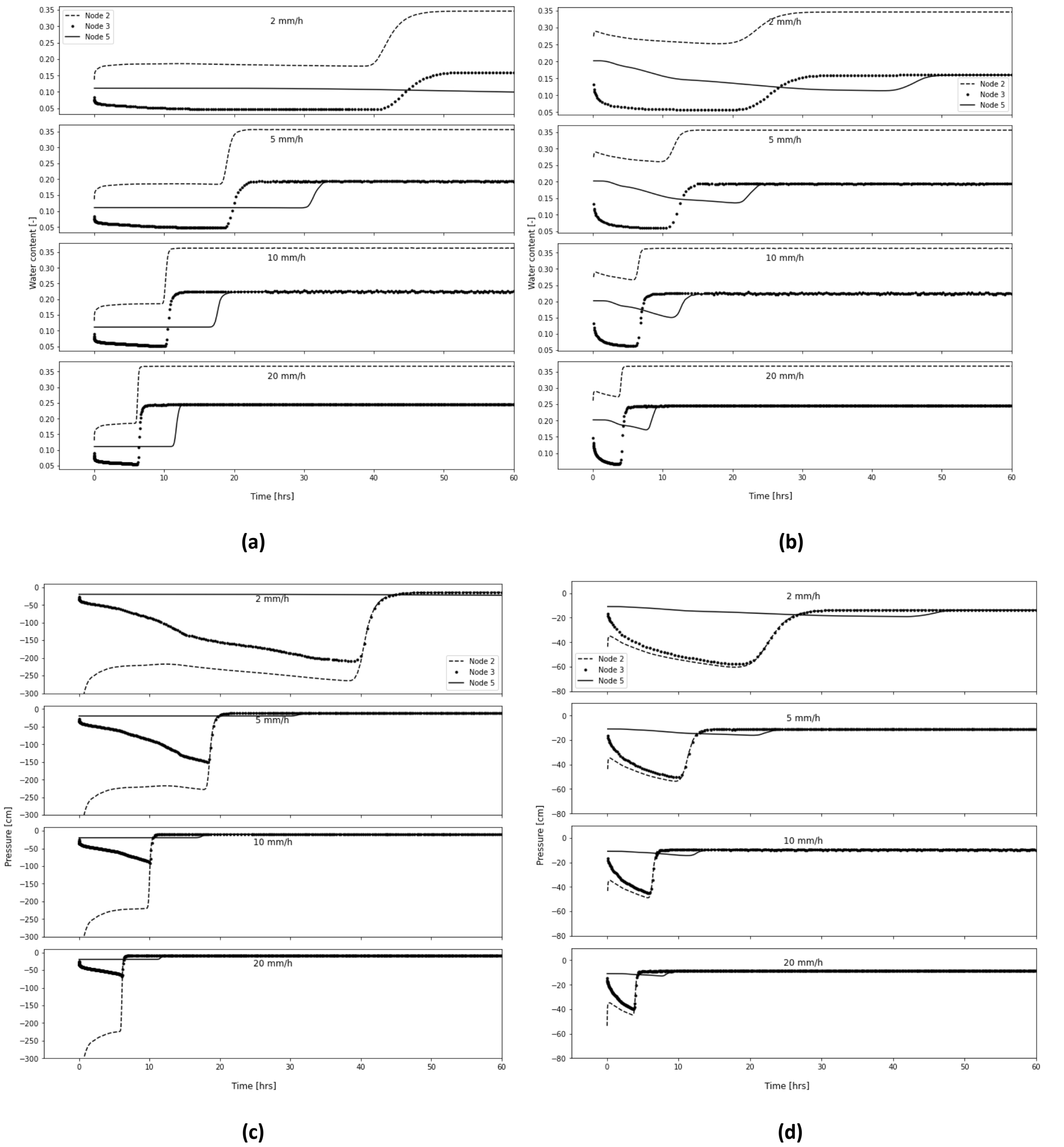


Figure 3.4. Model run results at observation points above interface (Node 2, dashed line), below interface (Node 3, dotted line), and near the lower boundary (Node 5, continuous line). Model runs with initial water content of 11% on the left, and with initial water content of 20% on the right. The top plots show water content, and the lower plots show pressure head, note that the y-axis scale is different in subfigures c and d.

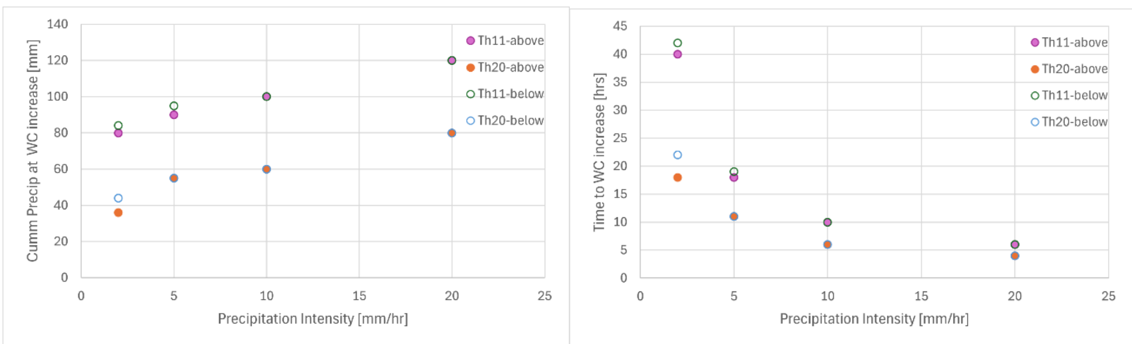


Figure 3.5. Conditions at which wetting front crosses interface, for initial conditions of 11% water content and 20% water content, (a) Cumulative Precipitation, (b) time.

I Appendix: Conceptual model

Contents:

Additional Model Functions and Model Process Plots

These equations were used, in addition to those described by Benschop (2022).

Penman-Monteith (equation I) to calculate potential evapotranspiration where:
ET_0 is the reference evapotranspiration,
Δ is the slope of the saturation vapor pressure-temperature curve,
R_n is the net radiation at the crop surface,
G is the soil heat flux density,
γ is the psychrometric constant,
T is the air temperature at 2 meters above the crop surface,
u_2 is the wind speed at 2 meters above the crop surface,
e_s is the saturation vapor pressure,
e_a is the actual vapor pressure,
rs is the surface resistance, and
ra is the aerodynamic resistance.

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T+273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2) \cdot \left(1 + \frac{rs}{ra}\right)} \tag{2}$$

Pedotransfer function from Rajkai et al. (2004) (Equation 3), to calculate van Genuchten parameters, where:
θ_s in the saturated moisture content,
ρ is the bulk density,
OM is the organic matter content [%],
C is the clay content [%],
S is the sand content [%],
S_i is the silt content [%],

$$\theta_s = 118.76 - 60.02 \times \rho - 0.25 \times OM - 0.0007 \times C^2 - 1.99 \times \ln(C) + 9.78 \times \rho^2 - 0.04 \times \rho \cdot S + 0.116 \times \frac{S}{S_i} + 0.00078 \times \rho^2 \cdot C^2 \tag{3}$$

Manning equation (Eq. 4) for flow in the quickflow reservoir, where:
- Q is the flow rate (mm/hr)
- n is the Manning's roughness coefficient
- A is the cross-sectional area of flow (mm^2), set equal to S_{LPD}
- P is the hydraulic radius (mm), approximated as 2 * S_{LPD} + 1
- S is the slope of the channel

$$Q = \frac{1}{n} \left(\frac{A}{P}\right)^{2/3} \cdot S^{1/2} \tag{4}$$

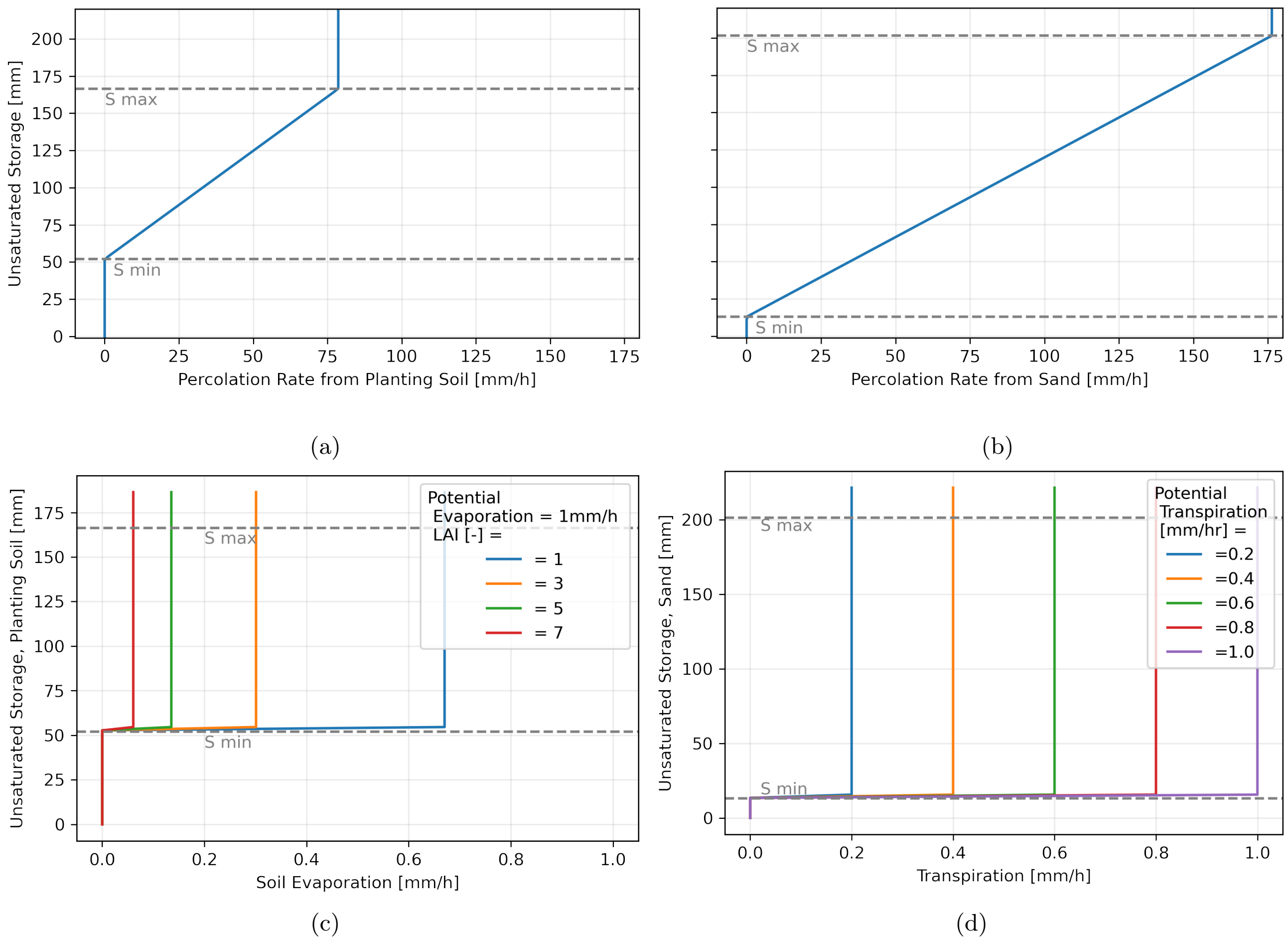


Figure 46: Less interesting subsurface flow partitioning functions. Percolation rate for (a) planting soil and (b) sand. Evapotranspiration fluxes from the subsurface storages: (c) soil evaporation from planting soil and (d) transpiration from sand.

Additional results

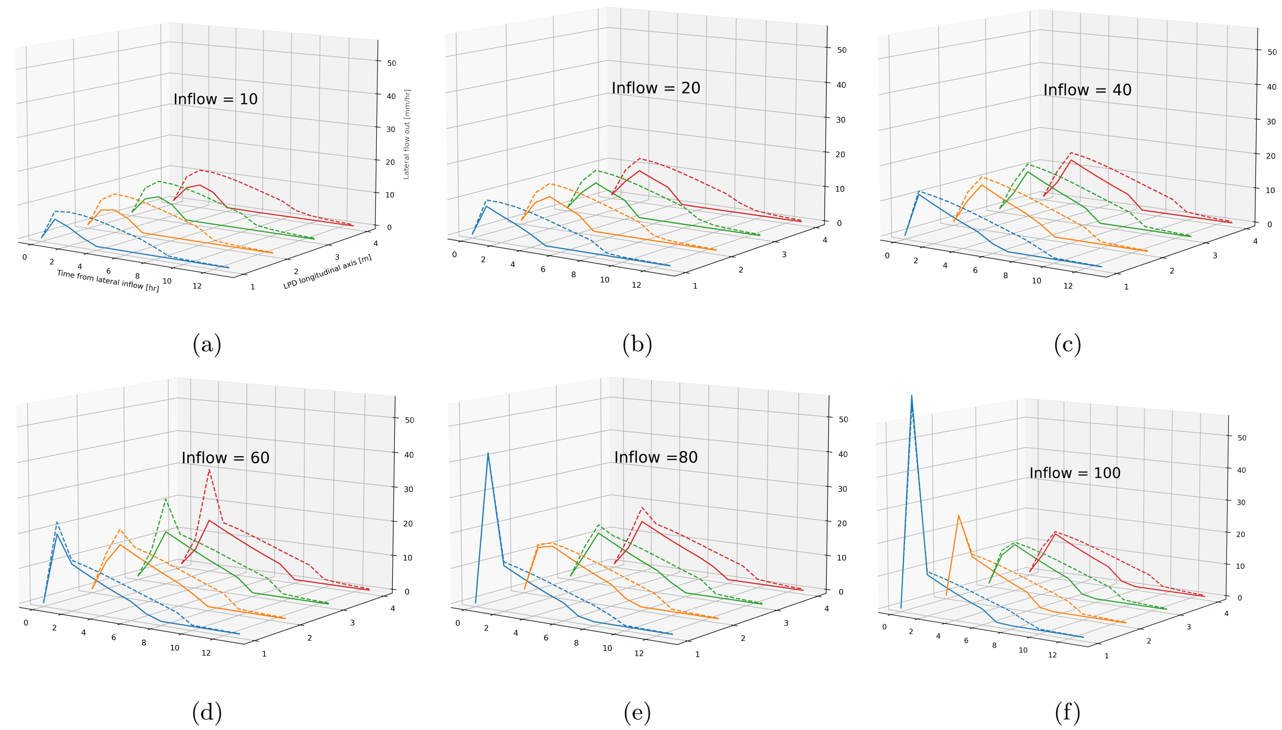


Figure 47: Lateral outflow from each meter of length of LPD for intial soil moisture conditions of field capacity (solid lines), and 25% saturation (dashed lines) with applied inflows at t=1 of (a) 10 mm, (b) 20mm (c) 40mm, (d) 60mm (e) 80mm, (f) 100 mm.

(a) p50 internal (b) p50 out-flux

(c) p62.5 internal (d) p62.5 out-flux

(e) p75 internal (f) p75 out-flux

(g) p87.5 internal (h) p87.5 out-flux

(i) p99 internal (j) p99 out-flux

Figure 48: Internal fluxes and absolute value of out-fluxes for each synthetic forcing scenario.

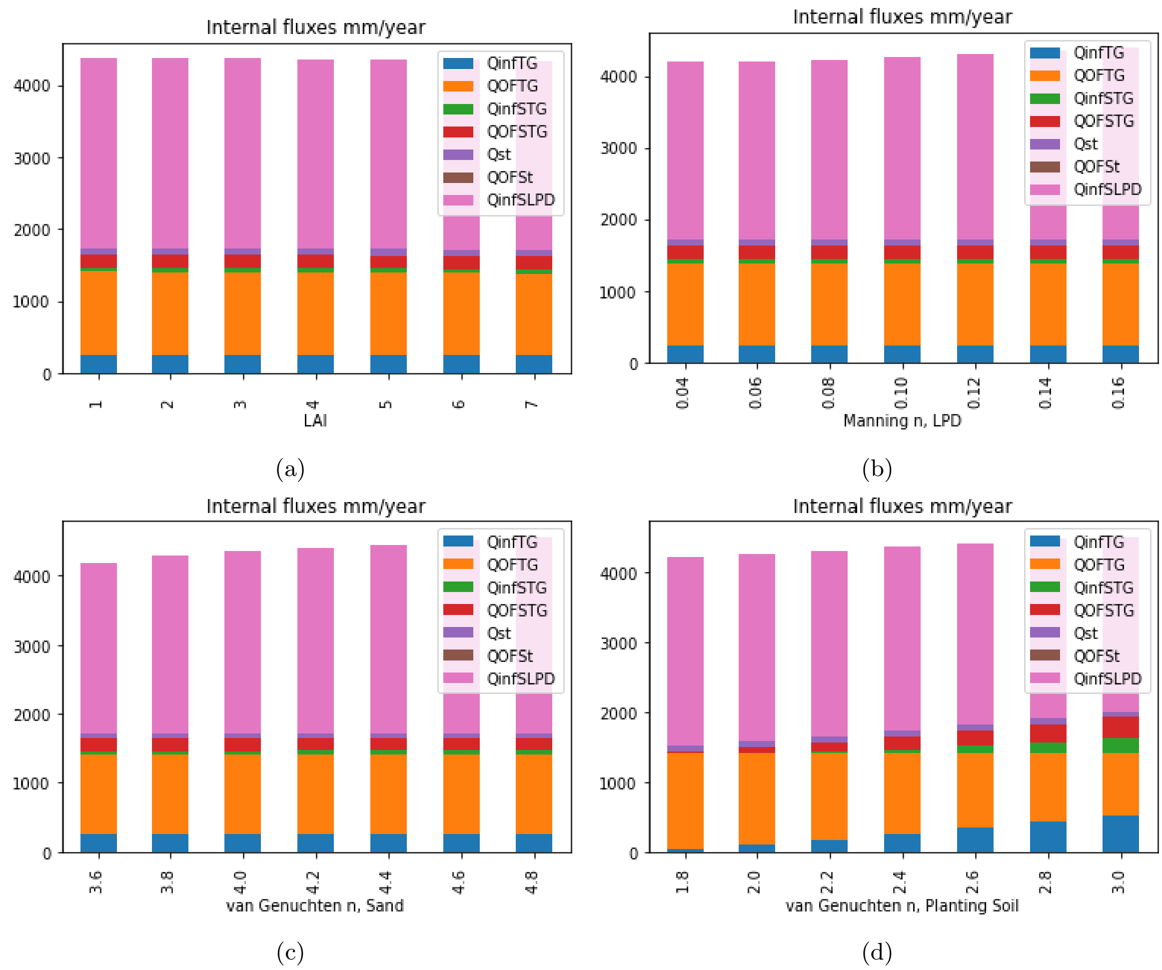


Figure 49: Internal fluxes in sensitivity analysis scenarios

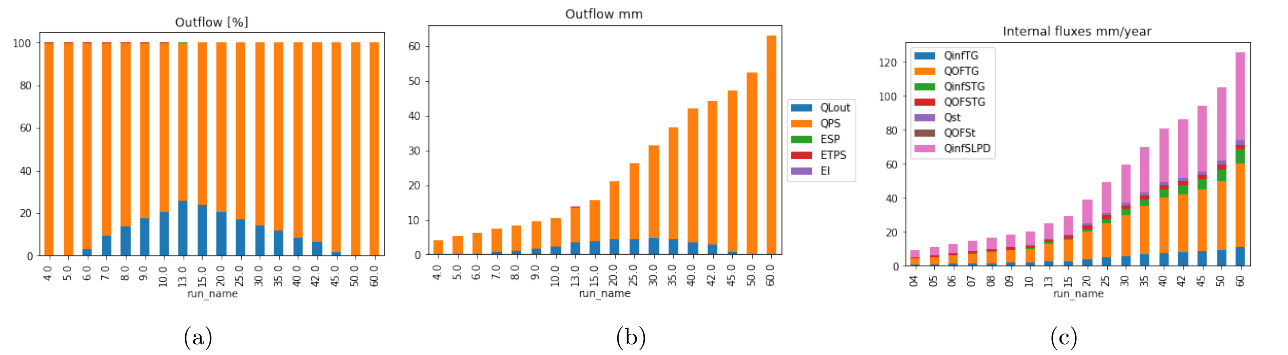


Figure 50: Precipitation only synthetic forcing, (a) Percentage of flow partitioning, (b) Absolute value fo flow partitioning, (c) internal fluxes partitioning

R model Input Parameters

```
# VALUES OF INPUT PARAMETERS AND VARIABLES
# These values can be changed according to the characteristics of the LPD, its surroundings and the season.
#----
# Version 1 (EBv)
# Author: Eefje Benschop
# Contact: eefjebenschop@gmail.com

#Version 2 (LCv)
# Edits by: Linnaea Cahill
# Contact: rc.linnaea@gmail.com

#----
# SOIL, SLOPE and LPD (constant)
#----
# general
angle <- 15
i <- sin(angle * (pi/180)) #sin of slope degree
slope <- tan(angle * (pi/180)) # longitudinal slope
dt <- 1 #time step (h)

# EBv ==> Only one unsaturated storage for LPD and soil in and around it.
# LCv ==> Multiple storages for soil types and LPD

#Sand
d.sand <- 650 #depth of sand (mm)
th.fc.sand <- 0.02 #soil moisture content at wilting point (-)
ksat.sand <- 7200 #saturated hydraulic conductivity (mm/h) #lab estimate = 7200
n.sand <- .31 #porosity (-)
n.genuchten.sand <- 4.0 #Van Genuchten parameter # test array n.genuchten.sand = [3.6, 3.8, 4, 4.2, 4.4], normally = 4
alpha.sand <- 0.25 #Van Genuchten parameter (mm3/mm)

#Teelgrond
d.TG.total <- 400 #depth of planting soil (mm) note it contains the LPD, adjusted value below.
th.fc.TG <- 0.2 #soil moisture content at wilting point (-)
ksat.TG <- 50.4 #saturated hydraulic conductivity (mm/h)
n.TG <- .64 #porosity (-)
n.genuchten.TG <- 2.4 #Van Genuchten parameter # test array n.genuchten.TG = [2.0, 2.2, 2.4, 2.6, 2.8], normally = 2.4
alpha.TG <- 0.12 #Van Genuchten parameter (mm3/mm)

# LPD, LCV ==> added Option 1 the LPD is assumed to function as an open channel with manning parameter,
#      EBv ==> Option 2 the LPD is assumed to function as a porous media with vG parameters
d.LPD.dia <- 300 #diameter bundle (mm)
n.LPD <- 0.43 #porosity (-)
th.fc.LPD <- 0.02 #LPD moisture content at wilting point, assume it can dry out as much as the sand.
#Option 1 -->
n.manning.LPD <- 0.14 # Manning friction coefficient for a densely vegetated channel typ. 0.08 to 0.14 (Chow, 1959) # test array n.manning= [0.08, 0.10, 0.12, 0.14, 0.16]
#Option 2 -->
ksat.LPD <- 10000 # mm/h
n.genuchten.LPD <- 2.4 #Van Genuchten parameter
alpha.LPD <- 0.12 #Van Genuchten parameter (mm3/mm)

#Teelgrond and LPD within the same layer.
pct.LPD <- 0.35 # Percentage of top layer that is the LPD.
d.TG <- d.TG.total * (1 - pct.LPD)
d.LPD <- d.TG.total - d.TG


#----
# VEGETATION- and SEASON-RELATED
#----

# EBv ==> All vegetation and season related are global constants for each model run, and edited manually in this file.
# LCv ==> Vegetation and season related parameters are variable with time and come from input file "Q_base", "LAI", "p", "ps", "S", "Ac", "kc"
```

```
#         derived parameters (c.c), and (SI.max) are time variable as well, moving
them to the LPD runner.

#Planting soil parameters
SU.TG.max <- eq.SU.max(n.TG, d.TG) #maximum subsurface storage in planting soil (mm)
P.TG.max <- eq.P.max(SU.TG.max, d.TG, th.fc.TG, dt) #maximum percolation rate (mm/h)
SU.TG.min <- th.fc.TG * d.TG

#Sand parameters
SU.S.max <- eq.SU.max(n.sand, d.sand) #maximum subsurface storage in sand (mm)
P.S.max <- eq.P.max(SU.S.max, d.sand, th.fc.sand, dt) #maximum percolation rate (mm/h)
SU.S.min <- th.fc.sand * d.sand

#LPD parameters
S.LPD.max <- eq.SU.max(n.LPD, d.LPD) #maximum subsurface storage in LPD (mm)
S.LPD.min <- th.fc.LPD * d.LPD
```

R model Functions

```r
# FUNCTIONS FOR THE MODEL
# This file contains the functions used to determine the fluxes and update the model states
#----

#EBv = Version 1 by:
# Author: Eefje Benschop
# Contact: eefjebenschop@gmail.com

#LCv = Version 2 by:
# Author: Linnaea Cahill
# Contact: rc.linnaea@gmail.com

#in LCv, Part I (i.e. above ground) remains the same, Part II (below ground) uses most of the same equations as EBv,
#  but distributes subsurface fluxes between three storages instead of one.

#----


# INTERCEPTION STORAGE
# Eq. 1 direct throughfall
eq.PE.d <- function(P, p){
  PE.d <- p * P
  return(PE.d)
}

# Eq. 2 indirect throughfall
eq.PE.i <- function(SI, SI.max, dt=1){
  PE.i <- max(c((SI - SI.max) / dt, 0))
  return(PE.i)
}

# Eq. 3 stemflow
eq.Qst <- function(PE.d, PE.i, ps){
  Qst <- ps * (PE.d + PE.i)
  return(Qst)
}

# Eq. 4 total throughfall
eq.PE <- function(PE.d, PE.i, Q.st){
  PE <- PE.d + PE.i
  return(PE)
}

# Eq. 5 interception evaporation
eq.EI <- function(P, EP, SI, dt=1){
  if(P == 0){
    EI <-min(c(EP, SI/dt))
  }else{
    EI <- 0
  }
  return(EI)
}

# Eq. 6 maximum interception storage
eq.SI.max <- function(S, c.c, Ac.g){
  if(S == 0){
    SI.max <- 0
  }else{
    SI.max <- S / c.c * Ac.g
  }
  return(SI.max)
}

# Eq. 7 canopy cover fraction
eq.c.c <- function(kc, LAI){
  c.c <- 1 - exp(-kc * LAI)
  return(c.c)
}

# Before calling Part I: determine SI.max
# Eq. Part I
```

```r
part.I <- function(P, EP, SI, SI.max, p, ps, dt){
  # Interception and stemflow
  PE.d <- eq.PE.d(P, p)
  SI = SI + (1 - p) * P
  PE.i <- eq.PE.i(SI, SI.max, dt)
  Qst <- eq.Qst(PE.d, PE.i, ps)
  PE <- eq.PE(PE.d, PE.i, Q.st)
  EI <- eq.EI(P, EP, SI, dt)
  SI <- SI - (PE.i + EI)

  return(c(SI, EI, Qst, PE))
}


# INFILTRATION AND RUNOFF
# Eq. 8 Maximum subsurface storage
eq.SU.max <- function(n, d){
  SU.max <- n * d
  return(SU.max)
}

# Eq. 9EBv Van Genuchten for unsaturated hydraulic conductivity from EBv --> not used in LCv, instead, functions 9(a-d)
#eq.kr <- function(SU, alpha, n.genuchten){
#  m <- 1 - 1/n.genuchten
#  numerator <- (1 - (alpha * SU)^(n.genuchten-1) * (1 + (alpha * SU)^n.genuchten)^(-m))^2
#  denominator <- (1 + (alpha * SU)^n.genuchten)^(m/2)
#  kr <- numerator / denominator
#  return(kr)
#}

# Eq. 9(a)LCv Effective water content
eq.Se <- function(SU, SU.min, SU.max, adj.SE){
  theta <- max(c(SU, SU.min+1))
  Se = (theta - (SU.min-adj.SE)) / (SU.max - (SU.min-adj.SE))
  return(Se)
}

# Eq. 9(b)LCv  Saturated Hydraulic conductivity equation  (van Genuchten, 1980)
eq.KvG <- function(SE, ksat, n.genuchten){
  m <- 1 - 1 / n.genuchten
  l <- 0.5
  K = ksat * SE**l * (1-(1-SE**(1/m))**m)**2
  return(K)
}

# Eq. 9(c) saturation factor function
eq.fs <- function(SU, PE, SU.max, k.th){
  fs <- k.th * (1 - exp(- PE / k.th))
  return(fs)
}

# Eq. 9(d) infiltration submodel
inf.submodel <- function(SU, Pin, SU.max, SU.min, ksat, n.genuchten, adj.SE){
  SE <- eq.Se(SU, SU.min, SU.max, adj.SE) #eq 9a
  if (SU > SU.max){
    k.th.f <- ksat
  }
  else {
    k.th.f <- eq.KvG(SE, ksat, n.genuchten) #eq 9b
  }
  fs <- eq.fs(SU, Pin, SU.max, k.th.f) #eq 9c
  Qinf <- min(c(Pin * fs, Pin))
  QOF <- Pin - Qinf
  return(c(Qinf, QOF))
}


# LATERAL INFLOW #this function is not used in LCv
# Eq. 11 Incoming lateral flow
#eq.QL.in <- function(P, Qbase){
#  QL.in <- 0.2 * P + Qbase
```

```
#  return(QL.in)
#}

# EVAPOTRANSPIRATION
# Eq. 12 soil evaporation
eq.ESP <- function(EP, LAI, SU, SU.min){
  ESP.pot <- EP * exp(-0.4 * LAI)
  if ((SU - ESP.pot) > (SU.min+1)){
    ESP <- ESP.pot
  } else  if ((SU > SU.min) & ((SU-ESP.pot)<SU.min)){
    ESP <- SU - SU.min
  } else{
    ESP <- 0
  }
  return(ESP)
}

# Eq. 13 transpiration
eq.ET <- function(EP, ESP, SU, SU.min){
  if(EP == 0){
    return(0)
  }
  ET.pot <- (1 - ESP / EP) * EP
  if ((SU - ET.pot)> (SU.min+1)){
    ET <- ET.pot
  } else if ((SU > SU.min) & ((SU-ET.pot)<SU.min)){
    ET <- SU - SU.min
  } else{
    ET <- 0
  }
  return(ET)
}

# Eq. 14 evapotranspiration #not used in LCv
#eq.ETP <- function(ESP, ET){
#  return(ESP + ET)
#}

# PERCOLATION
# Eq. 15 Maximum percolation rate
eq.P.max <- function(SU.max, d, th.fc, dt=1){
  P.max <- 0.5 * (SU.max - th.fc * d) / dt
  return(P.max)
}

# Eq. 16 Percolation #LCv edited so percolation flux never empties the storage more than minimum storage
eq.QP <- function(SU, SU.max, P.max, SU.min){
  QPpot = max(c(P.max * min(c(SU-SU.min, SU.max-SU.min)) / SU.max, 0))
  if (SU <= SU.min){
    QP <- 0
    } else if(((SU - QPpot) <= SU.min)){
    QP <- SU - SU.min
    } else if((SU - QPpot) > (SU.min)){
    QP <- QPpot
    } else {
    QP <- 0
    }
  return(QP)
}

# FLOW THROUGH LPD (OPTION 2)
# Eq. 17 Lateral outflow
eq.QL.out <- function(SU, SU.max, k.th, d, ksat, i){
  if(SU < SU.max){
    QL.out <- (k.th * SU * i) / d
  }else{
    QL.out <- (ksat * SU * i) / d
  }
  return(QL.out)
}

#FLOW THROUGH LPD (OPTION 1)
```

```
#Eq. 18 Manning
eq.manning <- function(S.LPD, n.manning.LPD, slope, S.LPD.min, S.LPD.max){
  A <- S.LPD / 1000
  P <- (A * 2 + 1) / 1000
  Qmann <- (((A/P)^(2/3) * slope^(1/2)) / n.manning.LPD) / 3600  * 1000
  if (S.LPD < S.LPD.min) {
    QL.out <- 0
  }
  else if ((S.LPD - Qmann) <= S.LPD.min){
    QL.out <- S.LPD - S.LPD.min
  }
  else if(S.LPD <= S.LPD.max){
    QL.out <- Qmann
  }else if(S.LPD > S.LPD.max){
    QL.out <- S.LPD - S.LPD.max + Qmann
  } else {
    QL.out <- 0
  }
  return(QL.out)
}
# EBv ==> Eq. Part II include similar functions to LCv, but only for one unsaturated storage.
# Eq. Part II LCv ==>

part.II <- function(P, EP, PE, Qst, SU.TG, SU.S, S.LPD, SU.TG.max, SU.S.max, S.LPD.max, P.TG.max, P.S.max, n.genuchten.TG, n.genuchten.sand, n.genuchten.LPD, alpha.TG, alpha.sand, alpha.LPD, ksat.TG, ksat.sand, ksat.LPD, th.fc.TG, th.fc.sand, th.fc.LPD, SU.TG.min, SU.S.min, S.LPD.min, n.manning.LPD, slope, d.TG, d.sand, d.LPD, LAI, i, Qbase){

  # Update SU.S with stemflow (Stemflow bypasses planting soil layer ans infiltrates in lower sand layer, excess flux will channel to LPD)
  QOF.St <- max(c(0, SU.S + Qst - SU.S.max))
  SU.S <- min(c(SU.S + Qst, SU.S.max))
  S.LPD <- S.LPD + QOF.St

  # Determine infiltration and runoff for TG (Effective precipitation infiltrates into planting soil, excess flux will channel to LPD)
  Qinf.OFout.TG <- inf.submodel(SU.TG, PE, SU.TG.max, SU.TG.min, ksat.TG, n.genuchten.TG, 50) #SU, Pin, SU.max, SU.min, ksat, n.Genuchten
  Qinf.TG <- Qinf.OFout.TG[1]
  QOF.TG <-  Qinf.OFout.TG[2]
  SU.TG <- SU.TG + Qinf.TG
  S.LPD <- S.LPD + QOF.TG

  # Determine incoming lateral flow, this channels directly to LPD.
  QL.in <- Qbase #eq.QL.in(P, Qbase) #in LCv, Qbase is included in the input file.
  S.LPD <- S.LPD + QL.in

  # Determine soil evaporation  (from planting soil)
  ESP.TG <- eq.ESP(EP, LAI, SU.TG, SU.TG.min) #soil evap from TG
  SU.TG <- SU.TG - ESP.TG

  # Determine percolation fluxes from TG
  QP.TG <- eq.QP(SU.TG, SU.TG.max, P.TG.max, SU.TG.min)
  SU.TG <- SU.TG - QP.TG

  # Determine infiltration and runoff for TG to Sand (Percolation from planting soil infiltrates into sand, excess flux will channel to LPD)
  Qinf.OFout.S.TG <- inf.submodel(SU.S, QP.TG, SU.S.max, SU.S.min, ksat.sand, n.genuchten.sand, 10) #same as the infiltration into TG, but instead of infiltrating effective precipitation from above ground, it is infiltrating the percolation from the bucket above
  Qinf.S.TG <- Qinf.OFout.S.TG[1]
  QOF.S.TG <- Qinf.OFout.S.TG[2] # all OFout channels to LPD.
  SU.S <- SU.S + Qinf.S.TG
  S.LPD <- S.LPD + QOF.S.TG

  # Determine vegetation transpiration (from sand),
  ETP.S <- eq.ET(EP, ESP.TG, SU.S, SU.S.min) #transpiration from Sand
  SU.S <- SU.S - ETP.S

  # Determine infiltration and runoff for LPD to Sand (water in LPD infiltrates into
```

```
  sand at a rate controlled by the sand properties and state, excess remains in LPD)
  Qinf.OFout.S.LPD <- inf.submodel(SU.S, S.LPD, SU.S.max, SU.S.min, ksat.sand,
  n.genuchten.sand, 10) #same as the infiltration into TG, but instead of
  infiltrating effective precipitation from above ground, it is infiltrating the
  percolation from the bucket above
  Qinf.S.LPD <- Qinf.OFout.S.LPD[1]
  S.LPD <- S.LPD - Qinf.S.LPD
  SU.S <- SU.S + Qinf.S.LPD

  # Lateral flow OPTION 1--> this option is assumed for LPDs in earlier growth stages
  where macro-pores allow
  QL.out <- eq.manning(S.LPD, n.manning.LPD, slope, S.LPD.min, S.LPD.max)
  S.LPD <- max(c(0, S.LPD - QL.out))

  # Determine percolation fluxes from S.
  QP.S <- eq.QP(SU.S, SU.S.max, P.S.max, SU.S.min)
  SU.S <- SU.S - QP.S

  ## Lateral flow OPTION 2--> this option is assumed for LPDs in later growth stages
  where the LPD is mostly sedimented and behaves like a porous media
  #kr.LPD <- eq.kr(S.LPD.max - S.LPD, alpha.LPD, n.genuchten.LPD)
  #k.th.LPD <- kr.LPD * ksat.LPD
  #QL.out <- min(c(eq.QL.out(S.LPD, S.LPD.max, k.th.LPD, d.LPD, ksat.LPD, i), S.LPD))
  #S.LPD <- S.LPD - QL.out


  return(c(SU.TG, SU.S, S.LPD,
           Qinf.TG, Qinf.S.TG, Qinf.S.LPD,
           QOF.TG, QOF.St, QOF.S.TG,
           QP.TG, QP.S,
           QL.in, QL.out,
           ESP.TG, ETP.S))
}
```

R model Runner

```r
# MODEL RUNNER
# In this file, the model is run. Output is saved in the folder 3)OUTPUT.
#----

#EBv = Version 1 by:
# Author: Eefje Benschop
# Contact: eefjebenschop@gmail.com

#LCv = Version 2 by:
# Author: Linnaea Cahill
# Contact: rc.linnaea@gmail.com

#----
#LOAD FUNCTIONS
#----

source("2)RUN/2.1)LPD_functions.R")

#----
#INPUT
#----

# Specify the desired filename:
filename <- paste("1)INPUT/hourly_inputs_short_ts_only_Precip42_jan.csv", sep="")
filename_out <- paste("3)OUTPUT/Run_var_intens_onlyPRECIP_42.csv", sep="")


met.data <- read.table(filename, sep=",", dec=".", header=T)
colnames(met.data) <- c("datetime", "EPdata", "Pdata", "Qbase", "LAI", "p", "ps", "S", "Acg", "kc")
met.data$datetime <- as.POSIXct(met.data$datetime, format="%Y-%m-%d %H:%M")
rm(filename)

# Edit the file LPD_par_var.R to set the desired parameter and variable values
source("1)INPUT/1.1)LPD_par_var.R")

#Storages
#---------
#interception
SI <- NULL
SI[1] <- 0
#planting soil
SU.TG <- NULL
SU.TG[1] <- SU.TG.min
#sand
SU.S <- NULL
SU.S[1] <- SU.S.min
#LPD - quickflow reservoir
S.LPD <- NULL
S.LPD[1] <- S.LPD.min

#Fluxes
#-------
#SI fluxes
EI <- NULL
Qst <- NULL
PE <- NULL

#TG fluxes
Qinf.TG <- NULL
QOF.TG <- NULL
QP.TG <- NULL
ESP.TG <- NULL

#Sand fluxes
ETP.S <- NULL
Qinf.S.TG <- NULL
Qinf.S.LPD <- NULL
QP.S <- NULL
QOF.St <- NULL
QOF.S.TG <- NULL

#LPD fluxes
```

```
QL.in <- NULL
QL.out <- NULL

#----
#MODEL RUN
#----

for(i in 1:(length(met.data[,1]))){

  #---
  #TIME VARIABLE DERIVED PARAMETERS
  #LCv ==> in EBv these derived parameters were in 1.1)LPD_par_var.R, they are moved here because they now depend on the variable input parameters.
  #---
  c.c <- eq.c.c(met.data$kc[i], met.data$LAI[i]) #canopy cover fraction (-)
  SI.max <- eq.SI.max(met.data$S[i], c.c, met.data$Acg[i]) #maximum interception storage (mm)
  #----
  #RUNNING MODEL
  #LCv ==> the above portion stays the same as EBv. Below ground is edited to add additional storages and seasonal variation of parameters
  #----

  #LCv above.ground = EBv + input edits to draw vegetation parameters from input data file, instead of from file 1.1
  above.ground <- part.I(met.data$Pdata[i], met.data$EPdata[i], SI[i], SI.max, met.data$p[i], met.data$ps[i], dt)
  SI[i+1] <- above.ground[1]
  EI[i] <- above.ground[2]
  Qst[i] <- above.ground[3]
  PE[i] <- above.ground[4]

  #LCv below.ground = adapted to include additional storages and fluxes
  below.ground <- part.II(met.data$Pdata[i], met.data$EPdata[i], #forcing
                          PE[i], Qst[i], #Fluxes from above.ground
                          SU.TG[i], SU.S[i], S.LPD[i], #storages
                          SU.TG.max, SU.S.max, S.LPD.max,#maximum storages
                          P.TG.max, P.S.max, #maximum percolations
                          n.genuchten.TG, n.genuchten.sand, n.genuchten.LPD, #n.genuchten
                          alpha.TG, alpha.sand, alpha.LPD, #alpha.genuchten
                          ksat.TG, ksat.sand, ksat.LPD, #ksats
                          th.fc.TG, th.fc.sand, th.fc.LPD, #residual water content per mm
                          SU.TG.min, SU.S.min, S.LPD.min, #residual water content in layer
                          n.manning.LPD, slope, #parameter for open channel flow in LPD
                          d.TG, d.sand, d.LPD,# depths
                          met.data$LAI[i], i, met.data$Qbase[i]) #other params
  #states
  SU.TG[i+1] <- below.ground[1]
  SU.S[i+1] <- below.ground[2]
  S.LPD[i+1] <- below.ground[3]
  #INFfluxes
  Qinf.TG[i] <- below.ground[4]
  Qinf.S.TG[i] <- below.ground[5]
  Qinf.S.LPD[i] <- below.ground[6]
  #OFfluxes
  QOF.TG[i] <- below.ground[7]
  QOF.St[i] <- below.ground[8]
  QOF.S.TG[i] <-below.ground[9]
  #Pfluxes
  QP.TG[i] <- below.ground[10]
  QP.S[i] <- below.ground[11]
  #LPDfluxes
  QL.in[i] <- below.ground[12]
  QL.out[i] <- below.ground[13]
  #Evapfluxes
  ESP.TG[i] <-below.ground[14]
  ETP.S[i] <- below.ground[15]
  }

```

```r
# Create dataframe of output
df <- met.data
df$SI <- SI[1:(length(SI)-1)]
df$EI <- EI
df$Qst <- Qst
df$PE <- PE
df$SUTG <- SU.TG[1:(length(SU.TG)-1)]
df$SUS <- SU.S[1:(length(SU.S)-1)]
df$SLPD <- S.LPD[1:(length(S.LPD)-1)]
df$QinfTG <- Qinf.TG
df$QinfSTG <- Qinf.S.TG
df$QinfSLPD <- Qinf.S.LPD
df$QOFTG <- QOF.TG
df$QOFSt <- QOF.St
df$QOFSTG <- QOF.S.TG
df$QPTG <- QP.TG
df$QPS <- QP.S
df$QLin <- QL.in
df$QLout <- QL.out
df$ESP <- ESP.TG
df$ETPS <- ETP.S


# Save as csv file in folder 3)OUTPUT
write.csv(df, filename_out, row.names=F)
```

Generating input files:

Hourly meteo from KNMI and Delft Meet

In [1]:
```python
import logging
import sys
from datetime import datetime
from datetime import timezone

import requests

logging.basicConfig()
logger = logging.getLogger(__name__)
logger.setLevel("INFO")


class OpenDataAPI:
    def __init__(self, api_token: str):
        self.base_url = "https://api.dataplatform.knmi.nl/open-data/v1"
        self.headers = {"Authorization": api_token}

    def __get_data(self, url, params=None):
        return requests.get(url, headers=self.headers, params=params).json()

    def list_files(self, dataset_name: str, dataset_version: str, params: dict):
        return self.__get_data(
            f"{self.base_url}/datasets/{dataset_name}/versions/{dataset_version}/files",
            params=params,
        )

    def get_file_url(self, dataset_name: str, dataset_version: str, file_name: str):
        return self.__get_data(
            f"{self.base_url}/datasets/{dataset_name}/versions/{dataset_version}/files/{file_name}/url"
        )


def download_file_from_temporary_download_url(download_url, filename):
    try:
        with requests.get(download_url, stream=True) as r:
            r.raise_for_status()
            with open(filename, "wb") as f:
                for chunk in r.iter_content(chunk_size=8192):
                    f.write(chunk)
    except Exception:
        logger.exception("Unable to download file using download URL")
        sys.exit(1)

    logger.info(f"Successfully downloaded dataset file to {filename}")


def main():
    api_key = "eyJvcmciOiI1ZTU1NGUxOTI3NGE5NjAwMDEyYTNlYjEiLCJpZCI6IjkwNWMzZjRhMDZjNTQ4OTBhMDhjZjNiNjkxM2JiOGQxIiwiaCI6Im11cm11cjEyOCJ9"
    dataset_name = "zonneschijnduur_en_straling"
    dataset_version = "1.0"

    api = OpenDataAPI(api_token=api_key)

    # since the filenames are prefixed with a timestamp, we can use the current date to filter the files
    # and start listing files after the first file of the day
    timestamp = datetime.now(timezone.utc).date().strftime("%Y%m%d")
    begin = f"KMDS__OPER_P___10M_OBS_L2_{timestamp}"

    logger.info(f"Fetching first file of {dataset_name} version {dataset_version} on {timestamp}")

    # order the files by filename and begin listing after the specified filename
    params = {"order_by": "filename", "begin": begin}
    response = api.list_files(dataset_name, dataset_version, params)
    if "error" in response:
        logger.error(f"Unable to retrieve list of files: {response['error']}")
        sys.exit(1)

    file_name = "kis_tos_202312.gz"
    #file_name = response["files"][0].get("filename")
    #logger.info(f"First file of {timestamp} is: {file_name}")

    # fetch the download url and download the file
    response = api.get_file_url(dataset_name, dataset_version, file_name)
    download_file_from_temporary_download_url(response["temporaryDownloadUrl"], file_name)


if __name__ == "__main__":
    main()
```

```
INFO:__main__:Fetching first file of zonneschijnduur_en_straling version 1.0 on 20240205
INFO:__main__:Successfully downloaded dataset file to kis_tos_202312.gz
```

In [ ]:

In [4]:
```
import xarray as xr
import pandas as pd
import netCDF4
import gzip
import csv
import json
```

In [ ]:
```
"""
Step 1. Convert .gz output files from KNMI downloads to .csv
(This could probably be done directly in python, however for only 12 files, it was easier to do it manually)

a. open .gz file with notepad or another text editor,
b. save file as .txt,
c. open .txt in excel, remove the header rows, and save as .csv

"""
```

In [18]:
```
"""
Step 2.
Function to filter dataset to only include radiation observations from Rotterdam, and remove unnecesary columns from KNMI data.

only edit: file_path and out_file_path

"""

file_path = "kis_tos_20230131.csv"
out_file_path = "rad_rot_202301.csv"
df = pd.read_csv(file_path, delimiter=',')
column_names = df.columns.tolist()
column_names[2]
filtered_df = df[df['NAME'] == "Rotterdam locatie 24t"]
# Assuming you have a DataFrame named 'df' and a list of column names to delete
columns_to_delete = ['LOCATION', 'NAME', 'LATITUDE', 'LONGITUDE', 'ALTITUDE', 'QN_GLOB_10', 'QX_GLOB_10']
# Dropping the specified columns from the DataFrame
filtered_drop_df = filtered_df.drop(columns=columns_to_delete)

filtered_drop_df.to_csv(out_file_path, index=False)
```

In [9]:
```
# Read column names to check which to delete
file_path = "kis_tos_202301.txt"
df = pd.read_csv(file_path)
column_names = df.columns.tolist()
print(column_names)
column_names[0]

#Find unique values of 'NAME', we only want to select NAME=Rotterdam
unique_values = df['NAME'].unique().tolist()
print(unique_values)
```

In [9]:
```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import csv
```

In [ ]:
```
"""
Step 1: Input daylight hours per day for the location.
""""
#Daylight hours per day
#Source: https://www.worlddata.info/europe/netherlands/
N_month = [0, 7, 9, 10, 12, 13, 15, 15, 13, 12, 10, 8, 7]
```

In [2]:
```
"""
Step 2. Group radiation data from KNMI into hourly data.
'Sun' indicates minutes of sun per day and 'N' is maximum posible amount of sun per day.
To run for each month edit file_path, file_path_out, and N_month[MM]
"""
#Convert radiation dataframes
file_path = "rad_rot_202312.csv"
file_path_out = "hourlyRad_202312.csv"
N = N_month[12] * 60
# Read the CSV file and parse the 'DTG' column as datetime
df = pd.read_csv(file_path, parse_dates=['DTG'], dayfirst=True)
# Set the 'DTG' column as the DataFrame index
df = df.set_index('DTG')
# Resample the data to hourly intervals and calculate the mean of 'Q_GLOB_10' column
df_hourly =  df.groupby([df.index.date, df.index.hour]).agg({'Q_GLOB_10': 'mean', 'SQ_10': 'sum'})
df_hourly.reset_index(inplace=True)
df_hourly.columns = ['Date', 'Hour', 'Rad', 'Sun'] #
# Calculate the sum of 'SQ_10' for each date and hour group and assign the summed values to the new column 'SQ_10_sum'
df_hourly['sum_sun'] = df_hourly.groupby(['Date'])['Sun'].transform('sum')
df_hourly['N'] = N
# Save the DataFrame to a CSV file
df_hourly.to_csv(file_path_out, index=False)
```

In [82]:
```
"""
Step 3. Clean up Meteo Data and resample to hourly timestep
From https://wow.metoffice.gov.uk/  dowload monthly meteo data and save as meteo_YYYYMM.csv
In this case, data is downloaded from Delft Meet Station at Deltares, Delft
only edit file_path and file_path_out
"""
file_path = "meteo_202312.csv"
file_path_out = "hourly_meteo_202312.csv"
# Read the CSV file and parse the 'DTG' column as datetime
df = pd.read_csv(file_path, parse_dates=['Report Date / Time'], dayfirst=True)
# Set the 'DTG' column as the DataFrame index
df = df.set_index('Report Date / Time')
columns_to_delete = ['Id', 'Site Id', 'Longitude', 'Latitude', 'Wet Bulb', 'Dew Point', 'Concrete Temp.','Rainfall',
                     'Grass Temp.', 'Min. Temp. (last 24hr)', 'Max. Temp. (last 24hr)', 'Soil Temp. (at 10cm)',
                     'Soil Temp. (at 30cm)', 'Soil Temp. (at 100cm)', 'Mean Sea-Level Pressure', 'Rainfall Accumulation',
                     'Wind Direction', 'Wind Gust', 'Wind Gust Direction', 'Snow Depth', 'Soil Moisture', 'Present Weather',
                     'Visibility', 'Total Cloud Cover', 'Sunshine', 'Ground State', 'Day of Thunder', 'Day of Gales',
                     'Day of Hail', 'Day of Snow', 'Weather Diary', 'Travel Disruption', 'Hazards causing Travel Disruption',
                     'Property or Infrastructure Damage', 'Hazards causing Property or Infrastructure Damage',
                     'Personal Health and Safety', 'Hazards causing Personal Health and Safety', 'Utility Disruption',
                     'Hazards causing Utility Disruption', 'Service or Business Disruption',
                     'Hazards causing Service or Business Disruption', 'Agriculture Habitat Damage',
                     'Hazards causing Agriculture Habitat Damage', 'Disruption to Camping Events Leisure Activities',
                     'Hazards causing Disruption to Camping Events Leisure Activities', 'v1_Coastal',
                     'v1_Flood', 'v1_Ice', 'v1_Landslide', 'v1_Lightning', 'v1_PoorVisibility', 'v1_Snow',
                     'v1_Wildfire', 'v1_Wind', 'v1_Other']
#columns_to_keep = ['Air Temperature', 'Pressure (At Station)', 'Relative Humidity', 'Rainfall Rate', 'Wind Speed']
drop_df = df.drop(columns=columns_to_delete)
# Resample the data to hourly intervals and calculate the mean of 'Q_GLOB_10' column
df_hourly = drop_df.groupby([drop_df.index.date, drop_df.index.hour]).mean()
df_hourly.reset_index(inplace=True)
df_hourly.columns = ['Date', 'Hour', 'Temp', 'Press', 'RH', 'Precip', 'Wind_spd']
df_hourly.to_csv(file_path_out, index=False)
```

In [211…
```
"""
Step 4. Combine Meteo data from Step 3 and radiation data from Step 2 into one .csv file
"""
#Combine all data into one df
rad_file = "hourlyRad_202301.csv"
meteo_file = "hourly_meteo_202301.csv"
outfile = "hourly_all_202301.csv"
# Read the first CSV file
df1 = pd.read_csv(rad_file)
# Read the second CSV file
df2 = pd.read_csv(meteo_file)
# Merge the two DataFrames based on the common columns
merged_df = pd.merge(df1, df2, on=['Date', 'Hour'])
# Convert the 'hour' column to timedelta format
merged_df['Date'] = pd.to_datetime(merged_df['Date'])
merged_df['Hour'] = pd.to_timedelta(merged_df['Hour'], unit='h')
# Combine the 'date' and 'hour' columns to create a new datetime column
merged_df['datetime'] = merged_df['Date'] + merged_df['Hour']
merged_df.drop(['Date', 'Hour'], axis=1, inplace=True)
merged_df = merged_df[['datetime'] + merged_df.columns[:-1].tolist()]
```

```
# Save the merged DataFrame to a new CSV file
merged_df.to_csv(outfile, index=False)
```

In [225…

```
"""
Step 5. Add columns to meteo .csv file with average daily daylight hours per month
and monthly factor to multiply maximum Leaf Area Index by to adjust for seasons.
"""
#add column with N
N_month = [0, 7, 9, 10, 12, 13, 15, 15, 13, 12, 10, 8, 7]
#add column with LAI-phenology
LAI_phen_month = [0, 0, 0, 0, 0.05, 0.1, 0.5, 0.7, 1, 0.85, 0.55, 0.1, 0]
#specify file
infile = "hourly_all_202312.csv"
df = pd.read_csv(infile)
df['LAIphen'] = LAI_phen_month[12]
df.to_csv(infile, index=False)
```

Generating input files:

Potential Evaporation and Vegetation-Related Parameter scaling

In [3]:
```
# Importing required libraries
import numpy as np
import pandas as pd
from datetime import datetime
import matplotlib.pyplot as plt
import matplotlib.cm as cm
import matplotlib as mpl
from mpl_toolkits.axes_grid1 import make_axes_locatable
from mpl_toolkits import mplot3d
from mpl_toolkits.axes_grid1 import host_subplot
import mpl_toolkits.axisartist as AA
import matplotlib.dates as mdates
```

In [10]:
```
"""
Step 1. Combine all monthly meteo files into a yearly file
"""

df1 = pd.read_csv('hourly_all_202301.csv')
df2 = pd.read_csv('hourly_all_202302.csv')
df3 = pd.read_csv('hourly_all_202303.csv')
df4 = pd.read_csv('hourly_all_202304.csv')
df5 = pd.read_csv('hourly_all_202305.csv')
df6 = pd.read_csv('hourly_all_202306.csv')
df7 = pd.read_csv('hourly_all_202307.csv')
df8 = pd.read_csv('hourly_all_202308.csv')
df9 = pd.read_csv('hourly_all_202309.csv')
df10 = pd.read_csv('hourly_all_202310.csv')
df11 = pd.read_csv('hourly_all_202311.csv')
df12 = pd.read_csv('hourly_all_202312.csv')
output = "hourly_all_2023.csv"

merged_df = pd.concat([df1, df2, df3, df4, df5, df6, df7, df8, df9, df10, df11, df12])
merged_df.to_csv(output, index=False)
```

In [11]:
```
"""
Step 2. Define a function to generate Potential Evapotrasnpiration using Penman Monteith, function of meteo data and LAI.
"""

def pot_evap(input_filename, output_filename, LAI_max):
    """
    Calculates the potential evaporation for every INTERVAL
    Input variables:
    input_filename = filename of the input values
    output_filename = filename of the output
    temp = average air temperature [°C] (from Delft Meet)
    v = average wind speed measured at 2 m height [m/s] (from Delft Meet)
    rel_hum = relative humidity [-] (from Delft Meet)
    Rs_inwatts = incoming short wave radiaton [W/m^2 = J/s*m^2] (from KNMI)
    """

    # Load datasets from other .csv files
    data = pd.read_csv(input_filename, parse_dates=['datetime'], index_col=['datetime'])  # read the data from the CSV file

    temp = data['Temp'].values #deg C
    np.shape(temp)
    v_kn = data['Wind_spd'].values #kn
    v = v_kn / 0.514 # [m/s]
    RH = data['RH'].values # [%]
    rel_hum = RH / 100 # [-]
    Rs_inwatts = data['Rad'].values # [J/s*m^2]
    n = data['sum_sun'].values #minutes of actual sunshine per day [minutes]
    N = data['N'].values # mean daily duration of maximum possible sunshine hours per day (averaged per month) [minutes]
    Precip = data['Precip'].values # [mm/hr * 1 hr = mm]
    Pressure = data['Press'].values #hPa
    LAI_phen = data['LAIphen'] #LAI of willow m2/m2

    # Constants
    λ = 2.45e6 # latent heat [J/kg]
    ρ_w = 1000 # density of water [kg/m^3]
    ρ_a = 1.2 # density of air [kg/m^3]
    c_p = 1004 # specific heat of air at constant pressure [J/(kg*K)]
    γ = 0.0669 # psychrometer constant [kPa/°C]
    σ =  5.670374419e-8 # Stefan-Boltzmann constant [J/(s*m^2*K^4)]
    r = 0.20 # Albedo for grassland [-]
    rl = 150 #stomatal resistance for willow [s/m]
    k = 0.41 # [-] von Karman's constant
    zm = 2 # [m] height of measurements
    d = 0.5 # [m] zero plane displacement height
    zom = 1 # roughness length governing momentum transfer [m],
    #LAI_max = 1 # maximum LAI for willows in growth season 1st=3, 2nd=5, 3rd=7. <-- from input to function

    # Intermediate calculations
    #r_a = (245 / ((0.5 * v) + 0.5)) # aerodynamic resistence [sec/m] (when /86400 --> d/m)
    e_s = 0.61078 * np.exp((17.27 * temp)/(temp + 237.3)) # saturation vapour pressure for air at 2 m height [kPa] (Tetens eq.)
    e_a = e_s * rel_hum # actual vapour pressure [kPa]
    s = (4098 * e_s) / ((237.3 + temp) ** 2) # slope vapour pressure curve [kPa/°C]
    R_in = Rs_inwatts # incoming short wave radiation on the earth’s surface in [J/(s*m^2)]
    R_ns = (1 - r) * (R_in) # net short wave radiation R_ns  [J/(s*m^2)]
    R_nl = (0.9 * (n/N) + 0.1) * (0.34 - 0.139 * np.sqrt(e_a)) * σ * (temp + 273)**4 # net long wave radiation R_nl [J/(s*m^2)]
    R_n = (R_ns - R_nl) # net radiation [J/(s*m^2)]
```

```
    G = 0 # (for 0 - 30 days) #R_n * 0.1 # ground heat flux [J/(s*m^2)]
    LAI = LAI_phen * LAI_max * 0.5
    rs = rl / (LAI+0.1) #stomatal resistance
    zoh = 0.1 * zom # roughness length governing transfer of heat and vapour [m],
    ra_cnst = (np.log((zm - d)/zom) * np.log((zm - d)/zoh)) / (k**2)
    ra = ra_cnst / (v+0.1)

    # Final calculation
    E_p_0 = ((s * (R_n - G)) + (c_p * ρ_a * ((e_s - e_a) / ra))) / ((s + γ * (1 + rs / ra)) * λ) # potential evaporation [kg/(m
    E_p_meter = E_p_0 / ρ_w # potential evaporation [m/s]
    E_p = E_p_meter * 1000 * 60 * 60 # potential evaporation [mm/hr]

    # Save the potential evaporation as a DataFrame with the same 'Date/time' index as the input data
    df_ep = pd.DataFrame({'EP(mm)': E_p}, index=data.index)

#   df_ep['datetime'] = data['datetime
    df_ep['rain(mm)'] = Precip

    df_ep[df_ep < 0] = 0

    df_ep.to_csv(output_filename, index=True)

    plt.figure()
    plt.plot(df_ep['EP(mm)'])
```

In [34]:

```
"""
Step 3. Run function for each year and LAI scenario.

Manually change the filenames and the LAI_max value

"""
input_filename = "hourly_all_2023.csv"
output_filename = "hourly_P_Etp6_all2023.csv"
LAI_max = 6
pot_evap(input_filename, output_filename, LAI_max)
```

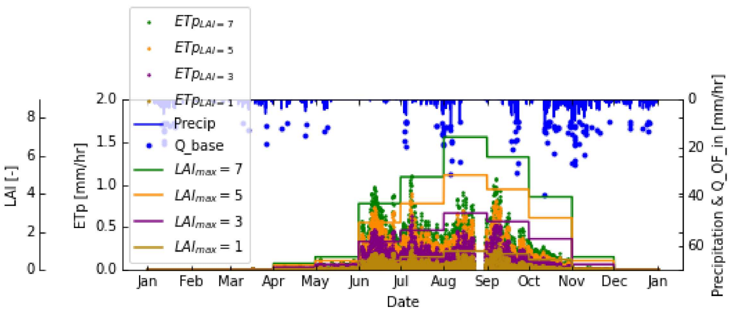
In [32]:

```
"""
Step 4. Add additional parameters to dataset, base flow and vegetation parameters, scaled by the season

Manually edit year and LAI value in input and output filenames. factor is the LAI value.

"""

infile = 'hourly_P_Etp7_all2023.csv'
outfile = 'hourly_P_Etp7_params_all2023.csv'
factor = 7

LAI_phen_month = [0, 0, 0, 0.05, 0.1, 0.5, 0.7, 1, 0.85, 0.55, 0.1, 0]
p_month = 0.5 / 7  # free throughfall coefficient m
ps_month = 0.05 / 7 # stemflow fraction ranges from 0.05 to 0.1
S_month = (0.72 / 7) # canopy storage capacity
Ac_month = 1 / 7 # area of canopy
kc_month = 0.6 / 7 # light extinction coefficient

df = pd.read_csv(infile)

df['Q_base'] = df['rain(mm)'].apply(lambda x: x * 3 if x > 3 else 0)
df['datetime'] = pd.to_datetime(df['datetime'])
df['LAI'] = df['datetime'].dt.month.map(lambda x: LAI_phen_month[x-1])

df['p'] = df['LAI'].apply(lambda x: (1- x * p_month * factor) if x > 0.01 else 1)
df['ps'] = df['LAI'].apply(lambda x: (0.05 + x * ps_month * factor) if x > 0.01 else 0.05)
df['S'] = df['LAI'].apply(lambda x: (x * S_month * factor) if x > 0.01 else 0)
df['Ac'] = df['LAI'].apply(lambda x: (x * Ac_month * factor) if x > 0.01 else 0)
df['kc'] = df['LAI'].apply(lambda x: (x * kc_month * factor) if x > 0.01 else 0)
df['LAI'] = df['LAI'].apply(lambda x: (x * factor) if x > 0.01 else 0)
#df.drop('Unnamed: 0', axis=1, inplace=True)
df.to_csv(outfile, index=False)
```

In [35]:

```
"""
Step . Plot Input data for each LAI scenario
"""

#functions for plotting precip data
def addzeros(a):
    my_list = []
    for x in a:
        my_list.append(x)
        my_list.append(0)
    return my_list

def adddates(a):
    my_list = []
    for x in a:
        my_list.append(x)
        my_list.append(x)
    return my_list


df1 = pd.read_csv('hourly_P_Etp1_params_all2023.csv')
df3 = pd.read_csv('hourly_P_Etp3_params_all2023.csv')
df5 = pd.read_csv('hourly_P_Etp5_params_all2023.csv')
```

```python
df7 = pd.read_csv('hourly_P_Etp7_params_all2023.csv')

datetime = pd.to_datetime(df1['datetime'])
precip = df1['rain(mm)']
plot_datetime = adddates(datetime)
plot_precip = addzeros(precip)

fig = plt.figure(figsize=(9, 5))
#fig, ax1 = plt.subplots(axes_class=AA.Axes) #figsize=(15, 6)
ax1 = host_subplot(211,  axes_class=AA.Axes) #figure=fig,
plt.subplots_adjust(right=0.75)
ax2 = ax1.twinx()
ax3 = ax1.twinx()
ax2.invert_yaxis()


#Keep axis labels from overlapping
offset = 60
new_fixed_axis = ax2.get_grid_helper().new_fixed_axis
ax2.axis["right"] = new_fixed_axis(loc="right", axes=ax2,
                                        offset=(0, 0))
ax3.axis["left"] = new_fixed_axis(loc="left", axes=ax3,
                                        offset=(-offset, 0))
ax1.axis["left"].toggle(all=True)
ax3.axis["left"].toggle(all=True)


# Plot the Precipitation and Q-base on ax2
ax2.plot(plot_datetime, plot_precip, color='blue', label='Precip')
filtered_df = df1[df1['Q_base'] != 0]
ax2.plot(pd.to_datetime(filtered_df['datetime']), filtered_df['Q_base'], '.', color='blue', label='Q_base')


# Plot LAI values on ax3
ax3.plot(pd.to_datetime(df7['datetime']), df7['LAI'] , color='green', label='$LAI_{max}=7$')
ax3.plot(pd.to_datetime(df5['datetime']), df5['LAI'] , color='darkorange', label='$LAI_{max}=5$')
ax3.plot(pd.to_datetime(df3['datetime']), df3['LAI'] , color='purple', label='$LAI_{max}=3$')
ax3.plot(pd.to_datetime(df1['datetime']), df1['LAI'], color='darkgoldenrod', label='$LAI_{max}=1$')


#plot Etp on ax1
ax1.plot(pd.to_datetime(df7['datetime']), df7['EP(mm)'], '.',color='green',  markersize = 3, label='$ETp_{LAI=7}$')
ax1.plot(pd.to_datetime(df5['datetime']), df5['EP(mm)'], '.',color='darkorange',  markersize = 3, label='$ETp_{LAI=5}$')
ax1.plot(pd.to_datetime(df3['datetime']), df3['EP(mm)'],'.', color='purple', markersize = 3, label='$ETp_{LAI=3}$')
ax1.plot(pd.to_datetime(df1['datetime']), df1['EP(mm)'], '.', color='darkgoldenrod', markersize = 3, label='$ETp_{LAI=1}$')

ax1.set_ylabel('ETp [mm/hr]')
ax2.set_ylabel('Precipitation & Q_OF_in [mm/hr]')
ax3.set_ylabel('LAI [-]')

# ax1.axis["left"].label
# ax2.axis["right"].label
# ax3.axis["left"].label

ax1.set_ylim([0, 2])
ax2.set_ylim([70, 0])
ax3.set_ylim([0, 9])

# Set the x-axis label and ticks
#dates = pd.to_datetime(df1['datetime'])
ax1.set_xlabel('Date')
ax1.xaxis.set_major_locator(mdates.MonthLocator())
ax1.xaxis.set_major_formatter(mdates.DateFormatter('%b'))
plt.xticks(rotation=45)

ax1.legend()
# Show the plot
plt.show()
```



Generating input files:

LPD input parameters

In [1]:
```
import numpy as np
```

In [22]:
```
"""
Notebook to estimate porosity of LPD, to use as input parameter to conceptual model

LPD consists of two dead bundles under one live bundle. total LPD area pproximated as an ellipse.
Porosity based on fraction of voids (i.e. space with no branches) to total LPD area.
the dead bundles are a bit more densly packed than the live bundles. Values presented below are a very rough estimate.

"""
# Calculate LPD area
a = 30
b = 20
total_area_LPD = np.pi*a*b #cm^2

#Per meter of layer with LPD and planting soil, the percentage of soil to LPD is?
total_depth = 45 #cm
width = 120 #cm
total_area = total_depth * width
pct_LPD = total_area_LPD/total_area

# Calcualte LPD porosity

dia_dead_bundle = 25 #cm
dia_live_bundle  = 14 #cm
total_twigs_live = 110 #twigs per bundle
total_twigs_dead = 400 #twigs per bundle
avg_twig_diameter = 1.5 #cm
twig_density = 0. # the length of each twig was more than half the length of the LPD, so they were a bit staggered.

area_twigs = np.pi*(avg_twig_diameter / 2 )**2 * total_twigs_live * twig_density
area_twigs_dead = np.pi*(avg_twig_diameter / 2 )**2 * total_twigs_dead * twig_density

area_bundle_live = np.pi*(dia_live_bundle / 2)**2
area_bundle_dead = np.pi*(dia_dead_bundle / 2)**2

live_LPD_porosity = (area_bundle_live - area_twigs)/area_bundle_live
dead_LPD_porosity = (area_bundle_dead - area_twigs_dead)/area_bundle_dead

avg_porosity = (live_LPD_porosity * area_bundle_live + dead_LPD_porosity * area_bundle_dead * 2 ) /
                (area_bundle_live + area_bundle_dead * 2 )

print(live_LPD_porosity)
print(dead_LPD_porosity)
print(pct_LPD)
print(avg_porosity)
```

Generating input files:

van Genuchten parameters

In [41]:
```python
import numpy as np
import matplotlib.pyplot as plt
```

In [ ]:
```python
"""
In this notebook, I look into estimating van Genuchten parameters with:

A. Pedotransfer functions according to equations by Rajkai et al, 2004
B. Pedotransfer functions in Hydrus software neural network calculator
C. Measured van Genuchten parameters from a review by Benson et al, 2014.
D. Check if these make sense compared to the typical ranges of these values by Lu & Griffiths, 2006
E. Plot SWRCs

Ultimately, the best fit was found based on C.

"""
```

In [31]:
```python
"""
A.
Linear adjusted pedotransfer functions from Table 2 of:

Rajkai, K., Kabos, S., & Van Genuchten, M. T. (2004).
Estimating the water retention curve from soil properties:
comparison of linear, nonlinear and concomitant variable methods.
Soil and Tillage Research, 79(2), 145-152.

For this study, the linear form including soil properties, derived soil properties, and Field water content (FC).
The Rsq value for the approximation of alpha is most influenced by including FC.

Inputs:
rho = bulk density (mg/m3)
OM = organic matter (%)
S = sand fraction (>50 mm);
Si = silt fraction (50-2 mm);
C = clay fraction (<2 mm);
ln (Si) = logarithm of silt fraction;
ln (C) = logarithm of clay fraction;
S/Si = sand-silt ratio;
FC = field capacity retention data [m3/m3]

Outputs:
theta_s = saturated water content
alpha = van Genuchten parameter
n = van Genuchten parameter

"""
def theta_s_FC(rho, OM, C, S, Si, FC):
    return 134.88 - 0.127 *  FC -  74.4 * rho - 0.19 * OM - 0.00027 * C**2 - 2.83 * np.log(C) + 14.37 * rho**2 - 0.053 * rho * S - 0.0074 * S / Si * 0.00087 * rho**2 * C**2
def alpha_FC(rho, OM, C, S, Si, FC):
    ln_alpha =  - 31.74 - 0.26 * FC - 0.37 * rho * Si + 0.81 * S/Si + 0.157 * C + 0.01 * rho**2 * C + 13.52 * np.log(Si) - 0.01 * Si - 0.0016 * C**2 + 0.0014 * rho**2 * Si**2
    return np.exp(ln_alpha)
def n_FC(rho, OM, C, S, Si, FC):
    ln_n = - 0.67 + 0.0039 * FC + 0.59 * rho - 0.01 * OM - 0.0001 * C**2 - 0.0005 * rho * S + 0.11 * np.log(C) - 0.012 * rho**2 * C + 0.013 * S / Si + 0.00018 * rho**2 * C**2
    return np.exp(ln_n)
def n_noFC(rho, OM, C, S, Si, FC):
    ln_n = - 0.287 + 0.47 * rho - 0.008 * OM - 0.00007 * C**2 + 0.06 * np.log(C) -0.00046 * rho * S - 0.01 *  rho**2 * C - 0.0068 * S/Si + 0.00015 * rho**2 * C**2
    return np.exp(ln_n)

"""
Inputs for Sand and Planting Soil in experimental setup, based on measurmeents in December 2023.
The measurement or calculation of input values, are described in chapter 5.5
"""
#Sand
rho_S = 1.81 #* 1000000000 #convert from g/cm3 to mg/m3
OM_S  = 0.1 # [%]
C_S   = 0 # [%]
S_S   = 98.9 # [%]
Si_S  = 1 # [%]
FC_S  = 0.02 # [m3/m3]

#Planting soil (teelgrond)
rho_TG = 0.96 #* 1000000000 #convert from g/cm3 to mg/m3
OM_TG  = 7 # [%]
C_TG   = 15 # [%]
S_TG   = 68 # [%]
Si_TG  = 10 # [%]
FC_TG  = 0.2 # [m3/m3]

theta_s_S = theta_s_FC(rho_S, OM_S, C_S, S_S, Si_S, FC_S)
alpha_S = alpha_FC(rho_S, OM_S, C_S, S_S, Si_S, FC_S)
n_S = n_noFC(rho_S, OM_S, C_S, S_S, Si_S, FC_S)

theta_s_TG = theta_s_FC(rho_TG, OM_TG, C_TG, S_TG, Si_TG, FC_TG)
alpha_TG = alpha_FC(rho_TG, OM_TG, C_TG, S_TG, Si_TG, FC_TG)
n_TG = n_noFC(rho_TG, OM_TG, C_TG, S_TG, Si_TG, FC_TG)

print("theta_s_S = "+ str(theta_s_S) +", alpha_S = "+ str(alpha_S) + ", n_S = " + str(n_S))
print("theta_s_TG = "+ str(theta_s_TG) + ", alpha_TG = " + str(alpha_TG) +", n_TG = " + str(n_TG))
```

In [36]:
```python
"""
B.
Results from Hydrus neural network predictor of van Genuchten parameters.
The neural network predictor does not include an input percentage of Organic matter,
therefore, for the planting soil, the 7% OM is included as 4% silt and 3 % sand.
"""
#Sand
theta_r_S = 0.0506 # [cm3/cm3]
theta_s_S = 0.2939 # [cm3/cm3]
alpha_S = 0.0419 # [1/cm]
n_S = 3.8274 # [-]
Ks_S = 887.86 # [cm/day]

#Teelgrond - 14 % Silt, 18 % Clay
theta_r_TG = 0.067 # [cm3/cm3]
theta_s_TG = 0.5520 # [cm3/cm3]
alpha_TG = 0.0250 # [1/cm]
n_TG = 1.3851 # [-]
Ks_TG = 186.63 # [cm/day]

#Teelgrond - 14 % Silt, 71 % Sand
theta_r_TG = 0.0613 # [cm3/cm3]
theta_s_TG = 0.5485 # [cm3/cm3]
alpha_TG = 0.0274 # [1/cm]
n_TG = 1.3893 # [-]
Ks_TG = 212.07 # [cm/day]
```

In [ ]:
```python
"""
C.
The previous methods do not include input data on the grain size distribution of sand, therefore,
to comapre the results of the previous methods to experimental results from literature, Benson et al (2014)
provide an overview of these values.

Benson, C. H., Chiang, I., Chalermyanont, T., & Sawangsuriya, A. (2014).
Estimating van Genuchten parameters α and n for clean sands from particle
size distribution data. In From soil behavior fundamentals to innovations
in geotechnical engineering: Honoring Roy E. Olson (pp. 410-427).
```

```
This estimation is based on d60, d10 , Cu = d60/d10, percent of fines and theta_s and theta_r

"""
#Sand - measured values
theta_r_S = 0.02 # [cm3/cm3]
theta_s_S = 0.32 # [cm3/cm3]
d10 = 0.3
d60 = 0.7
Cu = 2.33
percent_fines = 0.1

"""
For sand, # Lu is the best fit,
but Cu should be a bit lower (i.e. higher n)
and median particle size a bit higher (i.e. higher alpha)
"""

# Lu et al 2006, Poorly graded sand
# this is the closest with:
# d10 = 0.25
# d60 = 0.68
# Cu  = 2.70
# % fines = 0
# Theta_s = 0.369
# Theta_r = 0.030
alpha_S = 0.22 # [1/cm] <-- From literature
n_S = 3.23 # [-] <-- From literature

#Stormont and Anderson 1999
#d10 = 0.20
#d60 = 0.68
# Cu = 3.40
# % fines = 1
# theta_s = 0.35
# theta_r = 0.05
alpha_s = 0.13
n_s = 2.4

#WGL (Benson et al) - Suvarphuni sand and Turtle bay sand
#higher d10=0.45
alpha_s = 0.61
n_s = 5.29
#lower d10=0.15
alpha_s = 0.36
n_s = 2.42

# final estimation based on these studies -->
alpha_s = 0.25
n_s = 3.4

"""
Planting Soil
 Cu and % of fines values are between Baker 2001's NW19 fine sand and Rassam and Williams 1999's Kidston gold mine.
 however my d60 is higher than both of these studies. Based on the relations between alpha, n, and grain size distribution,
 the larger median grain size from my study should mean a larger alpha, and the coefficient of uniformity being roughly
 the average of the other two studies, my n should be somewhere between these values, leanign toward the lower value of n
 because n decreases parabolically with the increase of particle size distribution breadth
 (this is explained in figure 3 of Benson et al 2014)
"""

# measured values
theta_r_TG = 0.2 # [cm3/cm3]
theta_s_TG = 0.64 # [cm3/cm3]
d10_TG = 0.063
d60_TG = 0.25
Cu_TG = 4
percent_fines_TG = 0.25

# estimation based on reviewed studies from Benson et al
alpha_TG = 0.12 # [1/cm]
n_TG = 2.4 # [-]
```

In [71]:

```
"""
D.
Lu & Griffiths show typical van Genuchten parameters for different soil types in table one of their paper.
I checked that the final values I chose for each soil fall within the correct range.

Lu, N., & Griffiths, D. V. (2004).
Profiles of steady-state suction stress in unsaturated soils.
Journal of Geotechnical and Geoenvironmental Engineering,
130(10), 1063-1076.

"""
#Final values:

#Sand
theta_r_S = 0.02 # [cm3/cm3]
theta_s_S = 0.32 # [cm3/cm3]
alpha_S = 0.25
n_S = 4

#Teelgrond
theta_r_TG = 0.2 # [cm3/cm3]
theta_s_TG = 0.64 # [cm3/cm3]
alpha_TG = 0.12 # [1/kPa]
n_TG = 2.4 # [-]
```

In [76]:

```
"""
E.
Plot soil water retention curves
"""
def SWCC_theta(theta_r, theta_s, alpha, n, psi):
    return theta_r + (theta_s - theta_r) * (1 / ( 1 + (alpha * psi)**n))**(1-1/n)

psi = np.linspace(-1, -100, 100)
theta_TG = SWCC_theta(theta_r_TG, theta_s_TG, alpha_TG, n_TG, psi)
theta_S = SWCC_theta(theta_r_S, theta_s_S, alpha_S, n_S, psi)
```

In [77]:

```
plt.plot(theta_TG, -psi)
plt.plot(theta_S, -psi)
plt.yscale("log")
plt.xlim(0, 100)
```

In [ ]:

In [ ]:

Generating input files:

Rainfall Scenario input files

In [167…

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import scipy.stats as stats
from scipy.stats import norm
import warnings
warnings.filterwarnings('ignore')
```

In [3]:

```
"""
Step 1.1 For yearly runs, add a run-up time of one month by repeating january
31 days * 24 hours = 744 times steps.
Manually adjust input and output files for each year and LAI value.
"""

filename = 'hourly_P_Etp7_params_all2023.csv'
outfile = 'hourly_P_Etp7_params_2023_doublejan.csv'

df = pd.read_csv(filename, parse_dates=['datetime'], index_col=['datetime'])
df = df.replace('',0)
df = df.replace('',np.nan).fillna(0)

df_jan = df[:744]
df_out = pd.concat([df_jan, df])

df_out.to_csv(outfile, index=True)
```

In [4]:

```
"""
Step 2.1  generate rainfall intensities for mean rainfall, p62.5, p75, p87.5
"""
filename = 'monthly_intensity_duration_dist.csv'
df = pd.read_csv(filename)

def normal_distribution(mean, p95, month):
    # Calculate standard deviation
    std_dev = (p95 - mean) / 2
    # Generate x values for PDF
    x = np.linspace(mean - 5 * std_dev, mean + 5 * std_dev, 1000)
    # Calculate PDF
    pdf = stats.norm.pdf(x, mean, std_dev)

    plt.plot(x, pdf, label=month)

    # Calculate percentiles
    p62 = mean + 0.32 * std_dev
    p75 = mean + 0.675 * std_dev
    p88 = mean + 1.15 * std_dev

    return p62, p75, p88

#Add new values to data frame
df['p62_mm_hr'] = 0
df['p75_mm_hr'] = 0
df['p88_mm_hr'] = 0

for i in range(len(df['month_num'])):
    p62, p75, p88 = normal_distribution(df['mean_mm_hr'][i], df['p95_mm_hr'][i], df['month_name'][i])
    df['p62_mm_hr'][i] = p62
    df['p75_mm_hr'][i] = p75
    df['p88_mm_hr'][i] = p88

# Plot results
plt.xlabel('Precipitation intensity [mm/hr]')
plt.xlim([0, 8])
plt.ylabel('Probability Density')
plt.title('')
plt.grid(False)
plt.legend()
plt.savefig('R_model_scenarios_normaldist_precip', dpi=300)
plt.show()

plt.figure()
plt.plot(df_rain['month_num'], df_rain['p99_mm_hr'], '.', label='p99.0')
plt.plot(df_rain['month_num'], df_rain['p95_mm_hr'], '.', label='p95.0')
plt.plot(df_rain['month_num'], df_rain['p88_mm_hr'], '.', label='p87.5')
plt.plot(df_rain['month_num'], df_rain['p75_mm_hr'], '.', label='p75.0')
plt.plot(df_rain['month_num'], df_rain['p62_mm_hr'], '.', label='p62.5')
plt.plot(df_rain['month_num'], df_rain['mean_mm_hr'], '.', label='p50.0')
plt.legend()
plt.grid(alpha=0.25)
plt.xlabel('')
months = ['', 'Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov', 'Dec']
plt.xticks(np.linspace(0, 12 ,13), months)
plt.ylabel('Precipitation intensity [mm/hr]')
plt.savefig('R_model_scenarios_synthetic_precip', dpi=300)
```

In [2]:

```
"""
Step 2.2 For short time series runs,
- Clear all precipitation data and lateral inflow data
- Assign an index to the start of each month
- Add precipitation data back in for each month from the intensities file.
```

```
  save a yearly_mean, p25, p50, p75 and p99 file with events at the start of each month
- Split year into monthly segments
"""
filename = 'hourly_P_Etp3_params_all2023.csv'
df_in = pd.read_csv(filename, parse_dates=['datetime'], index_col=['datetime'])

#Set precip to 0 everyhere
df_in['rain(mm)'].values[:] = 0
df_in['Q_base'].values[:] = 0
#add a day-time column for easier comparison between months
#df.reset_index(inplace=True)
#df['day_and_time'] = df['datetime'].dt.strftime('%d-%H:%M:%S')

#find the index of the start of each month, for incomplete data set, adjust the dayspermonth and shift_hour manually
days_per_month = [0, 0, 31, 26, 30, 30, 31, 30, 31, 23, 30, 31, 30, 31]
shift_hr = [0, 0, 0, 0, 4, 3, 2, 2, 2, 1, 1, 1, 1, 0]
index_start_month = np.cumsum(days_per_month) * 24 + np.array(shift_hr)

#add precipitation data - one hour to the start of each month.
df_p500_a = df_in
df_p625_b = df_in
df_p750_c = df_in
df_p875_d = df_in
df_p990_e = df_in
for i in range(1, 13):
    #run these one at a time, and run corresponding function below:
    #df_p500_a['rain(mm)'][index_start_month[i]+24] = df_rain['mean_mm_hr'][i-1]
    #df_p500_a['Q_base'][index_start_month[i]+24] = df_rain['mean_mm_hr'][i-1] * 4
    #df_p625_b['rain(mm)'][index_start_month[i]+24] = df_rain['p62_mm_hr'][i-1]
    #df_p625_b['Q_base'][index_start_month[i]+24] = df_rain['p62_mm_hr'][i-1] * 4
    #df_p750_c['rain(mm)'][index_start_month[i]+24] = df_rain['p75_mm_hr'][i-1]
    #df_p750_c['Q_base'][index_start_month[i]+24] = df_rain['p75_mm_hr'][i-1] * 4
    #df_p875_d['rain(mm)'][index_start_month[i]+24] = df_rain['p88_mm_hr'][i-1]
    #df_p875_d['Q_base'][index_start_month[i]+24] = df_rain['p88_mm_hr'][i-1] * 4
    #df_p990_e['rain(mm)'][index_start_month[i]+24] = df_rain['p99_mm_hr'][i-1]
    #df_p990_e['Q_base'][index_start_month[i]+24] = df_rain['p99_mm_hr'][i-1] * 4

len_short_ts = 3*24 #10 days in hours
def save_dfs_to_csvs(df_pXXX, index_start_month, len_short_ts, months, scenario):
    for i in range(1, 13):
        df_out = df_pXXX[index_start_month[i]:index_start_month[i]+len_short_ts]
        outfile = 'hourly_inputs_short_ts_'+ scenario + '_' + months[i-1] + '.csv'
        df_out.to_csv(outfile, index=True)
    return outfile
#run these one at a time:
#save_dfs_to_csvs(df_p500_a, index_start_month, len_short_ts, months, 'p500')
#save_dfs_to_csvs(df_p625_b, index_start_month, len_short_ts, months, 'p625')
#save_dfs_to_csvs(df_p750_c, index_start_month, len_short_ts, months, 'p750')
#save_dfs_to_csvs(df_p875_d, index_start_month, len_short_ts, months, 'p875')
#save_dfs_to_csvs(df_p990_e, index_start_month, len_short_ts, months, 'p990')
```

In [145…

```
"""
Step 2.3 Generating file names and repetitive functions
"""
months = ['jan', 'feb', 'mar', 'apr', 'may', 'jun', 'jul', 'aug', 'sep', 'oct', 'nov', 'dec']
def filenames_gen(months):
    filenames = []
    for i in range(len(months)):
        filenames.append('hourly_inputs_short_ts_' + months[i] + '.csv')
    return filenames
def df_names_gen(months):
    df_names = []
    for i in range(len(months)):
        df_names.append('df_' + months[i])
    return df_names
def outfunc_gen(df_names, filenames):
    out = []
    for i in range(len(filenames)):
        out.append(df_names[i]+'.to_csv(' + filenames[i] + ', index=True)')
    return out
def plotEPmm(df):
    plt.plot(df['day_and_time'], df['EP(mm)'])
    return 0
```

Sensitivity Analysis

In [2]:
```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
```

In [ ]:
```
"""
Conceptual modeling ->
Functions to plot flow partitionign depending on the states of unsaturated storages.
"""
```

In [1]:
```
# Check manning equation
S_LPD_max = 60.2
S_LPD_min = 2.8
n = 0.14
slope = 0.27

def manning(SLPD, n, slope, S_LPD_min, S_LPD_max):
    QLout = np.zeros(len(SLPD))
    for i in range(len(SLPD)):
        A = SLPD[i] / 1000
        P = (A * 2 + 1) /1000
        Qmann = (((A/P)**(2/3) * slope**(1/2)) / n) / 3600  * 1000
        if (SLPD[i] <= S_LPD_min):
            QLout[i] = 0
        elif ((SLPD[i] - Qmann) <= S_LPD_min):
            QLout[i] = SLPD[i] - S_LPD_min
        elif (SLPD[i] <= S_LPD_max):
            QLout[i] = Qmann
        elif (SLPD[i] > S_LPD_max):
            QLout[i] = SLPD[i] - S_LPD_max + Qmann
        else:
            QLout[i] = 0
    return QLout

SLPD = (np.linspace(1, S_LPD_max+10, 150))

QLout = manning(SLPD, 0.14, slope, S_LPD_min, S_LPD_max)
plt.plot(QLout, SLPD, label = '0.14')

QLout = manning(SLPD, 0.12, slope, S_LPD_min, S_LPD_max)
plt.plot(QLout, SLPD, label = '0.12')

QLout = manning(SLPD, 0.10, slope, S_LPD_min, S_LPD_max)
plt.plot(QLout, SLPD, label = '0.10')

QLout = manning(SLPD, 0.08, slope, S_LPD_min, S_LPD_max)
plt.plot(QLout, SLPD, label = '0.08')

QLout = manning(SLPD, 0.06, slope, S_LPD_min, S_LPD_max)
plt.plot(QLout, SLPD, label = '0.06')

plt.axhline(y=S_LPD_min, color='gray', linestyle='--')
plt.text(20.5, S_LPD_min+2,'S LPD min', color='gray')
plt.text(0.5, S_LPD_max+2,'S LPD max', color='gray')
plt.axhline(y=S_LPD_max, color='gray', linestyle='--')
plt.xlabel('Lateral outflux [mm/h]')
plt.ylabel('Storage [mm]')
plt.legend(title = 'Manning n = ')
plt.grid(alpha=0.25)
plt.savefig(fname='R_model_processes_ManningLPD,jpg', dpi=300)
```

In [2]:
```
# Check infiltration submodel
# Eq. 9(a)LCv Effective water content
SUmin = 52
SUmax = 166.4
ksat = 50.4
nGenuchten = 2.4


def funSe(SU, SUmin, SUmax): #9a
    theta = max(SU, SUmin+1)
    Se = (theta - (SUmin-50)) / (SUmax - (SUmin-50))
    return Se

def KvG(Se, ksat, nGenuchten): #9b
    m = 1 - (1 / nGenuchten)
    l = 0.5
    kth = ksat * Se**l * (1-(1-Se**(1/m))**m)**2
    return kth

def inf(SU, Pin, SUmax, kth): #9c
    fs = kth * (1 - np.exp(-Pin / kth))
    Qinf = min(Pin * fs, Pin)
    QOFout = Pin - Qinf
    return Qinf, QOFout

def inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten): #9d
    Qinf = np.zeros(len(SU))
    QOFout = np.zeros(len(SU))
    for i in range(len(SU)):
        Se = funSe(SU[i], SUmin, SUmax)
        if SU[i] > SUmax:
```

```
            kth = ksat
        else:
            kth = KvG(Se, ksat, nGenuchten)
        Qinf[i], QOFout[i] = inf(SU[i], Pin, SUmax, kth)
    return Qinf, QOFout


Pin = 1
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='1')

Pin = 3
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='2')

Pin = 5
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='5')

Pin = 7
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='7')

plt.axhline(y=SUmin, color='gray', linestyle='--')
plt.text(1.4, SUmin-9,'S min', color='gray')
plt.text(0.2, SUmax-7,'S max', color='gray')
plt.axhline(y=SUmax, color='gray', linestyle='--')
plt.legend(title='n Genuchten = 2.4 \n Surface influx [mm/h] =', loc='upper right')
plt.xlabel('')
plt.ylabel('')
plt.grid(alpha=0.25)
plt.xlim([0, 7.25])
plt.ylim([-1, 180])
plt.xticks(color='w')
plt.yticks(color='w')
plt.title('')
plt.savefig(fname='R_model_processes_Infiltration_TGpin_b', dpi=300)


plt.figure()

Pin = 1
nGenuchten = 2.0
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='2.0')

nGenuchten = 2.2
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='2.2')

nGenuchten = 2.4
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='2.4')

nGenuchten = 2.6
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='2.6')

plt.axhline(y=SUmin, color='gray', linestyle='--')
plt.text(.28, SUmin-9,'S min', color='gray')
plt.text(0.45, SUmax-7,'S max', color='gray')
plt.axhline(y=SUmax, color='gray', linestyle='--')
plt.legend(title='Surface influx = 1mm/h \n n Genuchten [-] =', loc='upper left')
plt.xlabel('')
plt.ylabel('Unsaturated Storage, Planting Soil [mm]')
plt.grid(alpha=0.25)
plt.xticks(color='w')
plt.xlim([0, 1.05])
plt.ylim([-1, 180])
plt.title('')
plt.savefig(fname='R_model_processes_Infiltration_TGnG_a', dpi=300)
```

In [3]:
```
# Check infiltration submodel
# Eq. 9(a)LCv Effective water content
SUmin = 13
SUmax = 201.5
ksat = 7200
nGenuchten = 4


def funSe(SU, SUmin, SUmax): #9a
    theta = max(SU, SUmin+1)
    Se = (theta - (SUmin-10)) / (SUmax - (SUmin-10))
    return Se

def KvG(Se, ksat, nGenuchten): #9b
```

```
    m = 1 - (1 / nGenuchten)
    l = 0.5
    kth = ksat * Se**l * (1-(1-Se**(1/m))**m)**2
    return kth

def inf(SU, Pin, SUmax, kth): #9c
    fs = kth * (1 - np.exp(-Pin / kth))
    Qinf = min(Pin * fs, Pin)
    QOFout = Pin - Qinf
    return Qinf, QOFout

def inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten): #9d
    Qinf = np.zeros(len(SU))
    QOFout = np.zeros(len(SU))
    for i in range(len(SU)):
        Se = funSe(SU[i], SUmin, SUmax)
        if SU[i] > SUmax:
            kth = ksat
        else:
            kth = KvG(Se, ksat, nGenuchten)
        Qinf[i], QOFout[i] = inf(SU[i], Pin, SUmax, kth)
    return Qinf, QOFout


Pin = 1
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='1')

Pin = 3
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='2')

Pin = 5
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='5')

Pin = 7
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='7')

plt.axhline(y=SUmin, color='gray', linestyle='--')
plt.text(0.2, SUmin-10,'S min', color='gray')
plt.text(0.2, SUmax-10,'S max', color='gray')
#plt.text(5.76, 120,'n-G = 4.0', color='k')
plt.axhline(y=SUmax, color='gray', linestyle='--')
plt.legend(title='n Genuchten = 4.0 \n Surface influx [mm/h] =', loc='center right')
plt.xlabel('Infiltration Rate [mm/h], varying surface flux (Pin)')
plt.ylabel('')
plt.grid(alpha=0.25)
plt.xlim([0, 7.25])
plt.ylim([-1, 220])
plt.yticks(color='w')
plt.title('')
plt.savefig(fname='R_model_processes_Infiltration_Spin_d', dpi=300)



plt.figure()

Pin = 1
nGenuchten = 3
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='3.0')

nGenuchten = 3.5
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='3.5')

nGenuchten = 4
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='4.0')

nGenuchten = 4.5
SU = np.linspace(0, SUmax+10, 100)
Qinf, QOFout = inf_submodule(SU, Pin, SUmax, SUmin, ksat, nGenuchten)
plt.plot(Qinf, SU, label='4.5')

plt.axhline(y=SUmin, color='gray', linestyle='--')
plt.text(0.02, SUmin-10,'S min', color='gray')
plt.text(0.02, SUmax-10,'S max', color='gray')
plt.axhline(y=SUmax, color='gray', linestyle='--')
plt.legend(title='Surface influx = 1mm/h \n n Genuchten [-] =', loc='center left')
plt.xlabel('Infiltration Rate [mm/h]')
plt.ylabel('Unsaturated Storage, Sand [mm]')
plt.xlim([0, 1.05])
plt.ylim([-1, 220])
plt.grid(alpha=0.25)
```

```
plt.title('')
plt.savefig(fname='R_model_processes_Infiltration_SnG_c', dpi=300)
```

In [4]:

```
#constants
SUmax = 166.4
SUmin = 52
Pmax = 114.4
# Check percolation submodel
def funQP(SU, SUmax, Pmax, SUmin):
    if (SU <= SUmin):
        QP = 0
    else:
        QP = Pmax * min(SU-SUmin, SUmax-SUmin) / SUmax
    return QP

fig = plt.figure()
ax = fig.add_subplot(111)
ax.set_aspect(0.5)
SU = np.linspace(0, 220, 100)
QP = np.zeros(len(SU))
for i in range(len(SU)):
    QP[i] = funQP(SU[i], SUmax, Pmax, SUmin)
plt.plot(QP, SU)

plt.axhline(y=SUmin, color='gray', linestyle='--')
plt.text(3, SUmin-11,'S min', color='gray')
plt.text(0.02, SUmax-11,'S max', color='gray')
plt.axhline(y=SUmax, color='gray', linestyle='--')
plt.xlabel('Percolation Rate from Planting Soil [mm/h]')
plt.ylabel('Unsaturated Storage [mm]')
plt.grid(alpha=0.25)
plt.xlim([-10, 180])
plt.ylim([-1, 220])
plt.title('')
plt.savefig(fname='R_model_processes_PercolationTG', dpi=300)

fig = plt.figure()
ax = fig.add_subplot(111)
ax.set_aspect(0.5)

#constants
SUmax = 201.5
SUmin = 13
Pmax = 188.5

SU = np.linspace(0, SUmax+20, 100)
QP = np.zeros(len(SU))
for i in range(len(SU)):
    QP[i] = funQP(SU[i], SUmax, Pmax, SUmin)

plt.plot(QP, SU)
plt.axhline(y=SUmin, color='gray', linestyle='--')
plt.text(3, SUmin-11,'S min', color='gray')
plt.text(0.02, SUmax-11,'S max', color='gray')
plt.axhline(y=SUmax, color='gray', linestyle='--')
plt.xlabel('Percolation Rate from Sand [mm/h]')
#plt.ylabel('Unsaturated Storage[mm]')
plt.grid(alpha=0.25)
plt.xlim([-10, 180])
plt.ylim([-1, 220])
plt.yticks(color='w')
#plt.yticks([])
plt.title('')
plt.savefig(fname='R_model_processes_PercolationS', dpi=300)
```

In [5]:

```
# soil evap and transpiration
def soil_evap(EP, LAI, SU, SUmin):
    ESPpot = EP * np.exp(-0.4 * LAI)
    if ((SU - ESPpot) > (SUmin+1)):
        ESP = ESPpot
    elif ((SU > SUmin) & ((SU-ESPpot)<SUmin)):
        ESP = 0 #SU - SUmin
    else:
        ESP = 0
    return ESP

def transpiration(EP, ESP, SU, SUmin):
    if EP==0:
        return 0
    ETpot = (1 - ESP / EP) * EP
    if ((SU - ETpot) > (SUmin+1)):
        ET = ETpot
    elif ((SU > SUmin) & ((SU - ETpot) <= SUmin)):
        ET = 0 #SU - SUmin
    else:
        ET = 0
    return ET

#TG
plt.figure()
SUmaxTG = 166.4
SUminTG = 52
LAI = 1
EP = 1
```

```
SUTG = np.linspace(0, SUmaxTG+20, 100)
ESP = np.zeros(len(SUTG))
for i in range(len(SUTG)):
    ESP[i] = soil_evap(EP, LAI, SUTG[i], SUminTG)
plt.plot(ESP, SUTG, label = '= 1')
LAI = 3
SUTG = np.linspace(0, SUmaxTG+20, 100)
ESP = np.zeros(len(SUTG))
for i in range(len(SUTG)):
    ESP[i] = soil_evap(EP, LAI, SUTG[i], SUminTG)
plt.plot(ESP, SUTG, label = '= 3')
LAI = 5
SUTG = np.linspace(0, SUmaxTG+20, 100)
ESP = np.zeros(len(SUTG))
for i in range(len(SUTG)):
    ESP[i] = soil_evap(EP, LAI, SUTG[i], SUminTG)
plt.plot(ESP, SUTG, label = '= 5')
LAI = 7
SUTG = np.linspace(0, SUmaxTG+20, 100)
ESP = np.zeros(len(SUTG))
for i in range(len(SUTG)):
    ESP[i] = soil_evap(EP, LAI, SUTG[i], SUminTG)
plt.plot(ESP, SUTG, label = '= 7')

plt.legend()
plt.axhline(y=SUminTG, color='gray', linestyle='--')
plt.text(0.2, SUminTG-9,'S min', color='gray')
plt.text(0.2, SUmaxTG-9,'S max', color='gray')
plt.axhline(y=SUmaxTG, color='gray', linestyle='--')
plt.legend(title='Potential \n Evaporation = 1mm/h \n LAI [-] = ', loc='upper right')
plt.xlabel('Soil Evaporation [mm/h]')
plt.ylabel('Unsaturated Storage, Planting Soil [mm]')
plt.grid(alpha=0.25)
plt.xlim([-0.05,1.05])
plt.title('')
plt.savefig(fname='R_model_processes_SoilEvap', dpi=300)



plt.figure()
#Sand
SUminS = 13
SUmaxS = 201.5
ESP = 0.0
SUS = np.linspace(0, SUmaxS+20, 100)
EP = 0.2
ET = np.zeros(len(SUS))
for i in range(len(SUS)):
    ET[i] = transpiration(EP, ESP, SUS[i], SUminS)
plt.plot(ET, SUS, label='=0.2')

EP = 0.4
ET = np.zeros(len(SUS))
for i in range(len(SUS)):
    ET[i] = transpiration(EP, ESP, SUS[i], SUminS)
plt.plot(ET, SUS, label='=0.4')

EP = 0.6
ET = np.zeros(len(SUS))
for i in range(len(SUS)):
    ET[i] = transpiration(EP, ESP, SUS[i], SUminS)
plt.plot(ET, SUS, label='=0.6')

EP = 0.8
ET = np.zeros(len(SUS))
for i in range(len(SUS)):
    ET[i] = transpiration(EP, ESP, SUS[i], SUminS)
plt.plot(ET, SUS, label='=0.8')

EP = 1
ET = np.zeros(len(SUS))
for i in range(len(SUS)):
    ET[i] = transpiration(EP, ESP, SUS[i], SUminS)
plt.plot(ET, SUS, label='=1.0')

plt.legend()
plt.axhline(y=SUminS, color='gray', linestyle='--')
plt.text(0.02, SUminS+3,'S min', color='gray')
plt.text(0.02, SUmaxS-9,'S max', color='gray')
plt.axhline(y=SUmaxS, color='gray', linestyle='--')
plt.legend(title='Potential \n Transpiration\n [mm/hr] = ', loc='upper right')
plt.xlabel('Transpiration [mm/h]')
plt.ylabel('Unsaturated Storage, Sand [mm]')
plt.grid(alpha=0.25)
plt.xlim([-0.05,1.05])
plt.title('')
plt.savefig(fname='R_model_processes_Transpiration', dpi=300)
```